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# Rapid Climate Changes and human dynamics during the Holocene in the Eastern Mediterranean (Lower Strymon Valley, northern Greece)

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## HIGHLIGHTS

- Continuous chronostratigraphic sequence of 24.5 m covering the last seven millennia.
- Attested anthropogenic impact from the Late Neolithic.
- A dry period is recorded at 4.2 ka cal BP
- Continuous agricultural practices only evidenced since 4 ka cal BP.
- Human resilience indicates complex interplay between ecological and cultural factors.

## ABSTRACT

The study was conducted in the southern part of the lower Strymon valley, in northern Greece, and revealed up to 25 meters of fluvio-lacustrine sediments deposited over the last seven millennia. This sedimentary record represents a significant opportunity for high-resolution palaeoenvironmental studies of the period from 6 to 3 ka cal BP linked to land use and climate change. The results of geophysical investigations, multi-proxy sedimentological (grain size, magnetic susceptibility, loss-on-ignition), pollen and NPP analyses, based on high-precision radiocarbon dating enabled reconstruction of past landscapes as well as a comprehensive discussion of anthropogenic responses and their impact on the vegetation cover, especially during periods with well-known Holocene Rapid Climate Change events (5.6, 4.2 and 3.2 ka cal BP).

During the 7-5.7 ka cal BP corresponding to the Late and Final Neolithic, wet conditions created an extended lake surrounded by the densely wooded Strymon watershed, followed by a shift to a shallower lake environment that lasted until ca. 4.5 ka cal BP. The continuous presence of

48 anthropogenic taxa suggests the persistence of human activities even in the absence of formally  
49 recognized sites, suggesting the relocation of settlements. The first signs of human disturbance of  
50 the landscape at regional scale occurred toward 5.2 ka cal BP (onset of the Early Bronze Age). The  
51 so-called « 4.2 ka BP event », which coincided with the end of the Early Bronze Age and the  
52 transition to the Middle Bronze Age, is divided into three distinct periods (4.35-4.1, 4.1-3.95 and  
53 3.95-3.75 ka cal BP). The first corresponds to gradual aridification before a period with severe dry  
54 conditions that marks a tipping point toward wetland contraction. From this period on,  
55 diversification, and multiplication of anthropogenic species including *Olea*, *Juglans* and *Castanea*  
56 reflect a global trend toward cultural landscapes. The later periods are characterized by dramatic  
57 climatic change around 3.2-3 ka cal BP, at the end of Late Bronze Age, and increasing impacts of  
58 agro-pastoral activities and forest clearing starting at the beginning of Antiquity, around 2.8 ka cal  
59 BP (Thracian period). After the 4.2 ka cal BP event and we suggest that climatic adversity may have  
60 acted as a stimulus to innovation and relocation rather than retarding societal development in the  
61 region. To conclude, environmental factors in the lower Strymon valley were not sufficient on their  
62 own to trigger a social crisis similar to that mentioned in the Middle East

63

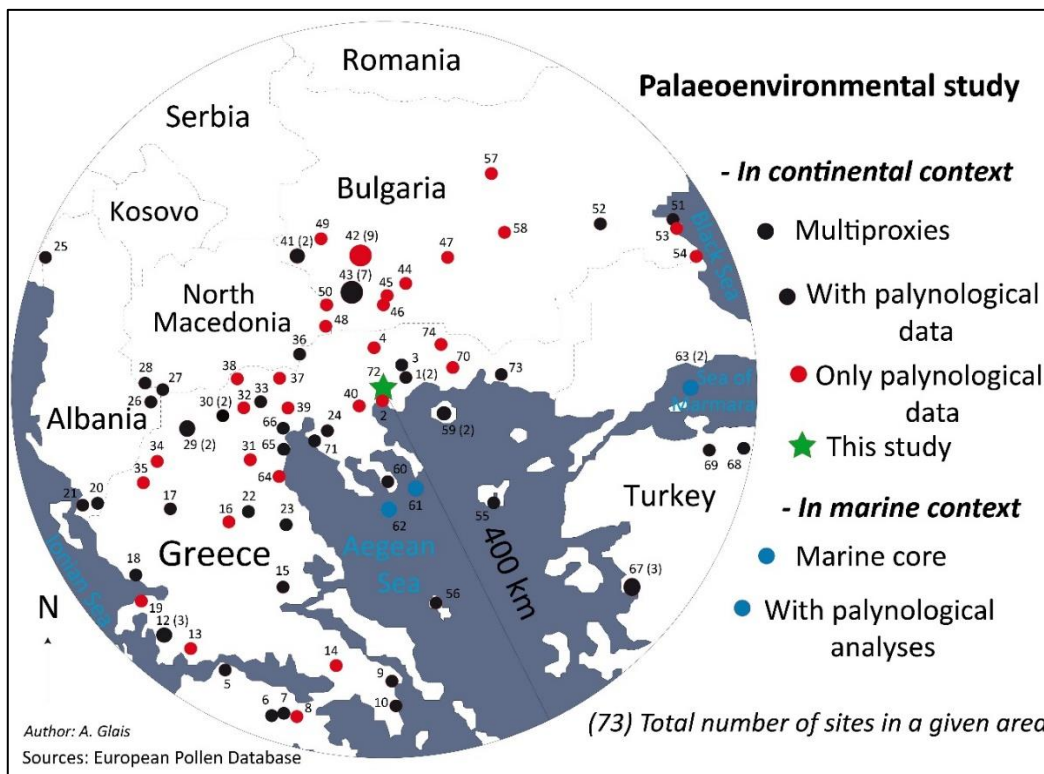
64 **Key words: Rapid Climate Changes; 4.2 ka cal BP event; human resilience; northern**  
65 **Aegean; fluvio-lacustrine archive; eastern Mediterranean.**

66

67 **1. Introduction**

68 Holocene Rapid Climate Changes (RCCs) characterize periods of 150 to 500 years and are often  
 69 considered as driving factors of socio-economic and cultural change (Mayewski *et al.*, 2004).  
 70 Numerous authors discuss the collapse of civilizations in response to some of these abrupt climate  
 71 changes in the Eastern Mediterranean (e.g. Weiss *et al.*, 1993; Weninger *et al.*, 2009; Büntgen *et al.*  
 72 *et al.*, 2011; Drake, 2012; Weiss, 2012; 2017; Kaniewski *et al.*, 2013, 2015, 2018; Wiener, 2014; Knapp  
 73 and Maning, 2016; Cookson *et al.*, 2019, Florescu *et al.*, 2019). Nevertheless, uncertainties remain  
 74 about the nature of this RCC, which could involve a combination of orbital, ocean circulation, large-  
 75 scale tropical volcanic eruptions, and solar forcing (Finné *et al.*, 2011; Wanner *et al.*, 2011), and  
 76 could explain the complexity of the mid-Holocene climate transition (Magny *et al.*, 2013;  
 77 Triantaphyllou *et al.*, 2009). Furthermore, the impacts of climate change need to be assessed in  
 78 terms of biophysical and social resilience and/or vulnerability (Butzer and Endfield, 2012). And there  
 79 is also a need for more site-specific detailed studies focusing on ecological foundations and  
 80 strategies (Flohr *et al.*, 2016; Lespez *et al.*, 2016). Only such work, closely interlinked to  
 81 multidisciplinary analyses within archaeological sites, will optimize our perception of forms of socio-  
 82 ecological resilience (Berger *et al.*, 2016; Lespez *et al.*, 2016). Research in lakes (Ohrid: Sadori *et al.*,  
 83 2016; Sinopoli *et al.*, 2018; Dojran: Francke *et al.*, 2013; Masi *et al.*, 2018; Prespa: Aufgebauer *et al.*,  
 84 *et al.*, 2012; Panagiotopoulos *et al.*, 2013; 2014) or from marine cores in the Aegean Sea (Kotthoff *et al.*,  
 85 *et al.*, 2008a; Triantaphyllou *et al.*, 2014) revealed the potential of the southern Balkans and the  
 86 northern Aegean Sea for obtaining data on climate trends in the eastern Mediterranean basin (Fig.  
 87 1; Table 3 in supplementary data). In this context, eastern Macedonia (Greece) offers high potential  
 88 for studying vegetation changes in response to climatic and anthropogenic processes (e.g.,  
 89 Wijmstra 1969; Greig and Turner, 1974; Tzedakis *et al.*, 2006; Pross *et al.*, 2007; 2009; Peyron *et al.*,  
 90 2011).

91



92  
 93  
 94  
 95

Figure 1: Location of the main previously published palaeoenvironmental investigations discussed in the text within a radius of 400 km around the study area (green star). For a complete list of sites summarized by the numbers on the map and the main reference cited, see supplementary data.

96 Despite the increasing number of investigations of the relationship between social processes and  
97 RCCs, the debate continues concerning their impact on settlement patterns, population dynamics  
98 or social adaptations. In eastern Macedonia, the lack of a signature of the 4.2 ka cal BP climatic  
99 event in the climatic and environmental proxies studied explains why, until now, the many studies  
100 conducted in this area (Atherden *et al.*, 2000; Bottema, 1982; Gerasimidis, 2000; Glais *et al.*, 2016a,  
101 b; Greig and Turner, 1974; Lespez, 2003; 2007, Peyron *et al.*, 2011; 2016) have not been able to  
102 explain the environmental transformations brought about by the RCC and its impact on societies.  
103 This research using multi-proxy palaeoecological studies provides independent lines of evidence of  
104 climate change to compare with local archaeological evidence (Hjelle *et al.*, 2012). But  
105 archaeological data are subject to biases due to the taphonomic processes that explain variations  
106 in the visibility of artefacts, or insufficient/inappropriate temporal resolution (e.g. Surovell *et al.*,  
107 2009; Tsirtsoni *et al.*, 2020a). Accordingly, one of the most difficult challenges is to reconstruct the  
108 population trends and to translate them into statistical data, either from a cultural or an eco-  
109 cultural perspective (Bevan *et al.*, 2019; Lawrence *et al.*, 2021; Weiberg *et al.*, 2019; Whitford,  
110 2018). In our study area (see below for description), i.e. the lower Strymon valley, which, together  
111 with the adjacent Philippi-Drama plain and the island of Thasos form the Greek region of Eastern  
112 Macedonia, such reconstructions are lacking, despite the great number of known settlements (e.g.  
113 Koukouli-Chryssanthaki *et al.*, 2008) and the great number of available radiocarbon dates from  
114 archaeological contexts (Tsirtsoni, 2016). From an archaeological perspective, the time interval  
115 considered in this study relates to the periods from the Late-Final Neolithic to the onset of  
116 Antiquity. Some periods show a dramatic decline in settlement, the most remarkable being the  
117 transition from the Neolithic to the Early Bronze Age, which partly coincides with the 5.6-5.2 ka cal  
118 BP event. Several authors consider it a major cultural break that also affected other parts of the  
119 Aegean and the Balkans (e.g. Todorova, 1995; Coleman 2011; Weiberg *et al.*, 2019), but others tend  
120 to minimize it, instead emphasizing signs of continuity (Andreou *et al.*, 1996; Demakopoulou, 1996;  
121 see also detailed discussion in Tsirtsoni 2016b, and Lespez *et al.*, 2014; 2016). Another obscure  
122 period is the end of the Early and the transition to the Middle Bronze Age, which coincides almost  
123 perfectly with the 4.3-3.8 ka cal BP event. Previously less discussed in the local archaeological  
124 literature than the preceding period, this apparent gap in settlement has recently received  
125 attention (Leshtakov and Tsirtsoni 2016).

126 In the present study, we use a *one-site* (local) scale, then combine our results with other one-  
127 site studies to reach a *one-area* (regional) scale (Mercuri *et al.*, 2014, 2019). We have already used  
128 this methodology in our previous studies in Eastern Macedonia (Dikili Tash: Lespez *et al.*, 2000;  
129 2013; Glais *et al.*, 2016a; 2017), as it has also been used in other Mediterranean contexts (Dispilio:  
130 Karkanas *et al.*, 2011; Kouli, 2015; La Draga: Revelles *et al.*, 2017). More specifically, the results  
131 from one core located close to an archaeological site in the lower Strymon valley are discussed from  
132 the perspective of a broader human-environment interaction. Our objective is to examine the  
133 nature of palaeoenvironmental transformations during three of the most important RCC events of  
134 this period (5.6-5.2, 4.3-3.8 and 3.2-2.8 ka cal BP), and their potential effects on land use by humans.

135

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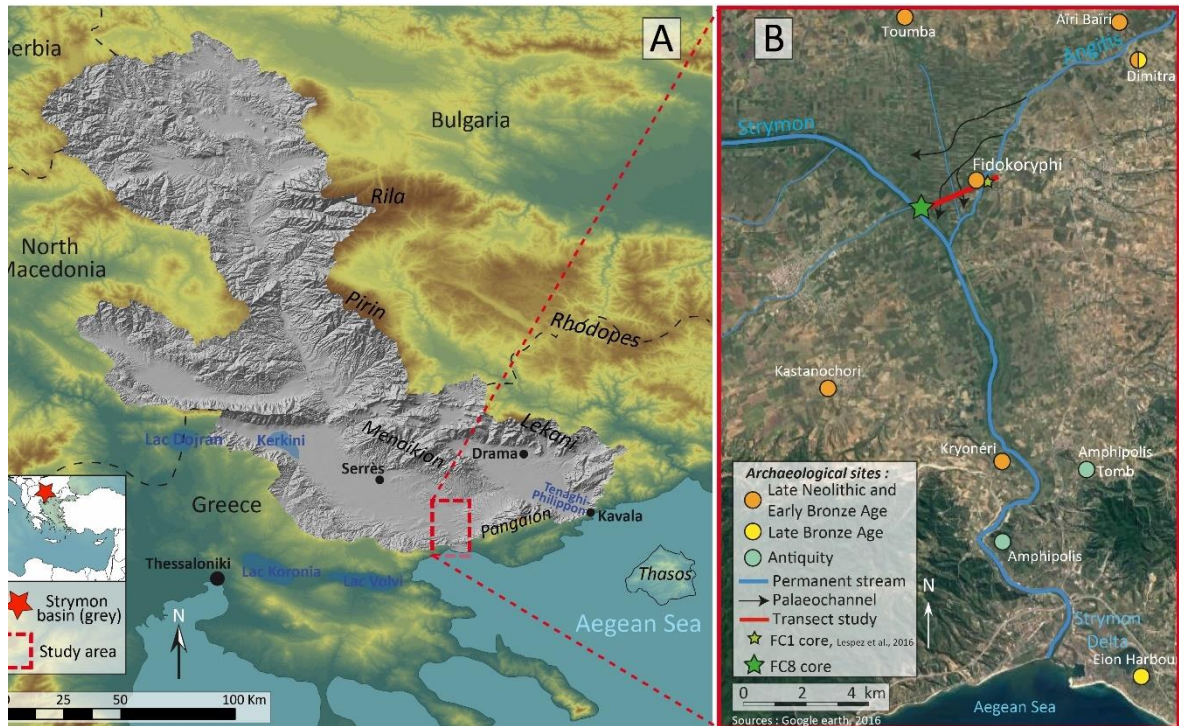
## 137 **2. Regional setting and previous research**

### 138 **2.1. Geological, Geomorphological, and environmental setting**

139 The River Strymon is a large permanent fluvial system running roughly north-south with an  
140 average stream flow of 80 m<sup>3</sup>/s. From its source, 415 km upstream in the Vitosha Mountains at an  
141 elevation of 2,180 m a.s.l., the watershed covers approximately 18,078 km<sup>2</sup> across Bulgaria, North  
142 Macedonia and Greece and ends where the river flows into the Aegean Sea at Orphanos Bay (Fig.  
143 2). The lower Strymon valley forms an 80 km long, 20 km wide, subsiding basin located along a  
144 Cenozoic fault detachment system, between the Serbo-Macedonian massif to the west and



145 southern Rhodope massif (Pangaion and Menoikion mountains) to the east that rise between 1,300  
 146 and 2,100 m a.s.l.. Tectonic activity was high during the Pleistocene and remains high today (Tranos,  
 147 2011; Mouslopoulou et al., 2014), although the study area has been relatively stable during the  
 148 Holocene (Broussoulis et al., 1991). The bottom of the valley is fringed by Neogene hills with  
 149 calcimagnesian soils and coalescing series of middle and upper Pleistocene alluvial fans, made of  
 150 gravelly reddish-brown sediments (Psilovikos, 1986). The climate is sub-Mediterranean with a  
 151 continental influence. Furthermore, local topography plays a significant role during atmospheric  
 152 disturbance. Despite marked interannual variability, the mean annual temperature is 15 °C and  
 153 annual precipitation in the plain is 600-650 mm (Horvat et al., 1974).  
 154

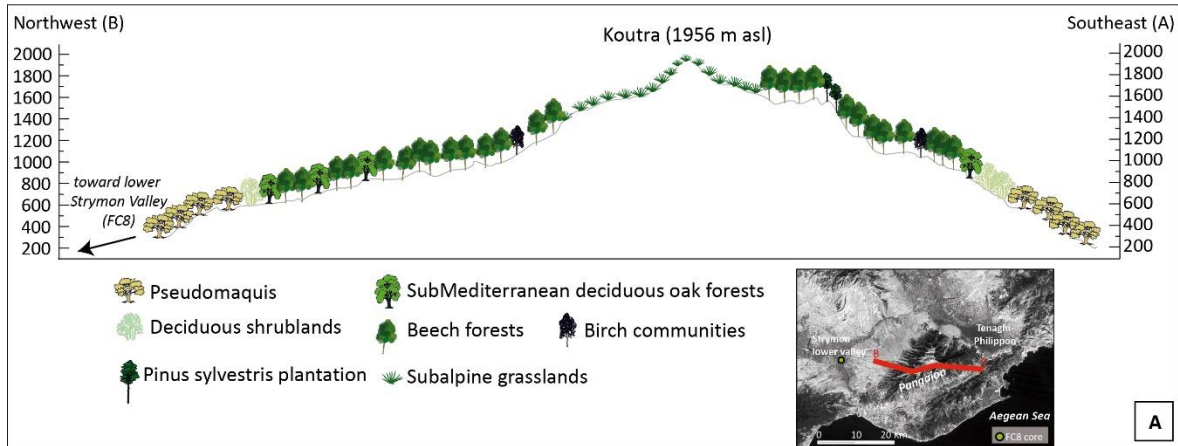


155  
 156 *Figure 2: A: Location of the Strymon watershed and the study area; B: Transect study and known archaeological*  
 157 *sites in the lower Strymon Valley*

158 The current landscape in the lower Strymon plain was extensively modified by the complete  
 159 drainage of Achinos Lake, which occupied the valley until 1930s (Lespez, 2008; Fig. 3). Although  
 160 affected by human disturbance, the vegetation on Mount Pangaion, which dominates the valley  
 161 eastwards, is divided into vertical vegetation zones with marked diversity resulting from the meso-  
 162 and microclimate and the different types of substrate (Fig. 3). At lower altitudes (200-600 m a.s.l.),  
 163 pseudo-maquis dominated by *Quercus coccifera* is well developed, mainly on slopes with southern  
 164 exposure that reach higher altitudes in some locations (up to 1,000 m a.s.l.). The pseudo-maquis is  
 165 gradually replaced by deciduous shrubland at higher altitudes (700-900 m asl), mainly composed of  
 166 *Carpinus orientalis*, *Fraxinus ornus*, *Acer monspessulanum*, *Ligustrum vulgare*, *Lonicera etrusca*,  
 167 *Cornus mas* and *Ostrya carpinifolia*, although this sub-Mediterranean vegetation probably results  
 168 from human impacts, overgrazing and forest fires (Tsiftsis et al., 2007). Above 900 m a.s.l.,  
 169 xerothermic sub-Mediterranean deciduous oak woodlands are mainly dominated by *Quercus*  
 170 *frainetto*, *Q. pubescens* and *Q. petraea* on northeastern slopes. Beech forests (*Fagus sylvatica*) grow  
 171 above the oak or localized chestnut forests on gneiss schist, marble, and, more rarely, on granite  
 172 (Papageorgiou et al., 2014), although at lower altitudes they form mixed stands with oaks (Tsiripidis  
 173 et Athanasiadis, 2003). On Mount Pangaion, beech forests grow down to 600 m a.s.l., while their  
 174 upper limits may reach 1,800 m a.s.l. forming the timberline (Fig. 3; Glais et al., 2016c). Above,

175 timberline subalpine calcareous grasslands are well developed (Strid and Tan, 1997;  
 176 Karagiannakidou et al., 2001), characterized by a diverse flora dominated by perennial grasses and  
 177 other forbs including *Sesleria achtarovii*, *Asperula petraeus*, *Dianthus petraeus*, *Festuca ovina* agg.,  
 178 *Carex halleriana*, *Festuca varia*, *Stipa pennata*, *Rostraria cristata*, *Vincetoxicum hirundinaria*,  
 179 *Polygala nicaeensis*, and *Scabiosa ochroleuca*.

180



181  
 182 *Figure 3: A: Synthetic altitudinal vegetation gradient on Mount Pangaion; B: Photo of the intensively cultivated and*  
 183 *temporarily flooded Strymon plain taken from the northwestern slope of Mount Pangaion (May 2015).*

184 **2.2. Archaeological background**

185 The Strymon River valley has always been an important communication route and a macro-scale  
 186 ecological transition zone through the Mediterranean and northern continental climatic zone. This  
 187 transitional environment was particularly involved in the spread of agricultural practices in Europe  
 188 at an early stage of the Neolithic period, around 8000 cal BP (ca. 6000 BC: Weninger et al., 2006;  
 189 Marinova, 2007; Marinova et al., 2012; Berger, 2017; Lespez et al., 2013, 2017; Reingruber et al.  
 190 2017; Krauss et al., 2017; Ivanova et al., 2018; Whitford, 2018). The two following millennia  
 191 witnessed a significant increase in the number of sites all along its course (Chohadzhiev, 2007;  
 192 Todorova et al., 2007). Most of the sites appear to have been temporarily or permanently

193 abandoned by the end of the 5<sup>th</sup> millennium BC, i.e. shortly before 6000 cal BP, like in most of  
194 northern Greece and Bulgaria (see Tsirtsoni 2016b; 2016d). One millennium later (beginning of the  
195 Early Bronze Age) the density of settlements again increased, but remained much lower than during  
196 the previous Neolithic and Chalcolithic periods (Grammenos and Fotiadis 1980; Grammenos 1991;  
197 Grebska-Kulowa and Kulow 2007). Sites dating from the Late Bronze Age (second half of the 2<sup>nd</sup>  
198 mill. BC, ca. 3500-3100 cal BP) are more numerous and sometimes more monumental than those  
199 dating from earlier periods (Atanassov *et al.*, 2012; Soukantos *et al.*, 2012). In fact, sites dating from  
200 the Middle Bronze Age (end of 3<sup>rd</sup> and first half of the 2<sup>nd</sup> mill. BC, ca. 4300-3500 cal BP) have not  
201 been found in the area. The Fidokoryphi settlement is one of the six known Late Neolithic and  
202 Bronze Age sites located in the lower Strymon valley within a radius of 10 km from its confluence  
203 with the Angitis, its main affluent to the east. The other sites are Dimitra, Airi Bairi, Toumba,  
204 Kastanochori and Kryoneri (Grammenos and Fotiadis, 1980; Grammenos, 1997; Malamidou, 2016:  
205 Fig. 2). Only Dimitra and Kryoneri have been partially excavated, the other sites are known only  
206 from surface finds (in fact, systematic excavation has started also at Toumba in 2022, but no report  
207 is published yet). Consequently, the periods indicated here (Fig. 2B) are only indicative and their  
208 true duration of occupation could be substantially longer.

209

### 210 **2.3. Previous geoarchaeological research**

211 The lower Strymon valley and the adjacent Drama plain to the east (comprising the former  
212 Tenaghi-Philippon marsh) have been the focus of intense geoarchaeological research for several  
213 years now and confirmed their archaeological and palaeoenvironmental potential (Gerasimidis,  
214 2000; Lespez, 2003; 2007; Lespez *et al.*, 2013; 2016; 2020; Glais *et al.*, 2016a; 2016b; 2017).  
215 Concerning the lower Stymon valley more particularly, a series of cores have been already drilled  
216 (maximum 10 meters thick in the current floodplain near the confluence with the Angitis River. The  
217 chronostratigraphic framework was established through 31 AMS based on seven cores and one  
218 sedimentary cross section of the riverbank and a multiproxy analysis was performed on the FC1  
219 core located at the foot of Fidokoryphi hill on bank of the River Angitis (Glais *et al.*, 2016b; Lespez  
220 *et al.*, 2016). The present study continues these investigations while focusing on the results  
221 obtained from core FC8, located ca. 2 km from FC1.

222

## 223 **3. Materials and methods**

### 224 **3.1. Coring**

225 The reconstruction of the landscape, climate and hydrological condition changes is based on a  
226 detailed study of sedimentary deposits extracted by coring. The analysis focused on core FC8,  
227 located on the left riverbank of the present Strymon channel (40° 54' 48.733" N; 23° 47' 54.225" E)  
228 corresponding to the westernmost core of a 2.5 km transect study. The 24.5 m core was obtained  
229 in July 2012 using a mechanical Longyear LY34 drill. It replicated a previous core (FC5) made with a  
230 hand-driven drill down to a depth of 11 m (Lespez *et al.*, 2016; Glais *et al.*, 2016b). For the present  
231 study, the data from the two cores were combined. A written description of core FC8 was produced  
232 in the field. Sediment samples were collected and subsampling at 5 cm intervals was performed  
233 immediately; the samples were stored at 5 °C prior to laboratory analysis.

234

### 235 **3.2. Electrical Resistivity Tomography (ERT)**

236 In addition, in January 2016, an ERT survey was conducted along a 2 km west-east profile (from  
237 FC8 to FC1) using a pole-dipole array. This array has not only a good investigation depth but also  
238 good horizontal coverage and a strong signal/noise ratio. Electrodes spaced 5 meters apart yielded  
239 a depth of investigation of 80 meters, even though the confidence limit was set at 60-70 meters to



240 account for the fact that few reliable values appear below this depth. The device used a multi-  
241 electrode system Abem Terrameter LS with 64 electrodes. Data inversion and data interpretation  
242 were carried out using Res2dinv software (Loke and Barker 1996).

243

### 244 **3.3. Chronology**

245 The chronostratigraphy of the FC5/FC8 core was determined by AMS dating using a series of 21  
246 samples from in-situ wood remains and total organic matter (Table. 1). Radiocarbon ages were  
247 calibrated using the IntCal20 atmospheric curve (Reimer et al., 2020). The age-depth model was  
248 obtained using Clam2.2 (Blaauw, 2010). The best fit was obtained applying a smooth spline  
249 solution. The confidence intervals of the calibrations and the age-depth model were calculated at  
250 95% ( $2\sigma$ ) with 1,000 iterations. Concerning the relative archaeological chronology, for the earlier  
251 (7<sup>th</sup> and early 6<sup>th</sup>) and later (late 3<sup>rd</sup> to early 1<sup>st</sup> mill. BC) periods, we follow the scheme and  
252 nomenclature of Tsirtsoni et al (2020b). Table 2 in supplementary data provides a comparison  
253 with the scheme used in the synthetic study of Weiberg et al (2019).

254

### 255 **3.4. Sedimentological analyses**

256 To characterize the depositional context and post-depositional processes, we applied standard  
257 geomorphic and sedimentological methods that include examination of the texture, structure and  
258 geometry of the sedimentary units such as those used by Miall (1996) and Brown (2008).  
259 Granulometry was measured on 189 samples collected along the 24.50m core using a laser particle  
260 analyzer (Malvern 2000), adjusting for measurements on the >2 mm fraction, after pre-treatments  
261 to remove any remaining organic matter and mixed with sodium hexametaphosphate as dispersing  
262 agent. Coarse material was removed for the laser analysis but re-integrated for each sample.  
263 Deposits were described using several variables including the median, average particle size, sorting  
264 index and overall texture. The carbonate and organic matter contents of 187 samples were  
265 measured using the loss-on-ignition (LOI) method of Dean (1974). Samples of relatively dry  
266 sediment weighing approximately 1 g were taken at intervals of less than 15 cm throughout the  
267 24.50 m sequence. After drying for 24 h at 105 °C to constant weight, the samples were heated at  
268 550 °C for 3 h to estimate organic content. A second heating period at 925 °C for 6 h was used to  
269 assess the proportion of carbonate in the sediment.

270

### 271 **3.5. Magnetic susceptibility measurements**

272 Magnetic susceptibility measurements were made at CEREGE (Aix-en-Provence, France) using  
273 an (Agico) MFK1 magnetic susceptibility meter. The FC8 sediment core was sampled at 7 cm  
274 resolution and yielded a total of 365 samples. These samples were placed in 8 x 3 cm plastic boxes,  
275 dried and weighed. In addition, measurements of low-field magnetic susceptibility, usually made at  
276 a frequency of 976 Hz, were made at 15.616 Hz. The sensitivity of the MFK1 susceptibility meter is  
277  $\approx 3 \times 10^{-8}$  SI at 976 Hz. The magnetic susceptibility values were divided by the density of the dried  
278 samples to derive specific susceptibilities ( $\chi$ ). The contribution of the superparamagnetic particles  
279 ( $< 0.03 \mu\text{m}$ ; Dearing et al., 1996) is given by frequency dependent susceptibility ( $F_d$  %) where  $\chi_{lf}$   
280 and  $\chi_{hf}$  are the specific susceptibilities measured at low and high frequency, respectively.

### 281 **3.6. Pollen analysis**

282 Pollen analysis was carried out on 96 samples of sediment weighing 5 to 10 g along the 24.50  
283 m FC8 sequence. Standard pollen extraction techniques were used (Faegri and Iversen, 1989). One  
284 *Lycopodium* tablet per sample was added to calculate the concentration of pollen (grains.cm<sup>-3</sup>)

285 (Stockmarr, 1971). To reconstruct changes in land cover, analyses focused on the identification of  
286 pollen and non-pollen palynomorphs (NPPs). Small aliquots of the residues were mounted in  
287 glycerin, sealed with Histolaque and the pollen and spores were identified and counted under a  
288 light microscope using 400x or 600x magnification, if necessary. Pollen grains, spores and NPPs were  
289 identified by comparing them with the reference collection at the Archaeobiology laboratory of  
290 Madrid (CCHS, CSIC), palynological keys and photo atlases (Moore et al., 1991; Reille, 1992; van  
291 Geel, 2001; Cugny et al., 2010). Pollen counts of up to 490 grains total land pollen (TLP) per sample  
292 were identified, excluding hydro-hygrophytic taxa and NPPs (expressed as percentages of the TLP),  
293 while the TLP average was 516 terrestrial pollen grains. Arboreal Pollen includes only tree taxa and  
294 not shrubby species. Pollen of aquatic or wetland plants as well as spores and non-pollen  
295 palynomorphs (NPPs) were excluded from the pollen sum in order to avoid biases from the local  
296 pollen representation and their percentages were calculated relative to the total land pollen sum  
297 of all terrestrial taxa taken as 100%. The pollen diagram based on these data was produced using  
298 Tilia and Tilia-Graph v. 2.0.b.5 software (Grimm, 1992, 2004). Local pollen assemblage zones (LPAZ)  
299 were defined based on agglomerative cluster analysis of the incremental sum of squares (Coniss)  
300 with square root transformed percentage data (Grimm, 1987). Figure 11 summarizes the  
301 palynological results coupled with some sedimentological data (Fig. 11).

302 We merged the species curves according to their ecological affinities. Anthropozoogenous taxa  
303 are plants associated with grazing pressure closely linked with human activities such as livestock  
304 farming, whereas anthropic-nitrophilous taxa are self-propagating plants associated with disturbed  
305 nitrophilous soil and are generally overrepresented in anthropogenic contexts, but are not crop  
306 plants (Behre, 1981; Bottema and Woldring, 1990; López-Merino et al., 2009; Florenzano et al.,  
307 2012; Marinova et al., 2012). The difficulty involved in identifying region-specific indices of human  
308 impact in pollen assemblages has to be taken into consideration due to the lack of standardization  
309 (Deza-Araujo et al., 2020). For the NPP groups (coprophilous, eu-mesotrophic, meso-oligotrophic,  
310 indicative of erosive processes, fire events or dry conditions) we used the nomenclature of Hugo  
311 de Vries (HdV Laboratory, University of Amsterdam), the ecological similarities and specific NPP  
312 study references (van Geel, 2001; Carrión and Navarro, 2002; van Geel et al., 2003; van Geel and  
313 Aptroot, 2006; Cugny et al., 2010; Gelorini et al., 2011; Miola, 2012; Kořaczek et al., 2013; Revelles  
314 and van Geel, 2016).

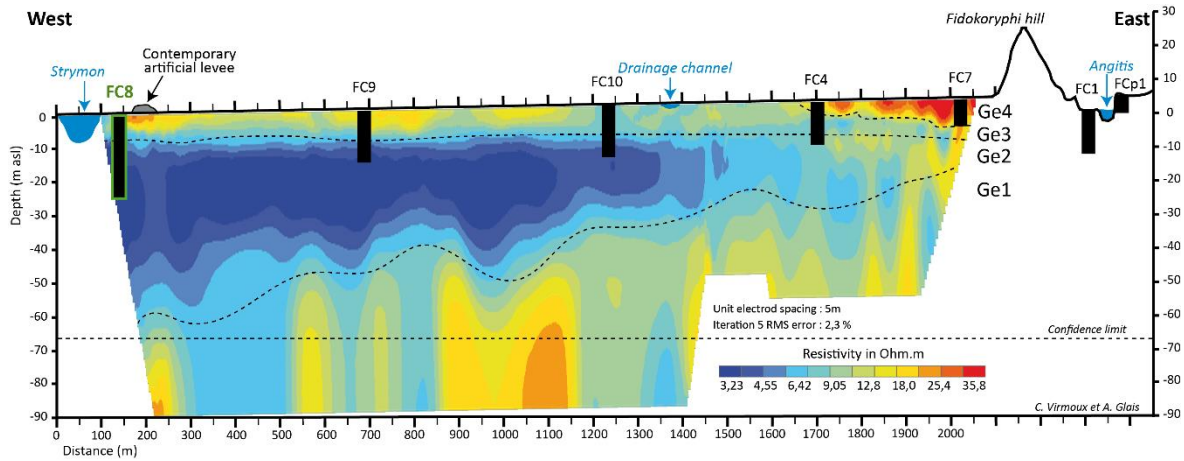
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## 316 **4. Results**

### 317 **4.1. Geometry of the sediments**

318 The ERT cross-section revealed relatively low resistivity values (< 40 Ohm.m) characteristic of a  
319 fine sediment fill. Although low, the dynamics of the observed values allowed us to understand the  
320 morphology of the lower Strymon valley (Fig.4). The main unit indicates a gentle slope from the  
321 east (Fidokoryphi hill) to the west (Strymon) forming a depression, in which the deepest point was  
322 located approximately below the current Strymon channel even though none of the cores reached  
323 the base of this sediment layer. Four main geoelectric units (Ge1, Ge2, Ge3 and Ge4) can be  
324 distinguished. Ge1 values range from 5 to 25 ohm.m<sup>-1</sup> at a depth situated from ca. 90 and 30 m  
325 below the surface and, according to Bennett and Buck (2016), may correspond to the irregular limit  
326 between Neogene substratum and Holocene deposits. Ge2 shows the lowest resistivity signal,  
327 generally below 5 ohm.m<sup>-1</sup>, between 40 and 8 m below the surface. Ge3 extends from ca. 8 m deep  
328 to the present-day surface topography: the values are generally low, between 5 and 20 ohm.m<sup>-1</sup>. A  
329 local increase in the resistivity signal is observed. In the top five meters, the ERT results show two  
330 transition layers with higher resistivity (> 13 Ohm.m<sup>-1</sup>) located respectively 700-800 m and 950-  
331 1100m eastward from the current main Strymon riverbed. Ge4 is located between core FC4 and

332 the western area of the Fidokoriphi hill and from the surface to a depth of ca. 10 m. Ge4 has the  
 333 highest resistivity values of the whole profile, ranging from 15 to 35 ohm.m<sup>-1</sup>, corresponding to the  
 334 presence of coarser deposits (sandy silt, fine micaceous to coarse sand) and the displacement of  
 335 Angitis channel during the last millennia. The significant resistivity values (> 20 Ohm.m) situated at  
 336 a distance of 100 m east of the channel correspond to the riverbank deposits (laminated fine to  
 337 medium sand) and the artificial levee built during the last century for protection against river floods.  
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 340 *Figure 4: Electrical resistivity tomography profile from Strymon to Angitis River (2 km) and the location of the 7 cores*  
 341 *including FC8.*

342 **4.2. Chronological and sedimentary sequences**

343 According to the ERT results, the sedimentary sequence analysis of core FC8 and its correlation  
 344 with the stratigraphy of the drilling set (i.e., Fig.5 FC8/FC5, FC9, FC10 and FC4) shows lacustrine  
 345 sediments more than 20 m thick deposited over a period of 6000 years. The high-resolution  
 346 chronological definition (Table 1 and Fig. 7) allowed us to define four sedimentological units  
 347 corresponding to different hydromorphological dynamics (Fig. 6). However, the sedimentary hiatus  
 348 identified between a depth of 500 and 450 centimeters should be interpreted with caution due to  
 349 potential reworking of these sediments attested by two incorrect radiocarbon data and peaks of  
 350 vesiculate pollen percentages (infra: Fig. 9).

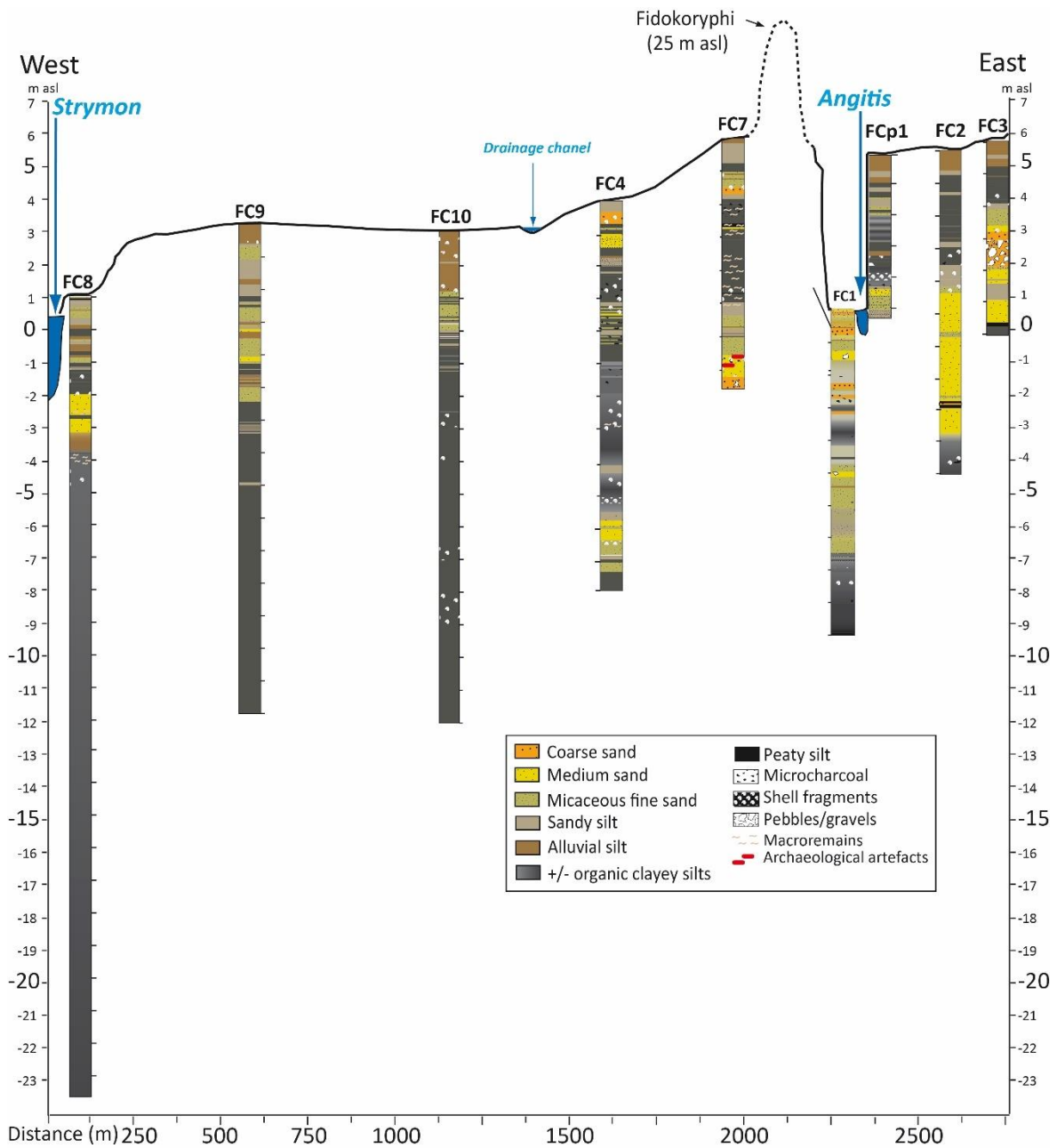
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Sample code	Depth (cm)	Material	Laboratory Code	Age BP	Age Cal BP (2σ)	Age Cal BC/AD
<b>FC5-314</b>	314-314,5	Woody remains	Lyon-8112	175±30	>293	>1658AD
<b>FC5-422</b>	422-424	Organic sediment	Lyon-8113	365±30	498-316	1453-1635 AD
<b>FC5-478</b>	478-480	Organic sediment	Poz-58677	5825±30	6735-6505	4786-4556 BC
<b>FC5-5 484</b>	484-486	Organic sediment	Lyon-7190	4630±30	5464-5305	3515-3356 BC
<b>FC5-554</b>	554-556	Organic sediment	Lyon-8115	2175±30	2310-2059	361-110 BC
<b>FC5-684-686</b>	684-686	Organic sediment	Poz-58620	4070±35	4800-4435	2851-2476 BC
<b>FC5-850-852</b>	850-852	Organic sediment	Lyon-8116	3310±35	3633-3452	1684-1503 BC
<b>FC5-1048-1050</b>	1048-1050	Organic sediment	Lyon-7191	3665±35	4088-3899	2139-1950 BC
<b>FC5-1080-1082</b>	1080-1082	Organic sediment	Lyon-8117	3550±35	3968-3716	2019-1767 BC
<b>FC5-1090-1100</b>	1090-1100	Organic sediment	Lyon-8118	3605±35	4074-3779	2123-1830 BC
<b>FC8-7 1235</b>	1235-1237	Organic sediment	SacA-30526	3635±30	4081-3849	2132-1900 BC
<b>FC8-8 1350</b>	1350-1352	Organic sediment	Poz-58621	3715±35	4217-3966	2268-1981 BC

<b>FC8-8 1425</b>	1425-1426	Organic sediment	SacA-30527	3925±30	4506-4246	2557-2297 BC
<i>FC8-9 1515</i>	<i>1515-1517</i>	<i>Organic sediment</i>	<i>Poz-58622</i>	<i>6780±40</i>	<i>7680-7574</i>	<i>5731-5625 BC</i>
<b>FC8-9 1563</b>	1563-1564	Organic sediment	SacA-30528	4710±30	5575-5322	3626-3373 BC
<b>FC8-10 1764</b>	1763-1764	Organic sediment	SacA-30529	4805±30	5591-5477	3642-3528 BC
<b>FC8-10 1840</b>	1840-1841	Organic sediment	Poz-58623	4950±35	5744-5594	3795-3645 BC
<b>FC8-11 1961</b>	1961-1962	Organic sediment	SacA-30530	5260±30	6179-5933	4230-3984 BC
<b>FC8-12 2158</b>	2158-2159	Organic sediment	SacA-30531	5500±30	6393-6211	4444-4262 BC
<b>FC8-13 2309</b>	2309-2310	Organic sediment	SacA-30532	6045±30	6976-6794	5027-4845 BC
<b>FC8-13 2441</b>	2441-2442	Organic sediment	SacA-30533	6065±30	7149-6796	5200-4847 BC

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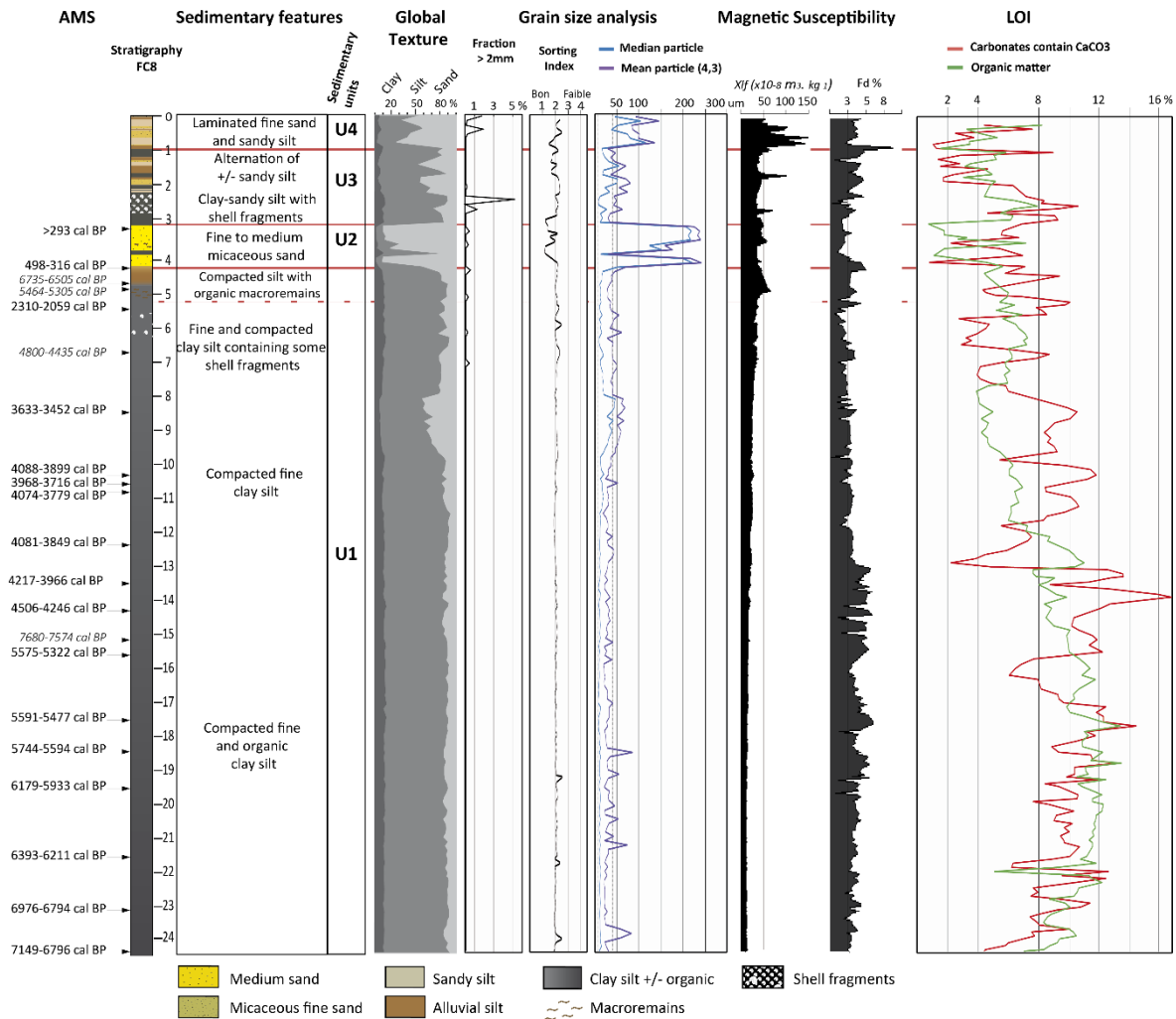
Table 1: 21 AMS radiocarbon data calibrated from cores FC5 and FC8. AMS data excluded from the age-depth model are in italics.



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Figure 5: Transect study of the lower Strymon valley sedimentary fill from boreholes modified after Lespez et al., 2016 and Glais et al., 2016b. For chronostratigraphical units, see the second reference.



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*In italic, the AMS data probably reworked and excluded from the age-depth model*  
 Figure 6: Synthetic log of FCB and sedimentological proxies: sedimentary features, grain size analysis, magnetic susceptibility and loss on ignition (LOI).

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*Sedimentary Unit 1 (2450 to 425 cm; ca. 6950-600 cal BP): compact and homogeneous fine lacustrine silts and clays.*

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The first sedimentary unit (**U1**) corresponds to fine homogeneous clayey-silt deposits 2,000 cm thick. The sediments are well sorted with a large proportion of silt (73 to 83%) whereas clay and sand percentages fluctuate respectively between 7.5 to 13% and 7 to 21%. The median particle size remains consistent at around 18  $\mu\text{m}$  (range 9 to 43  $\mu\text{m}$ ) and the mean size oscillates between 21 and 63  $\mu\text{m}$ , with no more than 0.2% of particles more than 2 mm in size. Only two minor phases interrupt this homogeneous pattern. The first one occurs at the bottom between 2,400 and 1,850 cm (ca. 6900-5700 cal BP) during which several peaks of fine sand particles are recorded (50 to 87  $\mu\text{m}$ ). The second occurs between 950 and 795 cm, corresponding to 3800-3430 cal BP and is characterized by a temporary increase in the sandy fraction from 20 to 41.5%. Along this unit, the magnetic susceptibility ( $\chi\text{lf}$ ) signal is low with a gradual increase from  $10 \cdot 10^{-8}$  to  $40 \cdot 10^{-8} \text{ m}^3 \cdot \text{kg}^{-1}$  around 1600 cal BP. After which,  $\chi\text{lf}$  values rapidly reached  $67 \cdot 10^{-8} \text{ m}^3 \cdot \text{kg}^{-1}$  while at the same time, we observe the presence of organic macro remains and ochre marks in the sediments. Two incorrect AMS results at this depth suggest hydromorphological change and a disruption of the deposition process.



376 On the other hand, the contribution of superparamagnetic particles (Fd %) revealed another  
377 pattern. From 2,450 to 1,325 cm (ca. 6950-4030 cal BP), the frequency dependent susceptibility  
378 underwent a consistent increasing trend, from 2.5% to 6% with an average of 4.2% for this period.  
379 Then, between 1,325 and 425 cm (ca. 4030-600 cal BP), the trend was reversed with a decrease  
380 from 3.7% to 1.6% (average 2.4%). Loss on ignition data showed a similar trend even though  
381 amplitude had a stronger effect. From 2,450 to 1,780 cm (ca. 6950-5575 cal BP), the trend in  
382 carbonate and organic matter content generally increased at relatively high values, between,  
383 respectively, 4.2% to 14.4% and 7% to 13.4%. From 1,780 to 780 cm the general trend of organic  
384 percentages gradually decreased to reach 4%, while carbonate content reached its maximum  
385 (16.7%) at 1,400 cm (ca. 4290 cal BP). The tipping point for frequency dependent susceptibility  
386 occurred around 1,325 cm which corresponds to an abrupt drop in carbonate content from 16.7%  
387 to 2.2%. Between 1,175 and 425 cm, the carbonate percentages fluctuated significantly (range 11.8-  
388 2.7%) with a decreasing tendency, while organic matter remained relatively stable at around 6%,  
389 between 780 and 425 cm.

390 *Sedimentary Unit 2; 425 to 315 cm; ca. 600-80 cal BP – Fine to medium micaceous sand: alluvial*  
391 *inputs.*

392 **U2** is composed of micaceous and well-sorted sand, i.e. a significant change compared with the  
393 first unit (SU1). During this stage, the percentage of sand oscillated between 42% and 90.6%. The  
394 sand was fine to medium, characterized by median and mean particle size values ranging between  
395 125 and 240  $\mu\text{m}$ . Only a thin layer (373-362 cm) of silt (79.8%) containing sand (10.5%) and clay  
396 (9.5%), similar to previous lacustrine silty deposits, interrupted the second unit. Sandy sediment  
397 corresponded to the lowest percentages of organic matter (< 2%). Carbonate content fluctuated  
398 between 5.5 to 7%.

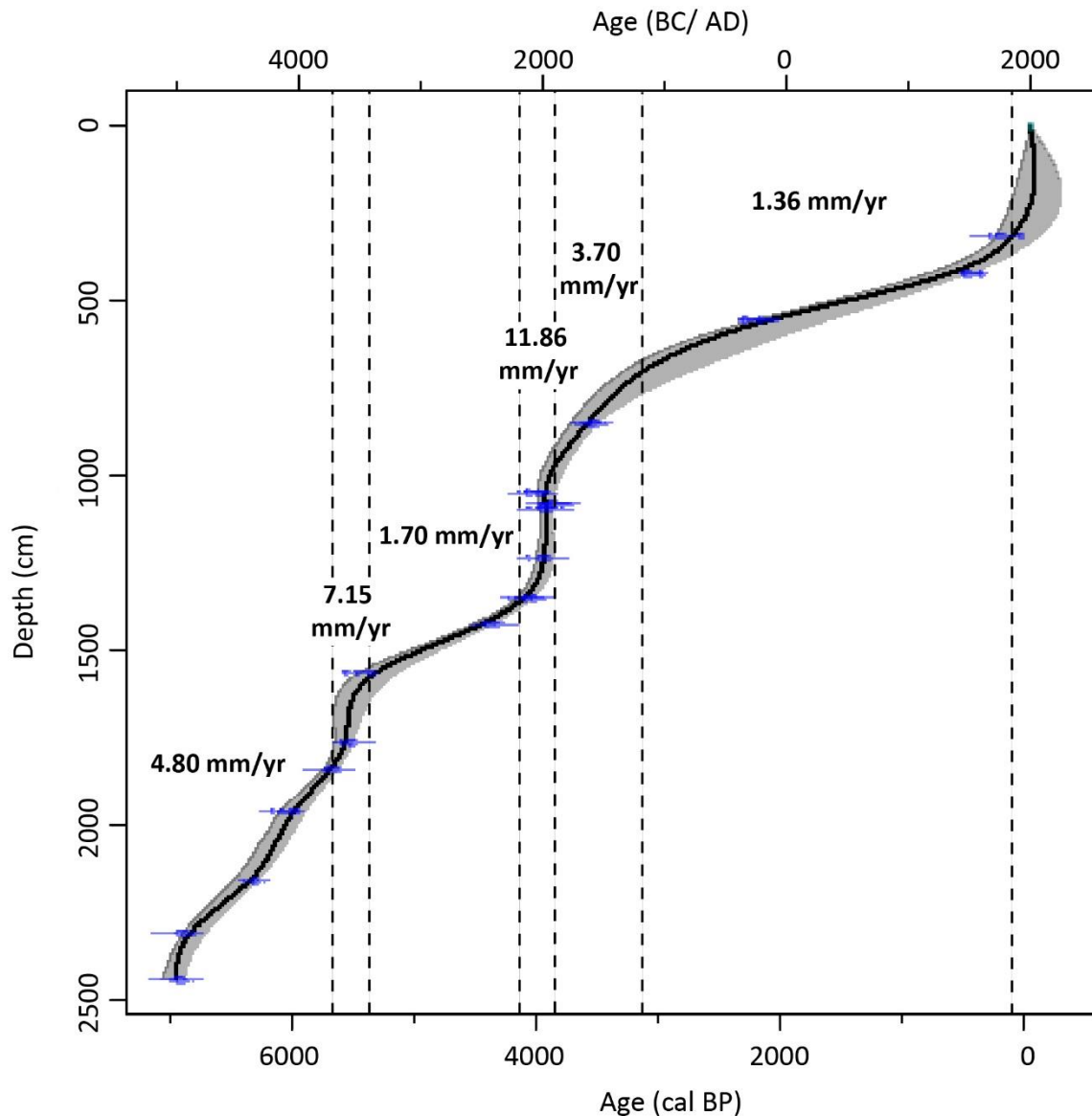
399 *Sedimentary Unit 3; 315-100 cm; later than 80 cal BP – Alternating clay silt and sandy silt.*

400 **U3** shared similar features with SU1, its overall texture was dominated by silt (52-84.8%), sand  
401 (15-45%) and clay (2.5-11.8%). Nevertheless, sedimentary and pedological features revealed some  
402 differences. The deposit corresponded to alternating millimeter thick layers of silt containing  
403 indeterminate shell fragments and microcharcoals. The percentages of organic matter and  
404 carbonate content followed the same decreasing tendency from 7.8/10.5% to 3.5/1.5%, while the  
405 frequency dependent susceptibility showed the opposite trend, although interrupted by peaks,  
406 suggesting pedogenesis.

407 *Sedimentary unit 4: 100-0 cm; undated, probably contemporary – Alternating fine sand and sandy*  
408 *silt.*

409 The last unit identified (**U4**) corresponds to the most recent, including modern, sediment  
410 accumulation following intensive drainage of the lake in the 1930s. The alternation of fine sand and  
411 silty sand ranging between 85 and 135  $\mu\text{m}$  mean particle size, representing proximal floodplain  
412 deposits. Frequency dependence values reached their maximum (9.2%) at bottom of this layer at a  
413 depth of around 96 cm while low frequency susceptibility reached  $152.10^8 \text{ m}^3 \cdot \text{Kg}^{-1}$  at a depth of  
414 around 66 cm.

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*Figure 7: Age-depth model of FC5/FC8 core from 17 AMS radiocarbon data.*

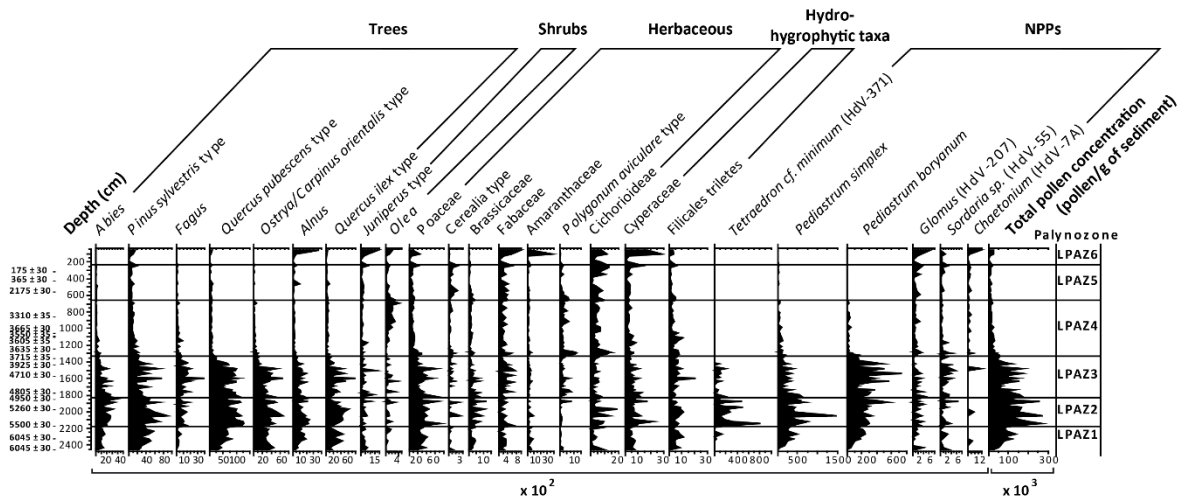
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419 **4.3. Pollen analysis**

420 The concentration of pollen was always good, as can be seen in the synthetic concentration  
 421 diagram (Fig. 8) but due to the lacustrine to fluvio-lacustrine nature of the sedimentation, it varied,  
 422 indicating aerial and fluvial inputs. The average concentration was 68,235 grains/g, despite a clearly  
 423 defined separation between the 1,320 upper centimeters corresponding to the least rich samples  
 424 (16,200 grains/g) and the 1,130 deeper centimeters, where the average concentration was more  
 425 than 108,000 grains/g. Further, the high taxa diversity (50 taxa minimum constitute the TLP), pollen  
 426 and NPPs in a perfect state of preservation and the similarity between the percentage curves and  
 427 concentration curves for each taxon confirmed that conditions were favorable at the time of the  
 428 sediment deposits. The FC8 core provides particularly interesting data for this time interval, thanks  
 429 to very high-resolution analysis of approximately 6 meters of sediment between 4.5 and 3.5  
 430 ka cal BP (a total of 25 samples were analyzed), something that was never previously possible in  
 431 the eastern Mediterranean. This sequence provides a multi-decadal resolution for this period  
 432 within the LPAZ3 and LPAZ4 palynozone (Table 3).

Palynozone	Depth	Estimated chronology	Palynological trend
<b>LPAZ1</b>	2450-2170 cm	6950-6380 cal BP	<b>The forested landscape (AP: 71.4-83.6%)</b> comprised <i>Quercus pubescens</i> type (14.2-30%), <i>Q. ilex</i> type (2.5-13.3%), <i>Pinus sylvestris</i> type (8.8-17.7%) and <i>Ostrya/Carpinus orientalis</i> type (6.3-15.6%) as the main representative species. <i>Abies</i> , <i>Carpinus betulus</i> , <i>Corylus</i> and <i>Quercus suber</i> percentages fluctuated between 2 and 6.5%. The increase in mixed oak forest was to the detriment of other mesophilous taxa. Riparian trees were not much affected ( <i>Alnus</i> : 2.3-5.1%; <i>Salix</i> : 0.5-3.3% and <i>Ulmus</i> : 1.2-2.7%). Shrub vegetation accounted for less than 5%. Herbaceous vegetation (13.3-28.5) was mainly composed of grasses (7.2-14.2%). Hydro-oligotrophic-hygrophytic taxa represented 6.5-12.2%. NPPs were subject to open water conditions: meso-oligotrophic ( <i>Pediastrum simplex</i> and <i>Anabaena</i> : 15.8-103.9%) or eu-mesotrophic (mainly <i>Pediastrum boryanum</i> up to 73.9%).
<b>LPAZ2</b>	2170-1810 cm	6380-5620 cal BP	<b>Arboreal Pollen (AP) fluctuated between 64% and 85.3% while shrubby pollen were weakly represented (1.1-3.4%)</b> . There was a slight increase in <i>Abies</i> (5.2 to 7.8%), <i>Fagus</i> (> 1% and occasionally 3.5-4.5%) evergreen <i>Quercus</i> type (4.7-12.6%), along with the temporary appearance of <i>Castanea</i> and a decrease in <i>Corylus</i> (< 3.3%). <b>Herbaceous pollen percentages (12.1-32%)</b> were mainly composed of grasses (7.1-14.2%). Major changes were observed in wetland indicators: aquatic condition NPPs ( <i>Anabaena</i> , <i>Botryococcus</i> and <i>Tetraedron</i> ) and high values of <i>Pediastrum simplex</i> (60.4%-253.8% of total land pollen TLP) and <i>Pediastrum boryanum</i> (35.8%-13.8% of TLP). At the end, peak of coniferous and altitudinal forest ( <i>Abies</i> : 14.2% and <i>Pinus sylvestris</i> type: 16.8%) and drop of thermophilous taxa ( <i>Quercus ilex</i> type: 2.2% and <i>Quercus suber</i> : 0.2%).
<b>LPAZ3</b>	1810-1320 cm	5620-4020 cal BP	On average: <b>AP, 73.8%, Shrubs, 3.7% and Herbaceous species 22.5%</b> . Mixed oak forests were composed of <i>Quercus pubescens</i> type (17.5-30.3%), <i>Ostrya/Carpinus orientalis</i> type (3.6-14.3%), <i>Quercus ilex</i> type (2.6-12.5%), <i>Q. suber</i> (1.5-5.7%), <i>Carpinus betulus</i> (1-5.1%), <i>Corylus</i> (1-2.9%), <i>Tilia</i> (0.2-2%) with more frequent occurrences of <i>Castanea</i> . Altitudinal forest was composed of coniferous ( <i>Abies</i> : 1.9-8.1% and <i>Pinus sylvestris</i> type: 4.2-19.1%) and <i>Fagus</i> (0.7-6.4%). <i>Erica arborea</i> type (0.4-2%) and <i>Juniperus</i> type (0.4-4.6%) were the main components of shrubby vegetation. The herbaceous taxon assemblage was dominated by grasses (7.4-14.2%). More frequent occurrence of Cerealia type percentages (< 1%). Based on wet NPP indicators, eu-mesotrophic conditions (45-220% of TLP; <i>Pediastrum boryanum</i> , <i>Tetraedron</i> , <i>Botryococcus</i> and <i>Spirogyra</i> ) appeared to predominate over meso-oligotrophic conditions (32.8-160% of TLP; <i>Pediastrum simplex</i> and <i>Anabaena</i> ). The percentages around 1,410 cm (4340 cal BP) characterized a reversal of wet indicators until the end of LPAZ3 (1,320 cm; 4,020 cal BP), concomitant with marked decrease in the total pollen concentration (124,825 to 43,964 pollen grains/g of sediment). During these two and a half centuries, the percentages of hydro-hygrophytic taxa increased from 9.6% to 15% and several herbaceous taxa, like <i>Amaranthaceae</i> , <i>Polygonum aviculare</i> type, <i>Artemisia</i> and <i>Cichorioideae</i> , also increased even though their percentages never reached more than 5%. Between 0.2% and 3.9% of Coprophilous NPPs were observed almost continuously.

<b>LPAZ4</b>	1320-665 cm	4020-2920 cal BP	<p>The beginning of LPAZ4 represents a tipping point in all pollen diagrams (Fig.7; Fig.8; Fig.9 and Fig.10). The <b>percentage of woodland</b> no longer dominated, falling <b>from 63.3% to 45%</b>. The <i>deciduous Quercus</i> curve declined and reached only 5.8% while <i>Tilia</i> almost disappeared. Likewise, <i>Carpinus-Betulus</i>, <i>Ostrya/Carpinus orientalis</i> type, <i>Pinus sylvestris</i> type, <i>Quercus ilex</i> type and <i>Fagus</i> decreased (respectively between 2% and 9%), even if in the case of the last three, the decline was only temporary. Woodland showed evidence of taxonomic diversification, with the spread of xerothermophilous species and progressive replacement of mesophilous forest by a thermo-Mediterranean vegetation cover. Initially, the percentage of <b>shrubs was still low at around 3.3%</b>. Then, starting from 1,215 cm (3920 cal BP), the spread of these taxa fluctuated (5.3% - 9.2%). Changes in wooden species occurred in parallel with a steep <b>increase in the percentage (from 33% to 56.3%) of herbaceous species</b>. The biggest increases occurred in perennial pasture plants (Brassicaceae, Caryophyllaceae and Fabaceae), anthropozoogenous taxa (Amaranthaceae, <i>Plantago lanceolata</i> type and <i>Polygonum aviculare</i> type), anthropic-nitrophilous taxa (<i>Aster</i> type and Cichorioideae), <i>Artemisia</i> and cultivated taxa such as Cerealia type (0-1.5%). The continuous presence of <i>Glomus</i> (HdV-207) and <i>Pseudoschizaea circula</i>, the increase in coprophilous NPPs (<i>Coniochaeta</i>, <i>Podospora</i> and <i>Sordaria</i> sp.) and NPPs is indicative of dry or fire events (<i>Chaetonium</i>, <i>Gelasinospora</i>, <i>Pleospora</i> and HdV-200). At around 751 cm (3290 cal BP), the rapid change mostly affected wet indicators and <i>Pediastrum</i> colonies practically disappeared. A dry event caused temporary drying up of the wetland before a return to initial conditions at the end of the zone.</p>
<b>LPAZ5</b>	665-220 cm	2920-200 cal BP	<p>Throughout the palynozone (excluding the 500-450 cm interval of probable sedimentary reworking), the proportion of <b>forest taxa remained relatively low (33-52.9%)</b>, while the <b>bushlike vegetation cover (5-9.5%)</b> was dominated by <i>Juniperus</i> type, <i>Erica arborea</i> type and <i>Olea</i>. The process of opening up of the landscape that started during LPAZ4 intensified and the majority of mesophilous taxa declined. The percentages of NPPs indicative of dry or fire events (0.6-3.8%), coprophilous NPPs (3.2-8.6%) and herbaceous taxa (Cerealia type: 0.4-3.2%; anthropic-nitrophilous taxa: 4-30%; anthropozoogenous taxa: 3-12%; perennial pasture plants: 4.5-10%) confirmed increasing anthropization. From a hydrological point of view, the decrease and subsequent disappearance of <i>Pediastrum</i> colonies at the end of the zone in parallel with the increase in the percentage of hydro-hygrophytic taxa (from 14.5% to 28.2%) and in the percentage of NPPs of erosive processes (from 0.9% to 6.9%) is evidence for the intensification of alluviation and aggradation processes. Riparian taxa spread (<i>Alnus</i>, <i>Salix</i> and <i>Ulmus</i>) after the sedimentary hiatus phase.</p>
<b>LPAZ6</b>	220-0 cm	200-50 cal BP	<p>LPAZ6 was characterized by the continued <b>degradation of woodland</b> except riparian forest which increased significantly (<i>Alnus</i> from 3.7% to 24.3%; <i>Salix</i> from 1.7% to 4.3% and <i>Ulmus</i> from 0.2% to 2.8%). This reflected the drying up of the wetland that allowed the development of a post-pioneer tree stratum. Nevertheless, despite having dried out, the alluvial valley was frequently flooded because the NPPs indicative of eu-mesotrophic conditions continued at a rate ranging between 5.4% and 17.2 % and maximum percentages of NPPs indicative of erosion processes (3.2%-9.8%). Similarly, the percentage of pioneer hydro-hygrophytic vegetation remained stable at between 16.4% and 25.1% (mostly Cyperaceae and <i>Equisetum</i>). Access was easy and the vegetation was suitable for livestock rearing as indicated by coprophilous NPPs (4.1-15.2%). The foothills were probably covered by <b>shrubby species (9.3-15.4%)</b>, type Phrygana or thermo-Mediterranean forest.</p>



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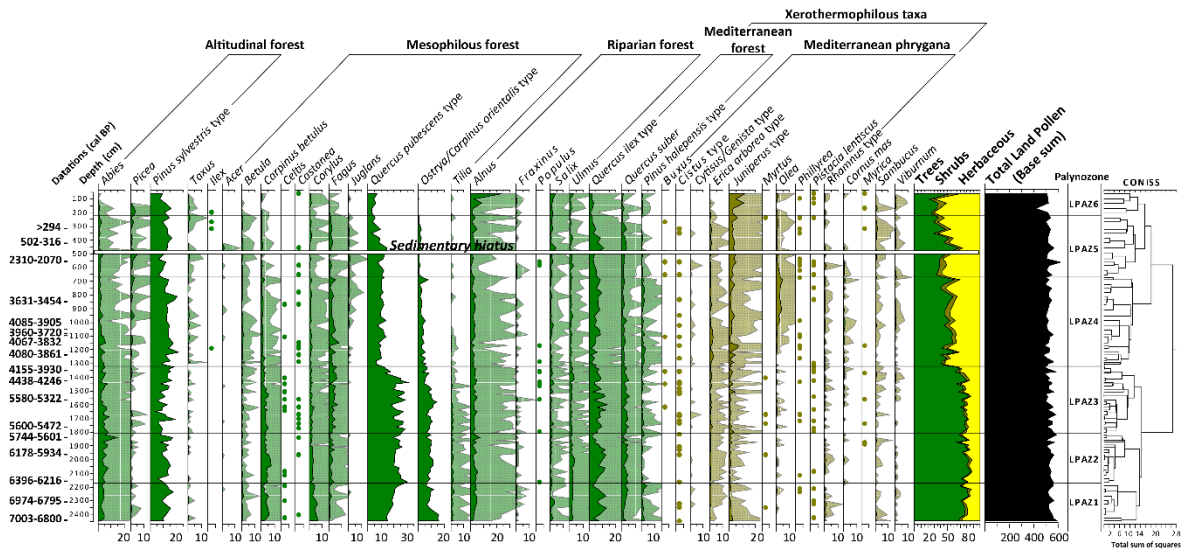
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Figure 8: Pollen concentration curves from the FC8 core. The taxa shown correspond to representative taxa from various ecological associations.

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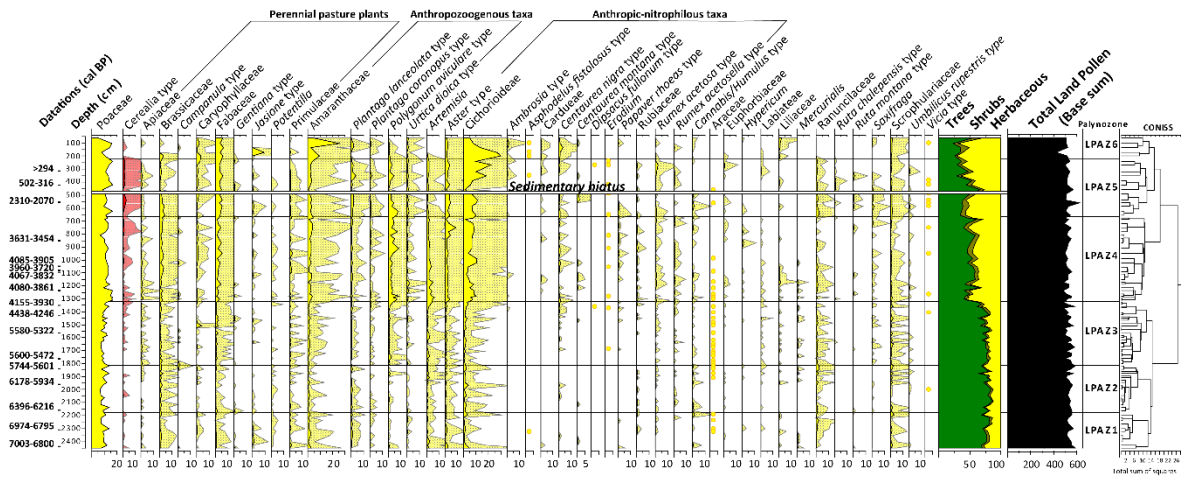
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Figure 9: Tree and shrub pollen diagram showing percentages of TLP from the FC8 core. Light color curves result from a tenfold exaggeration of the original curves. Species representing 0.5% and 1% are represented by dots, while species with a percentage below 0.5% are not shown.

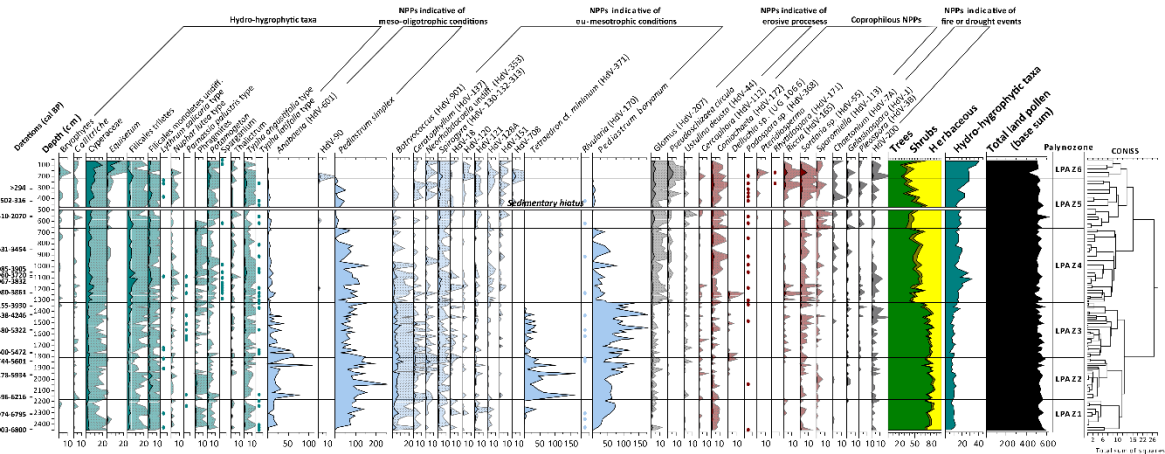
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447 *Figure 10: Pollen diagram of herbaceous taxa showing percentages of TLP from the FC8 core. Light color curves*  
 448 *represent a tenfold exaggeration of the original curves. Species representing 0.5% and 1% are represented by dots, while*  
 449 *species whose percentage was below 0.5% are not shown.*



450

451 *Figure 11: Hydro-hygrophytic taxa and non-pollen Palynomorph (NPP) pollen diagram showing percentages of TLP from*  
 452 *FC8 core. Light color curves result from a tenfold exaggeration of the original curves. Species representing 0.5% and 1%*  
 453 *are represented by dots, while species whose percentage was below 0.5% are not shown.*

454 **5. Discussion**

455 **5.1. Wet conditions, site and scale effects in the detection of landscape anthropization (ca. 7-4.5**  
 456 **ka cal BP)**

457 **5.1.1. From 7 to 5.7 ka cal BP, (ca. 5050-3750 BC)**

458 The onset of this period corresponds to relatively wet conditions, also observed in the eastern  
 459 Mediterranean region (Digerfeldt *et al.*, 2007; Finné *et al.*, 2011; 2019; Francke *et al.*, 2013;  
 460 Miebach *et al.*, 2016; Triantaphyllou *et al.*, 2014). This resulted in a huge lake (former Achinos Lake)  
 461 with eu-mesotrophic conditions, like in the neighboring Dojran (Masi *et al.*, 2018). The exact palaeo-  
 462 depth of the lake is difficult to estimate. Nevertheless, around 7 ka cal BP (ca. 5050 cal BC), it was  
 463 probably several meters deep at the location of core FC8 considering the relatively low percentages  
 464 of hydro-hygrophytic taxa and the difference in altitude (ca. 20 meters) between the level of  
 465 sedimentation in the center of the valley (FC8) and on the margin of the wetland, two kilometers  
 466 to the east (FC1; Glais *et al.*, 2016b; Lespez *et al.*, 2016). Taking the lower valley substratum  
 467 morphology and topography into account (Fig.4), subsidence and compaction, even though  
 468 pronounced at the center of the basin, are not enough to explain this range (Bennett and Buck,  
 469 2016). A gradual sea level rise may explain the increase in the water level in the lower Strymon

470 valley and may have played a key role in maintaining the lacustrine context by blocking surface  
471 freshwater (Lespez et al., 2016). Despite the densely wooded Strymon watershed, these  
472 hydrological conditions support aggradation into the lower valley. The average accumulation rate  
473 was 4.8 mm.yr<sup>-1</sup> during the period 7-5.7 ka cal BP (ca. 5050-3750 cal BC). The wetland was  
474 surrounded by riverine forest, with mixed oak and deciduous forest on the lower slope and  
475 coniferous forest on the upper part of the surrounding mountains. This vegetation pattern agrees  
476 with other regional data (e.g. Tenaghi-Philippon; Ioanina, Iznik, Dojran, etc.; Bottema, 1974; Greig  
477 and Turner, 1974; Willis, 1994; Lawson et al., 2004; Miebach et al., 2016; Masi et al., 2018; Weiberg  
478 et al., 2019).

479

#### 480 5.1.2. From 5.7 to 4.5 ka cal BP (ca. 3750-2550 cal BC)

481 During this period, the long-lasting presence of wetland corresponds to a shallow lake  
482 environment, despite some previously outlined hydrological fluctuations (Lespez et al., 2016) and  
483 a period of enhanced aridity. This pattern occurs during the transitional period (5.3-4.9 ka cal BP)  
484 from the overall wetter conditions of the Early Holocene to generally drier conditions in the Balkan  
485 region in the Late Holocene (Finné et al., 2019). Around 5.7 ka cal BP (ca. 3750 cal BC), an  
486 aggradation period (Fig.7) considerably increased the sedimentation rate (ca. 7.15 mm.yr<sup>-1</sup>) for  
487 approximately 3 centuries, followed by 15 centuries with a sedimentation rate of 1.7 mm.yr<sup>-1</sup>. This  
488 hydro-sedimentary change was confirmed by variations in carbonate content and by fluctuations  
489 in the pollen diagram. The obvious instability of the tree curves (particularly of the altitudinal forest  
490 taxa: *Fagus*, *Quercus pubescens* type and xerothermophilous taxa) confirms this hypothesis, which  
491 matches the short-term minimum of non-coniferous arboreal pollen percentages in the northern  
492 Aegean (Kotthoff et al., 2008a; 2008b). Furthermore, the instability of hydrological and  
493 environmental data probably corresponds to enhanced fluvial activity, previously identified at the  
494 wetland margins during 5.8-5.7 cal BP (ca. 3850-3750 cal BC) (Lespez et al., 2016). The enhanced  
495 flow resulted from an incursion of cold air masses to eastern Mediterranean and from a more  
496 intense/pronounced anthropogenic activity in the studied area. Despite the relative instability, the  
497 average percentage of arboreal pollen at Fidokoryphi (76.4%) during the 7-5.2 cal BP period (ca.  
498 5050-3250 cal BC) remained noticeably higher than the mean AP percentage in the whole northern  
499 region of Greece prior to major human conversion of the land cover about 4 ka cal BP (ca. 2050 cal  
500 BC) (62.51%; Roberts et al., 2019a).

501

#### 502 5.1.3. Human impact at regional scale

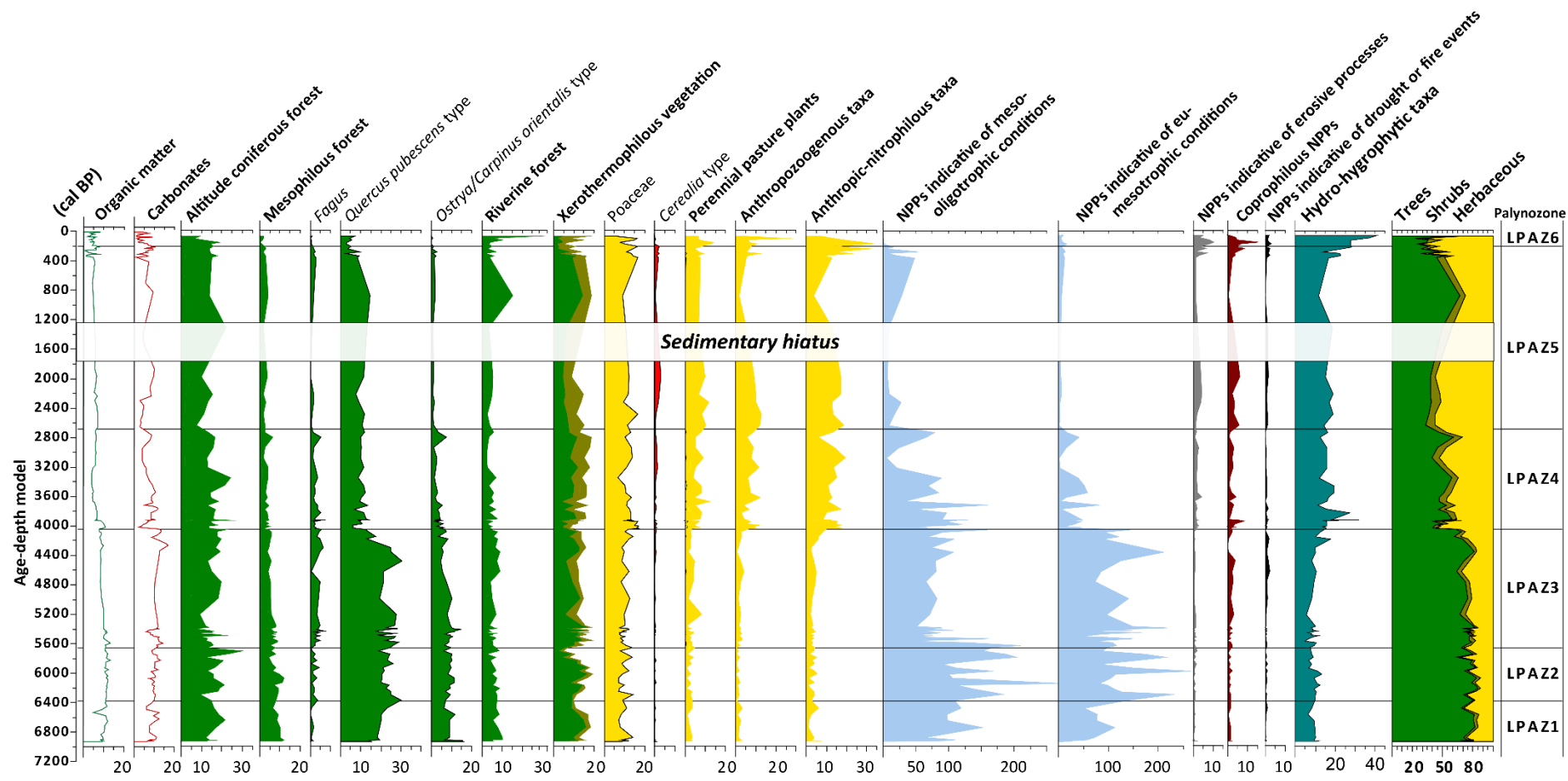
503 At the end of the Late Neolithic I and during the Late Neolithic II (7-6.4 ka cal BP, (ca. 5050-4450  
504 BC), anthropogenic pressure on the landscape was only visible close to population settlements.  
505 Population spread and the increase in the number of settlements has been confirmed by  
506 archaeological data all over northern Greece (Weiberg et al., 2019), and in particular, in the Philippi-  
507 Drama and Strymon plains (Koukoulis-Chryssanthaki et al., 2008), but according to the regional  
508 pollen record, had only modest effects. For the first time, a significant landscape anthropization  
509 signal was recorded synchronously in the Lower Strymon Valley and on the eastern edges of  
510 Tenaghi-Philippon from 6.45-6.3 ka cal BP (4500-4350 BC) (Lespez et al., 2016; Glais et al., 2017), in  
511 a period during which no climate changes have been recorded (Kotthoff et al., 2008b; Peyron et al.,  
512 2011, 2016). At Dikili Tash (Glais et al., 2016a), opening of the vegetated landscape coincided with  
513 cereal cultivation, an increase in erosion, a local fire signal and, even if in a less significant  
514 proportion, the development of shrubby Mediterranean vegetation, as recorded at Dispilio in  
515 western Macedonia (Kouli et Dermitzakis, 2008; Kouli, 2015; Karkanis et al., 2011). During the 6-  
516 5.2 ka cal BP interval (ca. 4050-3250 BC), in which none of the known archaeological sites of the

517 lower Strymon Valley appear to have been occupied, fluctuations in the regional vegetation cover  
518 revealed no significant anthropogenic change. This pattern corresponds to local persistence of  
519 agropastoral practices, like those recorded at Zazari Lake with the spread of *Fagus sylvatica*  
520 accompanied by *Pistacia* (Gassner et al., 2019).

521 Anthropogenic pollen indicators in Bronze Age landscapes correspond to a continuous cereal  
522 signal (0.3-1%). Furthermore, the marked decrease in oak woodland, the intensification of  
523 pastoralism, the increase in maquis and in indicators of erosion as well as the dominance of  
524 anthropozoogenous, anthropic-nitrophilous and perennial pasture plants in open environments are  
525 attested. Even though these agropastoral activities are well documented, the first indicators of a  
526 human-made landscape recorded at regional scale indicate no widespread woodland clearing, since  
527 tree taxa remain largely dominant. From the beginning of the Early Bronze Age (ca. 5.2 ka cal BP,  
528 3250 BC), many sites were again settled (Maniatis et al., 2014) following a period with sparse  
529 knowledge of the settlement pattern, (Koukouli-Chrysanthaki, 1998; Weiberg et al., 2019).

530 Except for a few palynological sequences located close to Neolithic settlements such as Dikili  
531 Tash (Glais et al. 2016a) and Dispilio (Kouli, 2015) in Macedonia, the first signs of landscape change  
532 of anthropogenic origin in regional records appeared progressively. In central Greece, an  
533 anthropogenic signal is attested between 6.2 and 5.5 ka cal BP at Kopais Lake (Greig and Turner,  
534 1974) and about 5.5 ka cal BP at Voulkaria Lake (Jahns, 2005), while in northern Greece, human  
535 pressure has been recorded since 5.15 ka cal BP at Ioannina (Lawson et al., 2004), since about 5  
536 ka cal BP at Nisi (Lawson et al., 2005), between 5-4.5 ka cal BP at Dojran (Athanasiadis et al., 2000;  
537 Masi et al., 2018; Thienemann et al., 2017) and in Epirus (Gerasimidis et al., 2009). Other sites in  
538 northern Greece showed an agropastoral impact later, at around 4.5 cal BP at Giannitsa (Bottema,  
539 1974) like in the region of Maliq Lake in Albania (Denèfle et al., 2000), since 3.85 ka cal BP at  
540 Tenaghi-Philippon (Greig and Turner, 1974) and between 3.5 and 3 ka cal BP at Gramousti, Rezina  
541 (Willis, 1992; 1994) and Edessa (Bottema, 1974). In northwestern Anatolia, evidence for human  
542 activities became more solid after the Early Bronze Age, at around 4.8 cal. BP (Miebach et al., 2016).  
543 In southwestern Bulgaria, like in our study area, the first anthropization indicators were observed  
544 early close to settlements, i.e., between 7.5 and 7 ka cal BP, but a regional impact was only  
545 perceived after 3.35 ka cal BP (ca. 1400 BC) (Marinova et al., 2012).

546 To summarize, evidence for anthropization from pollen studies challenges assumptions  
547 concerning the intensity of human pressure from the Neolithic on in northern Greece. In the Lower  
548 Strymon Valley, the time interval between recordings of cereal cultivation on the margins of  
549 Neolithic sites (FC1; Lespez et al., 2016) and its recording at core FC8, less than 2 km away, is two  
550 millennia. This can be explained by both landscape and environmental factors. It is likely that cereals  
551 have long been cultivated on the thick, hilly soil (near FC1), far from the center of the lake basin the  
552 location of core FC8. Given that cereal pollen grains have a low dispersal capacity and low  
553 productivity (Berglund, 1985; Diot, 1992), it is not possible to record the presence of Cerealia in a  
554 more distant environment. In any case, the anthropization signal in pollen records from lake or  
555 swamp sites located far from cultivated areas is delayed compared to regional agricultural activities,  
556 as attested by archaeological analyses (Greig and Turner, 1974; Gerasimidis, 2009; Masi et al.,  
557 2018). For this reason, the anthropogenic signal record is highly dependent on the location of the  
558 core, highlighting the inability of some lacustrine records to capture the dynamics of landscape  
559 anthropization. The research conducted in the Lower Strymon valley, concludes that the thresholds  
560 for this detection remain highly dependent on local conditions of agricultural development and  
561 survey sites.



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Figure 12: Synthetic pollen diagram of selected taxa and NPPs, linear time, correlated with LOI and carbonate content from FC8. (For interpretation of the references to color in this figure legend, see the web version of this article).

565 **5.2. Welcome to Meghalayan (Late Holocene): reinforcement of anthropization signal around 4.3-**  
566 **3.8 ka cal BP**

567 All records obtained in eastern Macedonia during the period 4.3-3.8 ka cal BP (ca. 2350-1850 BC)  
568 show readjustment of wetland pollen and hydrosedimentary records (Greig and Turner, 1974; Glais et  
569 *al.*, 2017; Lespez et *al.*, 2016).

570 **5.2.1. Climate changes**

571 Records of this period in the Mediterranean basin are frequently lacking (e.g. Combourieu-Nebout,  
572 2009; Dormoy et *al.*, 2009; Fleitmann et *al.*, 2003; 2009) and the reading of the climate remains the  
573 subject of debate (Magny et *al.*, 2009; Wanner et *al.*, 2008; 2011; Bini et *al.*, 2019). The 4.2 ka RCC is  
574 often subdivided into three distinct time periods: in the central Mediterranean (Magny et *al.*, 2009;  
575 2013), the western Mediterranean (Hinz et *al.*, 2019; Schirmacher et *al.*, 2020), and the Levant  
576 (Kaniewski et *al.*, 2018). The results obtained from core FC8 also show such tripartition. Between **4.35**  
577 **and 4.1 ka cal BP**, there was a drop in NPPs indicative of eu-mesotrophic conditions, and the deciduous  
578 oak forests on the piedmont and lower slopes were replaced by beech woodland, coniferous forest  
579 and xerothermophilous vegetation. This change corresponds to gradual aridification probably  
580 associated with decreasing temperatures as observed by Kotthoff and *al.* (2008a), and also coincides  
581 with the beginning of an erosive phase about 4.15 ka cal BP, also attested at Zazari Lake (Gassner et  
582 *al.*, 2019), in Greece and in western Mediterranean areas (Finné et *al.*, 2019; Walsh et *al.*, 2019).

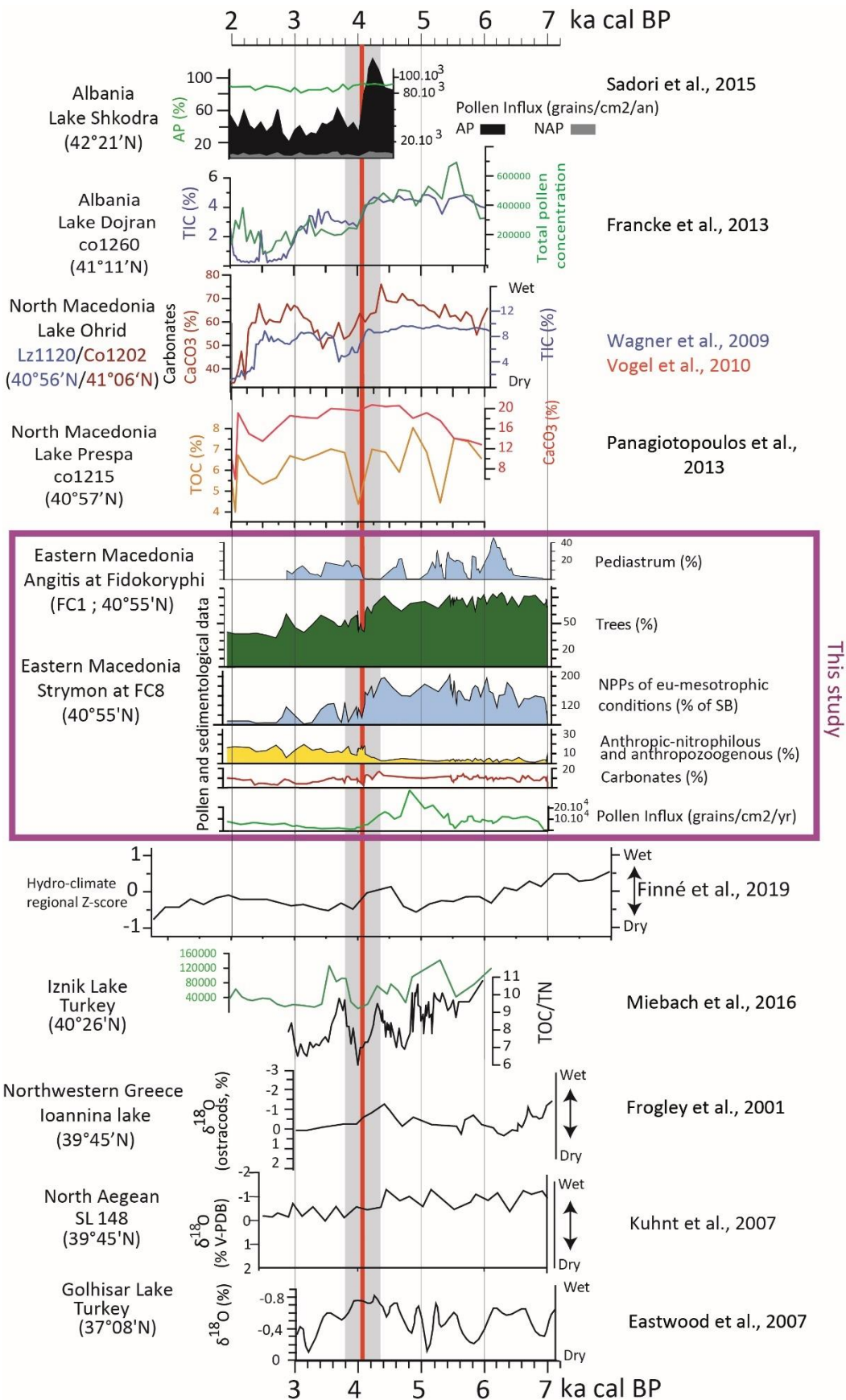
583 The second period, **4.1-3.95 ka cal BP**, corresponding to the LPAZ3-LPAZ4 transition (Fig.12) is  
584 synchronous with that recorded in central Mediterranean areas (Magny et *al.*, 2009). This period was  
585 characterized by a severe dry period that is detectable in a wide range of palaeo-indicators/proxies  
586 and is indicative of a lowering of the Achinos water level. According to NPPs, wetland transformed eu-  
587 mesotrophic into meso-oligotrophic conditions. The lowering of the water level coincides with an  
588 inflexion point in the sediment curve (Fig.7), and with colonization of the margins of the wetland by  
589 hygrophilous and herbaceous taxa. Conversely, woodland underwent an abrupt decrease and  
590 deciduous forest was particularly affected. Reduced magnetic susceptibility, carbonate content and  
591 organic matter confirm these hydroclimatic changes (Fig.6; ca. 13m). These features, which  
592 characterize pronounced drought, indicate a period of intensive climate change (Jung and Weninger,  
593 2015) similar to the records from Ohrid Lake (Wagner et *al.*, 2009; Vogel et *al.*, 2010), Dojran Lake  
594 (Masi et *al.*, 2018), Iznik Lake (Miebach et *al.*, 2016), Van Lake (Wick et *al.*, 2003) and Soreq cave in the  
595 Middle East (Bar-Matthews et *al.*, 1999). They confirm the global scale of these hydroclimatic  
596 transformations corresponding to the 4.2 event.

597 The last period, between **3.95 and 3.75 ka cal BP**, was characterized by a return to wetter  
598 conditions and the expansion of woodland taxa, like in the Tenaghi-Philippon marsh (Peyron et *al.*,  
599 2016). Nevertheless, the woodland ratio did not reach the level observed before the 4.2 ka RCC. In the  
600 Central Mediterranean area, an increase in erosion was recorded between 3.95 and 3.8 ka cal BP  
601 (Magny et *al.*, 2009, 2013). This trend was not as apparent in the NPPs but was perceptible in the  
602 temporary increase in sediment grain size and in the percentage carbonate content from 3.8 ka cal BP  
603 (Fig.6). The same overall pattern was observed farther west for the Dojran, Ohrid and Prespa lakes  
604 (Fig.13). A decline in forest cover due to drought can increase the vulnerability of Mediterranean soil  
605 and its sensitivity to erosion, as suggested at Dojran (Thienemann et *al.*, 2017).

606 Thus, although our study area is located at latitude 40° 54' N, the hydrological pattern recorded at  
607 FC8 is better suited of the southern 40°N trend recorded in the Central Mediterranean area with a dry  
608 trend inferring lowering of the water level in the lake (Desprat et *al.*, 2013; Magny et *al.*, 2011; 2013;  
609 Sadori et *al.*, 2011). This observation is consistent with the eastern Mediterranean pattern  
610 characterized by marked dry period (e.g. Bar-Matthews et *al.*, 2003; Eastwood et *al.*, 2007; Kotthoff et



611 *al.*,2008a; Roberts *et al.*, 2001, 2011; Francke *et al.*, 2013; Kaniewski *et al.*, 2013; 2018). Nevertheless,  
612 no clear latitudinal contrast is visible in the results obtained in the Aegean area (Fig.13), whereas  
613 Triantaphyllou *et al* (2014) exhibited an N-S transgressive aridification gradient around the Aegean  
614 Sea, most probably associated with the reorganization of the general atmospheric circulation during  
615 the Mid-Holocene. In any case, even the “tripartite” event is the subject of debate (Zanchetta *et al.*,  
616 2016; Bini *et al.*, 2019): it is dominated by the lower lake level that supports the hypothesis of a  
617 significantly drier period. The results obtained from the FC8 core confirm the few existing palynological  
618 data indicative of this abrupt climate change (Masi *et al.*, 2018). The 4.2 event certainly represents a  
619 climatic tipping point showing the beginning of Meghalayan period in the Mediterranean basin,  
620 characterized by drying of the climate (Finné *et al.*, 2019) with locally different climatic expression (Bini  
621 *et al.*, 2019). Fluctuating aridity between 4.1-3.95 cal BP lasted no more than a few decades but  
622 appears to have caused long-term changes in hydrological features with precipitation failing to return  
623 to its level before the dry period.



This study

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Figure 13: Comparison of environmental changes recorded by selected analyses in the Aegean and eastern Mediterranean regions. Study period of the so-called “4.2 ka BP event” determined by Bini et al., 2019 is highlighted by the gray shaded area and by the red vertical line for the driest phase.

### 628 5.2.2. *Anthropogenic changes*

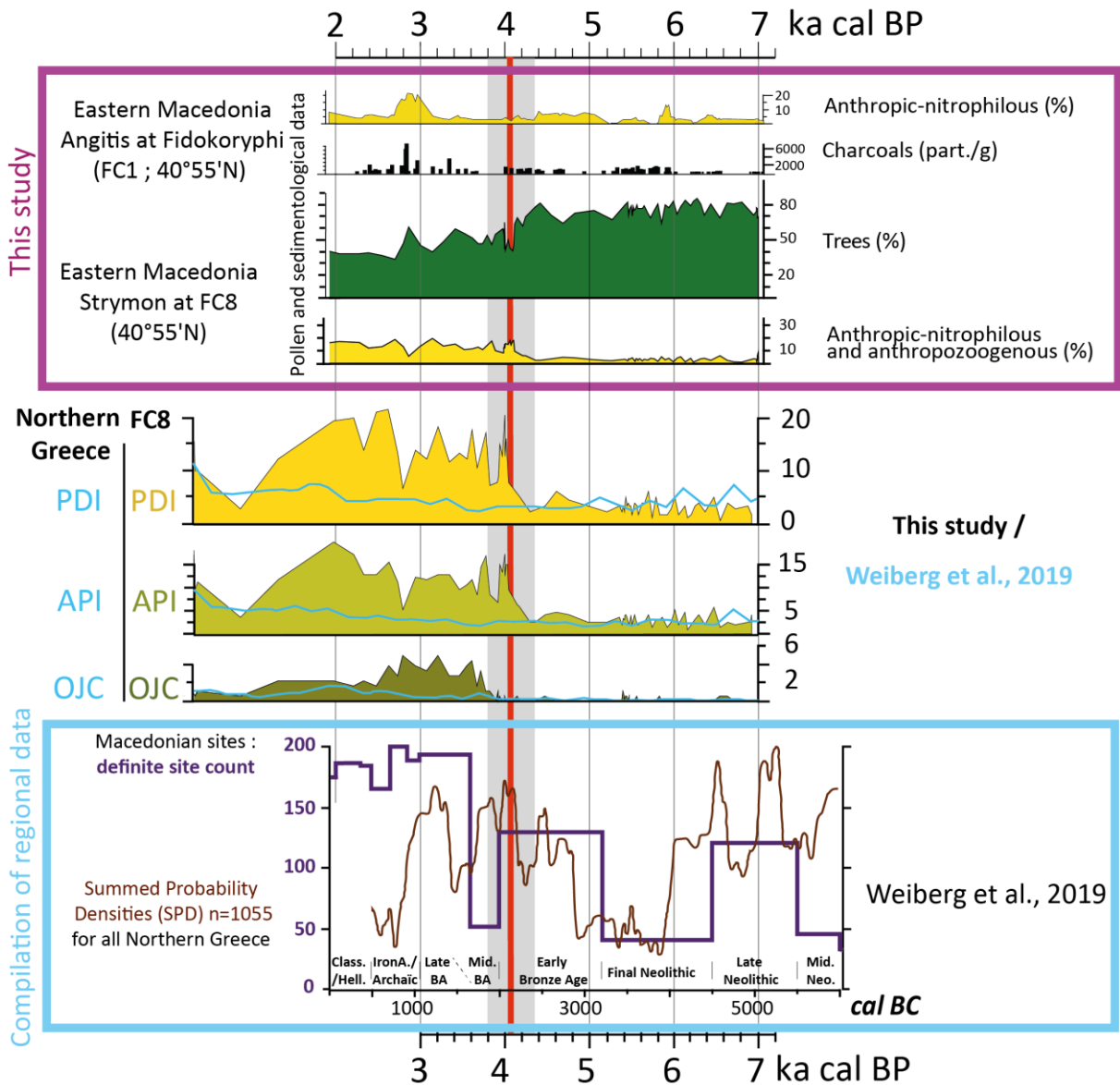
629 The FC8 sequence showed contrasting anthropization signals compared to the previous regional  
630 picture (Lespez et al., 2016; Glais et al., 2017; Masi et al., 2018). During the first period from **4.3 to 4.1**  
631 **ka cal BP (2350-2150 BC)**, the lake shores emerged and cultivated plants, erosion, pastoralism, and fire  
632 use signs are clearly recorded in core FC1 (Lespez et al., 2016). In the FC8 core, collected in the center  
633 of the shallow lake, the anthropogenic signal recorded an increase in secondary indicators of  
634 anthropization such as anthropozoogenous and anthropogenic-nitrophilous taxa curves (Fig.14), like  
635 at Zazari lake (Gassner et al., 2019). There was no clear change in primary anthropization indicators,  
636 and the reduction in oak forest cannot be directly linked with human pressure based on data available  
637 today. From the beginning of the driest intermediary phase toward **4.1 ka cal BP (2150 BC)**, all  
638 indicators of agropastoralism increased rapidly. This is in apparent agreement with the regional  
639 demographic pattern (Walsh et al., 2019). Cereals represented 1% and remained continuously around  
640 this value for several centuries, in contrast to the pollen spectra from the wetland margin, where cereal  
641 pollen were missing (Lespez et al., 2016). The percentage of perennial pasture plants,  
642 anthropozoogenous and anthropic-nitrophilous taxa reached levels two or three times higher than  
643 before the 4.2 ka cal BP event. This reinforcement of anthropogenic pressure was made possible by  
644 the contraction of open water wetlands. Likewise, the development of coprophilous fungi indicates  
645 the expansion of pastoralism. Scrubland vegetation grew on the slopes and erosive processes  
646 associated with high sedimentation accumulation rate are recorded for the first time in the lake center  
647 during this period like in central Anatolia (Roberts et al., 2019b). During the first decades of the last  
648 stage of the event, between **3.95 and 3.75 ka cal BP (2050-1850 BC)**, anthropozoogenous and  
649 anthropic-nitrophilous taxa declined sharply before reaching a new peak at the end of this interval.  
650 This sudden decrease may be linked with the temporary passage of wetter conditions (Peyron et al.,  
651 2016) including extension of the lake. In other respects, erosive processes recorded during previous  
652 phase could have been heightened under wetter conditions and by the extensive clearing of the  
653 landscape in the region. In fact, palynological analyses of Lake Dojran (Athanasiadis et al., 2000; Masi  
654 et al., 2018) and other pollen studies in mountainous areas in southwestern Bulgaria (Marinova et al.,  
655 2012) for the first time reported permanent anthropogenic signal (cereals, cultivated plants and  
656 secondary indicators). Hence, indicators of a decrease in population (Weiberg et al., 2019) coexist with  
657 high values for anthropogenic pollen indicators, suggesting a complex and unknown pattern of society-  
658 environment dynamics. The reinforcement of the anthropogenic signal in the environmental record  
659 during the EBA-MBA transition could be explained by several factors, perhaps in combination:

- 660 • An increase in human activities in the Strymon watershed or an increase in the number of  
661 settlements. However, this trend goes against the overall settlement model defined for northern  
662 Greece at the beginning of MBA (Fig. 14 from Weiberg et al., 2019).
- 663 • Displacement of activities as an adaptation to the new hydrological conditions that modified land  
664 occupation and use of the soils. In a large flat plain (<1%), in which extensive areas were previously  
665 subjected to seasonal fluctuations were no longer under water, means fertile land was available for  
666 cultivation using the pre-existing agricultural pattern. This shift toward wetland is the opposite of  
667 the pattern described for the end of the Chalcolithic in the south Balkans (Todorova, 1995; 2007).  
668 Nevertheless, it is consistent with the idea of a possible extension and intensification of  
669 crop/pastoral activities in previously unexploited and sensitive areas coinciding with a period of  
670 climate change (Walsh et al., 2019).
- 671 • Reduction of wetlands favors human presence on their margins, especially in summer. This pattern  
672 favors the recording of the impact of anthropization on the landscape, thanks to the reduced  
673 distance between the exploited land and the recording sites. This facilitates also the representation

674 of pollen with low dispersal capacity or low pollen productivity like the Cerealia type in pollen  
675 diagrams.

- 676 • Clearing and opening of the landscape, especially of riparian trees, which cannot play a crucial role  
677 as pollen filters. The contemporary decrease in total pollen flow (Fig. 13) indicates a reduction in  
678 overall plant biomass like that observed in Shkodra (Sadori et al., 2015) or Lake Dojran (Francke et  
679 al., 2013; Masi et al., 2018).

680 Before and after the 4.2 ka cal BP event, records from the lake shore in the lower Strymon valley  
681 (Lespez et al., 2016) contained anthropogenic signals, although discontinuous. In the present study,  
682 anthropogenic evidence became stronger after the beginning of the 4th millennium BP, as regionally  
683 indicated by anthropogenic pollen index and pastoral indicators (Mercuri et al., 2019; Walsh et al.,  
684 2019). The natural slowing down of the sea level rise combined with human-induced sedimentation  
685 had a significant effect on the creation of productive wetland and agricultural land, which in some  
686 cases, may have had significant demographic consequences (Bruckner et al., 2006). Resilient societies  
687 are thought to have adopted new strategies to cope with these environmental changes (Berger et al.,  
688 2016; Grove and Rackham, 2001; Walsh, 2013; Walsh et al., 2019). Unlike some regional case studies  
689 such as at Lake Shkodra (Mazzini et al., 2016), the water level rise cannot explain the lack of Bronze  
690 Age settlement. A dryer climate could bring about or favor the transformation and relocation of  
691 agricultural activities. If the local particularities and variabilities of climatic and ecological data are not  
692 excluded (Whitford, 2018), the continuity and reinforcement of agropastoral practices suggest a period  
693 of socioeconomic development at regional scale. Societies that develop in lowlands located close to  
694 wetlands are certainly more resilient than populations living in more sensitive contexts. For example,  
695 thinner soils, more clayey and sensitive to erosion or drought, are not fertile (e.g. southern Greece,  
696 Levant). This result addresses the question of the best scale to use in order to understand the social  
697 processes underway during climatic change. This is not to say that this period of RCC could not have  
698 negative societal consequences at annual or decadal timescales. At a centennial timescale, on the  
699 other hand, as suggested by Roberts et al. (2019a), our results suggest that this climatic adversity may  
700 have acted as a stimulus to innovation and relocation rather than retarding societal development in  
701 the region. Ultimately, the apparent paradox of fewer settlements but increased anthropogenic  
702 activity in the record could be explained if the settlements were simply of shorter duration, which is  
703 by no means synonymous with a more nomadic way of life. As already mentioned, in the lower  
704 Strymon valley, like in most other plains in northern Greece and in the southern Balkans, the majority  
705 of known Neolithic and Early Bronze Age settlements belong to the multi-layered type, i.e. are sites  
706 where the successive layers of occupation are mainly displayed vertically. Even the so-called “flat”  
707 settlements (as opposed to tells) usually comprise at least two or three layers one on top of the other  
708 (e.g. Kryoneri: see Malamidou 2016). Sites that develop horizontally could either have been overlooked  
709 by classical archaeological research, or wiped out due to erosion, subsequent activities, or be buried  
710 under more recent sediments. This hypothesis, which has already been put forward to explain the 4<sup>th</sup>  
711 millennium BC hiatus (the Neolithic-BE transition: Lespez et al., 2016; Tsirtsoni 2016c; 2016d), could  
712 also be supported here. In the neighboring Thracian plain in present-day Bulgaria, the existence of flat  
713 sites dating from the late Early Bronze Age to the Middle Bronze Age (late 3rd-early 2nd millennium  
714 BC) has been evidenced in recent years, and, in one case, even the horizontal development of the site  
715 between this period and the following LBA period (Leshtakov and Tsirtsoni 2016; Tsirtsoni 2021).



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Figure 14: Comparison of anthropization signal from FC8 and FC1 pollen data compiled from regional archeological data. The study period of the so-called “4.2 ka BP event” determined by Bini et al., 2019 is highlighted by the gray shaded area. Pollen Disturbance Index (PDI: *Centaurea* + *Cichorioideae*, *Plantago*, *Ranunculus acris* type, *Polygonum aviculare* type, *Sarcopoterium*, *Urtica dioica* type and *Pteridium*; Mercuri et al., 2013b; Kouli, 2015); Anthropogenic Pollen Index (API: *Artemisia*, *Centaurea*, *Cichorioideae*, *Plantago*, cereals, *Urtica* and *Trifolium* type; Mercuri et al., 2013b); *Olea-Juglans-Castanea* (Mercuri et al., 2013a).

### 723 5.3. Late Holocene, intensification of human impacts

#### 724 5.3.1. Toward a cultural landscape

725 During the Middle Bronze Age (3.95-3.55 ka cal BP: 2000-1600 cal BC), despite the displacement of  
726 agropastoral activities toward wetlands, the vegetation cover was still dominated by woodland with  
727 no clearance trend, as recorded in the Tenaghi-Philippou marsh (Greig and Turner, 1974). From a  
728 sociocultural point of view, the Middle to Late Bronze Age transition, around 3.55 ka cal BP (ca. 1600  
729 BC), is considered to have taken place gradually with no significant cultural interruptions, mainly in  
730 comparison with what was observed in neighboring areas, since local data are lacking (Koukoulis-  
731 Chryssanthaki, 1993; Andreou, 2010). Indeed, unlike the other region of northern Greece (Treuil et al.,  
732 2008; Weiberg et al., 2019), archaeological data from the Strymon watershed, particularly in the  
733 Philippi-Drama plain, indicate weak settlement density compared to the EBA period (Koukoulis-

734 Chryssantakhi et al., 2008) in accordance with paleoenvironmental records. For example, a clear  
735 release of anthropogenic pressure around Dikili Tash (no more cultivated plants, a decline in  
736 anthropogenic taxa and a low fire signal) is recorded, in agreement with the lack of occupation on the  
737 tell during the Middle Bronze Age (Glais et al., 2017).

738 From the beginning of the Late Bronze Age, woodland records gradually decreased, particularly  
739 mesophilous taxa, such as *Ostrya/Carpinus orientalis* type or *Quercus pubescens* type (Fig.9 and 12), in  
740 agreement with pollen data from Tenaghi-Philippon (Greig and Turner, 1974). Beech forest spread  
741 probably benefited from pastoral pressure on slopes and in mountainous areas, as also observed in  
742 Bulgaria (Marinova et al. (2012). This pattern is consistent with archaeozoological data indicating  
743 greater reliance on livestock (sheep and goats) adapted to this environment (Koukoulis-Chryssanthaki,  
744 1993). According to Gerasimidis (1995; 2000), the transfer of these activities to the mountainous  
745 regions was associated with political changes that forced the inhabitants of the lowlands to seek refuge  
746 in the mountains. Concurrently, palynological data show diversification and development of  
747 introduced taxa (walnut, chestnut, grape, olive) already recorded in the Balkans (Bottema and  
748 Woldring, 1990; Athanasiadis et al., 2000; Glais et al., 2017; Gassner et al., 2019) and suggested by  
749 archaeobotanical data (Marinova and Valamoti, 2014). This agrees with evidence from mainland  
750 northern Greece, where *Juglans* is positively correlated with the Summed Probability Densities  
751 according to Weiberg et al (2019). Diversification and multiplication of these anthropogenic species  
752 show a global trend toward cultural landscapes that was not limited to the surrounding of settlements  
753 (Mercuri et al., 2012). Since the LBA, increased anthropogenic indicators have been recorded  
754 throughout Greece and around the Aegean Sea, suggesting economic expansion in line with an  
755 increased number of sites and inferred population growth (Miebach et al., 2016; Weiberg et al., 2019).

756 At the end of the Bronze Age, the vegetation cover remained relatively wooded at regional scale,  
757 despite being increasingly fragmented by anthropogenic activities. This mosaic of increasingly  
758 diversified environmental contexts was subjected to a climatic event around 3.2-3 ka cal BP (Mayewski  
759 et al., 2004), corresponding to another dry period in the Mediterranean basin (e.g. Drake, 2012; Finné  
760 et al., 2011; Kaniewski et al., 2013; Magny et al., 2009; 2013; Roberts et al., 2011). In the lower  
761 Strymon valley, this RCC was characterized by more arid conditions, reduced fluvial activity and a drop  
762 in the water level. However, the pollen assemblage does not record a significant or lasting  
763 transformation except for a decrease in altitudinal coniferous forest and riparian forest, species that  
764 are considered to depend on hydrological inputs. The increase in environmental disturbance during  
765 the Bronze Age/Iron Age transition calls into question the spread of collapse patterns observed in  
766 southern Aegean and Middle East after the 3.2 ka cal BP event (e.g. Drake, 2012; Kaniewski et al.,  
767 2013). The decline or disappearance of numerous economic centers in southern Greece (Drake, 2012),  
768 the Middle East (Kaniewski et al., 2013) and more generally in Europe (Risch and Meller, 2015), for  
769 which climate changes are often mentioned to explain, do not obviously apply to communities in  
770 northern Greece. Some disturbances could have had negative effects on crops or hydrologically  
771 sensitive uses of the environment, but socio-environmental dynamics point to growing production and  
772 trade and to the intensification of land use at regional scale.

773 At the beginning of Antiquity around 2.8 ka cal BP (ca. 850 BC) there was both a local and regional  
774 increase in indicators of erosion, a decrease in mesophilous forest (except riverine taxa) probably  
775 replaced by degraded phrygana shrubs, in parallel with the increased impact of agro-pastoral activities  
776 and clearing of the forest using fire during the Thracian occupation (Athanasiadis et al., 2000; Glais et  
777 al., 2016b; Masi et al., 2018). Contemporaneously, beech forests, located at higher altitudes (from 600  
778 m to the timberline at 1,800 m a.s.l.) decreased dramatically for the first time since anthropization  
779 during the Late Neolithic. This beech woodland pattern is the opposite of the Limni Zazari pollen record  
780 (Gassner et al., 2019). Nevertheless, the openness of the woodland cover is in agreement with



781 reinforcement of sediment aggradation that started earlier and was widely recorded (Francke et al.,  
782 2013; Benito et al., 2015; Glais et al., 2016b; Roberts et al., 2019b; Styllas, 2020; Walsh et al., 2019).  
783 In the Strymon valley, this detritism probably originated from land use intensification on the slopes  
784 rather than due to climatic driving factors. In fact, contrary to central Mediterranean records above  
785 40°N where a wetter period is attested between 2.7 and 2.3 ka cal BP (Magny, 2013; Magny et al.,  
786 2007; 2012) no significant climatic trend is attested in the Aegean area (e.g. Finné et al., 2011; Kuhnt  
787 et al., 2007; Rohling et al., 2002).

788 As only a few archaeological excavations have focused on this period (Koukouli-Chryssanthaki,  
789 1998), the population dynamics is not well known and has only been deduced from a few data including  
790 some evidence of Thracian activities (Vokotopoulou et Koukouli-Chryssanthaki, 1993). According to  
791 Bulgarian investigations, this is probably linked to the development of farming practices using more  
792 mountainous areas than alluvial plains (e.g. Marinova et Tonkov, 2012; Marinova et al., 2012; Tonkov  
793 et al., 2008). Local tribes, settled in the middle or upper Strymon basin (Bulgaria), moved to high  
794 altitude lands during this period (Bozhkova et Delev, 2002; Lazarova et al., 2015). In eastern  
795 Macedonia, this settlement pattern could explain the low percentage of cultivated plants in all records,  
796 contrary to increasing pastoral evidence elsewhere (Glais et al., 2017; Lespez et al., 2016). In contrast,  
797 North Aegean colonization by Greek populations since 2.31 ka cal BP (Amphipolis was conquered in  
798 356 BC and Philippi in 352 BC) corresponds to significant landscape re-arrangement characterized by  
799 increasing clearance, increase in maquis and in anthropogenic impacts (cultivated plants, erosion and  
800 coprophilous NPPs), resulting in a notable decrease in the extent of volume of the body of water, in  
801 agreement with sedimentary data (Fig.6; Glais et al., 2016b).

802

### 803 5.3.2. *Olive tree records: cultural and climatic models?*

804 The first local occurrence of *Olea* pollen was recorded about 5.1 ka cal BP at Dikili Tash (Glais et al.,  
805 2017), whereas *Olea* pollen at FC8 reached 1% from 3.9 ka cal BP and more than 3% from 3.7 ka cal BP  
806 in the lower Strymon valley (Fig.9). Furthermore, the rise in the *Olea* pollen curve around 3.9 ka cal BP  
807 was not accompanied by an increase in pollen percentages of other xerothermophilous taxa curves, in  
808 contrast to other records for example, in Apulia (Italy), where the rise of *Olea* pollen curve is  
809 contemporaneous with an increase in *Phillyrea*, *Pistacia*, *Erica* undiff. and evergreen *Quercus* (Di Rita  
810 and Magri, 2009). This suggests that the development of olive cultivation in the Lower Strymon valley  
811 not only reflects favorable climatic conditions (Fig.9). In addition, in the Strymon delta (Orphano site,  
812 several km downstream of FC8), its cultivation is widely attested during the Late Bronze Age with  
813 percentages reaching 30% (Atherden et al., 2000). This is not to say that climate changes did not have  
814 a significant influence on these particular species, but it does imply that arboreal pollen and  
815 particularly the OJCV (*Olea-Juglans-Castanea-Vitis*) group percentages are unlikely to signal Holocene  
816 climatic variations in the Mediterranean (Mercuri et al., 2019; Roberts et al., 2019a). Microclimatic  
817 conditions and the geographical context of the Strymon catchment basin are probably not the main  
818 factors that explain the location of introduced plants. Conversely, introduction due to anthropogenic  
819 practices is worth considering showing that the reinforcement of socio-economic exchanges played a  
820 key role around the Aegean basin involving different agronomic choices, specialization and more  
821 complex agropastoral management from the Bronze age on than during the Bronze age (Marinova, et  
822 al., 2012; Valamoti, 2004; 2015; Valamoti et al., 2018). Our data fit the regional spread pattern of olive  
823 even if it is not well defined in palynological studies (Langgut et al., 2019). Olive cultivation began in 6-  
824 5.5 ka cal BP in Crete (Bottema and Sarpaki, 2003; Canellas-Bolta et al., 2018) and in the island of  
825 Zakynthos (Avramidis et al., 2013), around 4.2-3.8 ka cal BP in southern Greece (Atherden et al., 1993;  
826 Jahns, 1993; Kouli, 2012; Lazarova et al., 2012), around 4.6-4.5 ka cal BP in north-western Anatolia  
827 (Miebach et al., 2016). Nevertheless, it only cropped up about 3.2 ka cal BP in southwestern Anatolia

828 (Eastwood et al., 1999) and during Antiquity from 2.6 ka cal BP in western Greece (Lake Voulkaria -  
829 Jahns, 2005; Gramousti - Willis, 1992), for example in the vicinity of Lake Dojran, where olive cultivation  
830 probably began at 2.5 ka cal BP (Masi et al., 2018). Finally, the early cultivation of olive in northeastern  
831 Macedonia (Atherden et al., 2000; Greig and Turner, 1974) from the Middle or Late Bronze Age on  
832 remains to be evidenced with new archaeobotanical data. Indeed, except for the discovery of some  
833 olive pits at Stravroupoli (Central Macedonia – Margaritis, 2002), archaeological sites in northern  
834 mainland Greece are characterized by the almost complete absence of olive macro-botanical remains  
835 during the Neolithic and Bronze Age (Valamoti et al., 2018). Even though northern Greece does not  
836 belong to the natural bioclimatic area of wild olive tree, socio-economic exchanges and cultivation  
837 practices probably extended its distribution area (Langgut et al., 2019). It is likely that diversification  
838 of cultivated plants and the introduction of exogenous taxa (e.g. *Juglans*, *Lallemantia*; Valamoti and  
839 Jones, 2010) indeed result from these exchanges on both sides of the Aegean Sea and Balkan  
840 Mountains. Like the Axios river in Central Macedonia, used by the Mycenians to transport wood from  
841 huge oak groves located upstream to supply coastal shipyards (Athanasiadis et al., 2000), Strymon  
842 could also have been a transport route between Central Europe and the Aegean world. The foundation  
843 of Eion harbor in the mouth of Strymon, and the Mycenaean material discovered there, confirm this  
844 hypothesis (Atherden et al., 2000). Sharing of knowledge and of agricultural practices is less known  
845 than the exchange of products with culturally characteristic features such as ceramics, jewelry, tools,  
846 or housing style, but they probably followed the same processes as those suggested for olive groves in  
847 the Mediterranean basin (e.g. van Zeist, 1980; Zohary et Hopf, 2000; Kaniewski et al., 2012; Kouli,  
848 2012; Weiberg et al., 2016). As a perennial crop, olive and other cultivated trees were buffers against  
849 year-to-year fluctuations in rainfall and hence provided some freedom from the direct dependence of  
850 cereal-based agriculture on climate (Roberts et al., 2019a).

## 851 **6. Conclusions**

852 Core FC8 provides a new high-resolution reference sequence, particularly for the period 6-3 ka cal  
853 BP. Anthropogenic impacts are attested around the wetlands in the lower Strymon valley by  
854 palaeoenvironmental evidence from the Late Neolithic (c. 7.2 ka cal BP, or 5250 BC). Pollen records  
855 indicate the emergence of cereal cultivation on the eastern periphery of the ancient lake from 6.35 ka  
856 cal BP on (Lespez et al., 2016), while in the center of the depression, agricultural practices are clearly  
857 and continuously attested only from 4 ka cal BP on. This time lag is evidence for the complex interplay  
858 between ecological and cultural factors, and for the need for a multi-scale approach to identify the  
859 dynamics of ecosystem anthropization. The climatic event of 4.2 ka cal BP is indeed a tipping point in  
860 regional vegetation dynamics, but it is still not clear whether the anthropogenic pressure on  
861 ecosystems detected by the palynological results is (1) actual or exacerbated by climate change; (2)  
862 corresponds to population growth and/or climatic instability; or (3) transcribes societal adaptation to  
863 drier conditions, in particular through land-use changes and population shifts toward northern  
864 mountainous areas and/or retreat from wetlands. However, the causal link between decreasing  
865 precipitation and the political-economic collapse of cereal-dependent societies, which is often  
866 mentioned in the eastern Mediterranean (Arz et al., 2006; Cullen et al., 2000; Drysdale et al., 2006;  
867 Kaniewski et al., 2013; Staubwasser et al., 2003; Straubwasser and Weiss 2006; Weiss et al., 1993), is  
868 not yet proven by palaeoenvironmental data in eastern Macedonia. For this period, the lack of known  
869 archaeological sites or extensive archaeological excavations severely complicates interpretations  
870 when discussing the resilience and continuity of Bronze Age occupations. Nevertheless, we need to  
871 consider that the geographical setting of eastern Macedonia has resulted in physically highly  
872 contrasted environments, where it is often sufficient to move very short distances to find different  
873 environmental conditions and to develop local adaptations to global climate change (Lespez et al.,

874 2013; 2016). Therefore, local studies have a key role to play. Indeed, they are the only studies capable  
875 of exploring the concrete responses of rural societies to climatic or environmental changes and of  
876 considering the chain of causality. This knowledge should now inspire new multidisciplinary, local  
877 research to validate the results obtained through the multiplication of modeling or regional syntheses  
878 that discuss the link between demographic, climatic or environmental trends on a basis that remains  
879 essentially conceptual.

880

## 881 7. Author statement

882 **Arthur Glais:** Visualization, Investigation, Conceptualization, Formal analysis, Writing - Original Draft.  
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