

1 **The Würmian Late-Glacial and Early-Holocene vegetation and**
2 **environment of Gourds des Aillères in the Monts du Forez (Massif**
3 **Central, France) based on pollen and macrofossil evidence**

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22
23 ***Abstract***

24 Although there is a long history of palaeoecological investigation in the Massif Central,
25 detailed reconstruction of the flora, vegetation, and environment in the Late Pleniglacial, the
26 Würmian (Weichselian) Late Glacial, and Early Holocene in the Monts du Forez (Massif
27 Central, France) is still largely lacking. We inferred the palaeoecology of the area from
28 pollen, spores, and plant macrofossils preserved in the sediments of the palaeolake Gourds des
29 Aillères (1335 m a.s.l.). The lake formed in a glacial depression left by retreating glaciers at
30 the start of the Bølling period, ca. 14,700 cal yr BP. Sediment chronology is based on
31 radiocarbon dating and correlation with other, radiocarbon-dated palynological records from
32 the Monts du Forez. Changes in the regional and local vegetation during the Late Glacial and
33 Early Holocene could be correlated to the major climatic events identified in the Greenland
34 oxygen isotope records. We made a highly detailed reconstruction of the changes in the floral

35 diversity and vegetation in and around the lake. After the steppe-tundra of the Late
36 Pleniglacial, local vegetation cover increased and developed into shrub tundra with a few
37 trees forming the tree line in the Bølling and Allerød, with a short reversion during the Older
38 Dryas. During the Younger Dryas trees were eliminated and vegetation was reduced in
39 diversity and density. In the Early Holocene, birch (*Betula*) woodland with some pine (*Pinus*)
40 developed and was then replaced by mixed oak woodlands with *Corylus*. The forest limit rose
41 above the lake. Changes in the lake ecosystem, lake-levels, and nutrient availability were also
42 reconstructed. Hydroseral overgrowth of the lake to a *Sphagnum* peatbog took >6000 years.

43

44 *Keywords:* Late-Glacial plant diversity; Vegetation changes; Environmental changes;
45 Palaeolimnology; Pollen; Plant macrofossils

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47

48 **1. Introduction**

49

50 The Middle High Mountain project was established by C.R. Janssen (Janssen and Punt, 1998).
51 Four mountain ranges were selected along a climatological and phytosociological gradient
52 from Central Europe to the western Mediterranean region: the Vosges Mountains (NE
53 France), the Monts du Forez (Massif Central, France), the Sierra Cabrera Baja (western
54 Cantabria, Spain), and the Serra da Estrela (Portugal). All are medium-high mountain ranges
55 with summits not far above the present-day forest limit. They all have an underlying core of
56 granitic bedrock. Their climates all have pronounced Atlantic influences. The primary
57 research aim in the Monts du Forez subproject was to reconstruct the vegetation dynamics of
58 the upper forest zone and changes in the treeline. The study sites are small mires located along
59 an altitudinal transect on the southeastern slope of the highest peak of the Monts du Forez
60 (Pierre-sur-Haute Mountain, 1634 m a.s.l.) (van der Knaap et al., This Issue). The relatively
61 large mire of Gourds des Aillères (2 ha), containing Late Glacial and early Holocene
62 sediments played a central role in this subproject (Fig. 1). This study reports on the combined
63 pollen and plant-macrofossil analyses of a sediment core collected from the central part of the
64 Gourds des Aillères mire. The combination of detailed pollen and macrofossil analyses
65 provides better insight than either method alone into the past vegetation development of the
66 site and its surroundings, and allows the responses to environmental changes in the Late
67 Glacial and early Holocene to be more clearly evaluated.

68 A long tradition of palynological research exists in the Massif Central, where much
69 pioneer research was carried out (e.g. de Beaulieu et al., 1984, 1985, 1988, 1994a,b; Reille

70 and de Beaulieu, 1988), as also in the neighbouring French and Swiss Alps, on the Swiss
71 Plateau, and Jura Mountains (e.g. Ammann and Lotter, 1989; Lotter et al., 1992; Ammann et
72 al., 1994; Wohlfarth et al., 1994; Magny et al., 2006). There are a few Late-Glacial and early-
73 Holocene macrofossil studies in other parts of the Massif Central (Cubizolle et al., 2014, This
74 Issue); Fassion et al., 2015; Dendievel et al., 2015, This Issue). Pollen diagrams from Gourds
75 des Aillères itself are available from Etlicher et al. (1987), focussing on a Late-Glacial tephra
76 layer with two radiocarbon dates, from Janssen (1990), and from Cubizolle et al. (This Issue),
77 the latter made on a different core from the same mire and including macrofossils. There is
78 also a pollen diagram from Gros Fumé, a few hundred metres from Gourds des Aillères at
79 about the same elevation, covering the late Younger Dryas up to 6000 cal yr BP (van der
80 Knaap et al., This Issue) where the terrestrial vegetation reconstruction is similar to that at
81 Gourds des Aillères. The complete pollen diagram and the detailed macrofossil record
82 presented here were analysed in the late 1980's but were not published before now.

83 It is important to combine pollen and macrofossil analyses at Gourds des Aillères to
84 reconstruct plant diversity and vegetation dynamics in more detail. These proxies complement
85 each other in spatial scale and in taxonomic detail (e.g. Birks and Birks, 2000). Pollen reflects
86 a larger spatial scale as it can be derived from long distances as the regional pollen rain, but it
87 also reflects local vegetation (Janssen, 1973). Plant macroremains, on the other hand, are
88 usually deposited more locally (Birks, 1973, 2013), though in open, treeless areas small
89 macrofossils can be transported over longer distances by wind, meltwater, or streams,
90 especially in winter (e.g. Birks, 1973, 1991, 2013; Bos et al., 2004; Birks and Bjune 2010).
91 Pollen therefore contributes more to the reconstruction of the vegetation in the catchment and
92 beyond, whereas macrofossils are the main source of information for the (semi-) aquatic and
93 shoreline environment. So far, these palaeoecological aspects have not been fully explored in
94 the Monts du Forez.

95 In this study, we therefore focus on these two aspects: the regional vegetation
96 development including the movements of the tree line and forest limit; and the succession of
97 the local vegetation, the local hydrology, and trophic regimes. We aim to reconstruct 1) the
98 flora and vegetation of Gourds des Aillères and its surroundings during the Late Glacial and
99 Early Holocene, 2) vegetation responses to past climatic changes, 3) the dynamics of past
100 tree-lines in relation to the study site, 4) changes in the aquatic ecosystem (e.g. past lake-level
101 changes, nutrient status, and the local vegetation succession).

102

103 **2. Regional and local settings**

104

105 The Gourds des Aillères (45.65°N, 3.84°E, 1335 m a.s.l.) (Fig. 1) is located in the
106 northeast of the granitic part of the Massif Central, which is part of the igneous and
107 metamorphic primary basement of western Europe (Etlicher, 2005). The mountain range was
108 formed by Alpine uplift since the Miocene. During the last glaciation, the Würm, the upper
109 Forez massif (1400-1550 m a.s.l.) was covered by a small ice cap with glaciers flowing into
110 the valleys down to 1100 m, while periglacial landforms developed on the slopes. Because of
111 the relative thinness of the ice cap, the Pierre-sur-Haute Mountain (1634 m a.s.l.), was a
112 nunatak (Du Roselle, 1950). The peatland of Gourds des Aillères lies in a glacial depression
113 ("Gourds") in open terrain and covers about two ha. The slope above it runs directly to the top
114 of the Pierre-sur-Haute.

115 The Monts du Forez lies within the Atlantic influence of Western Europe, but a barrier
116 effect of the south/north orientation of the mountains influences the rainfall and the
117 temperature regimes on the western and eastern sides due to orographic rainfall (Suchel,
118 1990). The Gourds des Aillères peatbog lies on the eastern slope of the Monts du Forez,
119 where the climate is more continental. Annual precipitation ranges from 600 mm at lower
120 elevations up to 1600 mm on the summits, where much of it falls as winter snow. The mean
121 annual temperature ranges from 10°C in valleys to 3°C at the summits. The Monts du Forez
122 are within the upper catchment of the Loire River, between the Dore River to the west and the
123 Loire River to the east.

124 At present, the montane and subalpine vegetation of the Monts du Forez consists of
125 mixed *Abies-Fagus* forests, meadows, pastures, and *Calluna*- and *Vaccinium*-dominated
126 heathlands that are or have been grazed by husbandry animals (e.g. Thébaud, 1988;
127 Schaminée and Meertens, 1991; Schaminee and Hennekens, 1992; Schaminée et al., 1992;
128 Schaminée, 1993). Planted trees flourish within a fenced area above 1620 m, however,
129 suggesting that the natural upper forest limit is much higher and that in the past open forest or
130 scattered trees possibly occurred up to the top before grazing destroyed it.

131

132 **3. Material and Methods**

133

134 *Field and laboratory work, pollen and macrofossil identification, and diagram construction*

135 The sediment core studied was extracted on June 9 1982 from the deepest part of Gourds des
136 Aillères with a Livingstone piston corer with a diameter of 7.5 cm and a length of 1 m. The
137 analyses were carried out in the Laboratory of Palaeobotany and Palynology at the University
138 of Utrecht in the early 1980s. In the laboratory, microfossil samples (~1 cm thick) were
139 extracted from the sediment, washed through a 120 µm sieve and prepared for pollen analysis

140 following Fægri and Iversen (1989). The residues were suspended in silicone oil and slides
141 were examined systematically using a light microscope. Pollen grains and cryptogam spores
142 were identified using the reference collection of the Laboratory of Palaeobotany and
143 Palynology at the University of Utrecht with verification using keys of Moore and Webb
144 (1978), Beug (2004), and the NEPF Vol. I–V (Punt, 1976; Punt et al., 1988; Punt and Clarke,
145 1980, 1984). In line with the tradition of the laboratory, great efforts were made to achieve the
146 highest possible taxonomical resolution (Janssen and Punt, 1998). Microfossil taxa were
147 divided into regional and (extra-) local components following Janssen (1973). The pollen sum
148 used for calculations (100% by definition) was the total of AP (arboreal pollen: trees and
149 (dwarf-) shrubs) and NAP (non-arboreal pollen: upland herbs including Poaceae). Wetland
150 and aquatic plants were excluded, but their percentages were calculated based on the pollen
151 sum. Poaceae pollen is often included in the pollen sum in Late-Glacial and early-Holocene
152 studies as during these periods it is usually interpreted as regional and terrestrial in origin (e.g.
153 Lotter et al., 1992; Hoek, 1997; Bos et al., 2006, 2018).

154 After sub-sampling the sediment cores for pollen analysis, the remaining sediment was
155 sliced into 2.5 cm thick subsamples and the sample volume (~125 cm³) was measured by
156 displacement of water. Macrofossils were recovered by washing the subsamples over a 125
157 µm mesh sieve. They were handpicked from the residue and stored in Eppendorf vials with
158 preserving liquid. A dissecting microscope was used for extraction and identification.
159 Vascular plant macrofossils were identified by comparison with modern reference material
160 and the identification atlases of Katz et al. (1965), Berggren (1969, 1981), Beijerinck (1976),
161 and Anderberg (1994). Microscope slides were prepared for the identification of seeds of
162 *Juncus*, Poaceae, Caryophyllaceae, and Saxifragaceae.

163 The pollen and macrofossil diagrams (Figs. 2 and 3) were constructed using TILIA
164 software (Grimm 1992–2004). The botanical taxa are arranged stratigraphically and grouped
165 by inferred habitat. All pollen types are given in percentages of the pollen sum (100%).
166 Macrofossils are displayed as histograms giving total counts, adjusted to a standard volume of
167 100 cm³.

168

169 **4. Results and discussion**

170

171 ***4.1 Chronology of the Late-Glacial sediments***

172

173 Two radiocarbon dates of Allerød tephra from our core from Gourds des Aillères reported by
174 Etlicher et al. (1987), are insufficient to construct a chronology (Table 1).

175 In any case, our main purpose is to assign our vegetation changes to the major Late-
176 Glacial periods. To construct an outline chronology, we therefore used the dates of the
177 traditional Late-Glacial pollen zones valid for the Massif Central presented by Cubizolle et al.
178 (2014), following Richard (1999). In addition, we correlated our pollen sequence with that of
179 a different core in the same mire, “Gourd des Aillères” (Cubizolle et al., This Issue) on the
180 basis of regional pollen assemblages, which was straightforward. Eight radiocarbon ages were
181 therefore transferred from that sequence. Table 2 lists all available radiocarbon dates

182 For the Late-Glacial/Holocene (=Younger Dryas/Preboreal) transition the defined
183 marker horizon at 11653 cal. yr BP (=11703 b2k) (Rasmussen et al. (2006) was used. An
184 approximate age-depth model of the sequence was made by linear interpolation between the
185 listed points. The correlation with the traditional Late-Glacial pollen zones is given in Table
186 3.

187

188 **4.2 Biostratigraphy and vegetation reconstruction**

189

190 A gray/green sandy, clayey loam poor in organic material forms the base of the core at 5.75
191 m. The sediment sequence was described in Etlicher et al. (1987) and is displayed here as a
192 lithological column in the pollen and macrofossil diagrams (see below).

193

194 **Zone 1 (537.5–575 cm depth; before 14650 cal yr BP): Late Pleniglacial**

195 Tree- (<10%, mainly *Pinus*) and shrub-pollen values (~3%) are very low, while NAP (Non
196 Arboreal Pollen) values are high (~87%). The relatively high percentages of *Pinus* pollen
197 derive from long-distance transport and are magnified by the very low local pollen
198 productivity. Pollen of low and dwarf shrubs such as *Juniperus*, *Salix*, *Dryas octopetala*, and
199 *Ephedra* spp. is present. NAP includes *Helianthemum*, Brassicaceae, Caryophyllaceae,
200 Amaranthaceae, Asteraceae, *Thalictrum*, *Trollius europaeus*, *Plantago alpina*, *Rumex*,
201 *Saxifraga* spp. and *Armeria*. Percentages of Poaceae and *Artemisia* are high.

202 The macrofossil record indicates a mosaic of open environments. *Saxifraga* species (*S.*
203 *cespitosa*, *S. hypnoides*, *S. oppositifolia*, *S. rivularis*), Caryophyllaceae (*Silene acaulis*,
204 *Minuartia rubella*-type, *Cerastium tetrandrum*-type, *C. alpinum*-type), Brassicaceae, *Rumex*
205 *acetosella*, *Chaenorrhinum minus*, and *Chenopodium album* indicate local presence of bare,
206 dry or wet mineral soils. *Artemisia*, *Helianthemum*, Amaranthaceae, and *Thalictrum* indicate
207 dry grassy steppe-like plains.

208 Wet to moist subalpine meadow or fen was locally present with sedges (*Carex*),
209 grasses (*Poa*, *Agrostis*, *Calamagrostis*), and herbs (*Potentilla*, *Filipendula*, *Veronica* spp.,

210 *Trollius europaeus*, *Meum athamanticum*, *Pimpinella*, *Lotus*, *Sanguisorba officinalis*,
211 *Plantago alpina*, and *Ranunculus sceleratus*). *Sedum villosum*, *Chrysosplenium*, *Saxifraga*
212 *stellaris*, and *Saxifraga rivularis* indicate the presence of flushes and small mossy streams,
213 running into the lake, in the case of *S. rivularis*, with cold water derived from snowmelt.
214 *Menyanthes trifoliata* indicates shallow open water (compare Cubizolle et al., This Issue).
215 *Vaccinium myrtillus* points to dry, nutrient-poor and acidic soils.

216 This all suggests a very open landscape around the site, with a mosaic of marshes and
217 wet meadows, dry grasslands, and bare, mineral soils with pioneer communities of
218 heliophilous herbs. Some steppe-tundra vegetation with scattered (dwarf) shrubs was present
219 probably at lower altitudes. The assemblage can be correlated with the Oldest Dryas pollen
220 zone in the Massif Central (de Beaulieu et al., 1985, 1988, 1994a; Cubizolle et al., This
221 Issue). The Oldest Dryas (Table 3) is nowadays considered as the last part of the Pleniglacial
222 (or GS-2a, Rasmussen et al., 2006, 2014).

223

224 **Zone 2** (512.5–537.5 cm depth; 14640–14025 cal yr BP): Bølling

225 Shrub pollen (especially *Juniperus* and *Salix*) increases up to 25%, and shrub taxa such as
226 *Ephedra* spp. and *Hippophae rhamnoides* are present. NAP decreases slightly to 62%, while
227 tree pollen increases to ca. 15%, which is mainly due to *Betula*. Macrofossils of *Betula* sect.
228 *Alba* and *Salix* indicate denser vegetation in the surroundings with low shrubs and some birch
229 trees, in which woodland herbs could expand (e.g. *Anthriscus sylvestris*, *Heracleum*
230 *sphondylium*, *Chaerophyllum temulum*, *Cynoglossum officinale*, *Seseli libanotis*, *Anemone*,
231 *Phyteuma spicatum*).

232 Plant diversity strongly increased, even though many taxa typical of bare, mineral soils
233 disappeared. However, some open, mineral soils remained in the mountains above with
234 *Saxifraga hypnoides*, *Cerastium tetrandrum*-type, *Minuartia*-type, *Herniaria glabra*-type,
235 *Silene suecica*, *Sedum villosum*, *Sempervivum tectorum*, and *Peucedanum alsaticum*. On the
236 drier ridges around the lake, grassland or open grassy plains developed with *Artemisia*,
237 *Cynoglossum officinale*, *Rumex acetosa*, *Helianthemum*, *Campanula*, *Thalictrum*, and
238 *Botrychium*.

239 At the start of the Bølling, a lake formed in the basin, and gray/green sandy, clayey
240 lake mud, poor in organic matter (10–25%, Etlicher et al., 1987) was deposited. It contained
241 many *Nitella* oospores and some macrofossils of *Potamogeton*, *Ranunculus* subgen.
242 *Batrachium* (= *Ranunculus aquatilis* pollen type), and *Menyanthes trifoliata*. These aquatic
243 taxa indicate shallow base-poor oligotrophic to mesotrophic water, ca. 2 to 5 m deep
244 (compare Hannon and Gaillard, 1998; John et al., 2002). Around the lake a tall-herb wetland

245 developed with various sedges, grasses, *Galium*-type, Fabaceae, *Pimpinella*, *Epilobium* (*E.*
246 *obscurum*, *E. hirsutum*, *E. tetragonum*), *Filipendula*, *Sparganium erectum*, *Urtica dioica*,
247 *Caltha palustris*, and *Comarum palustre*, and flushes were occupied by *Sedum villosum* and
248 *Saxifraga stellaris*.

249 The assemblage indicates a change in the regional vegetation from open herb and
250 grass-rich steppe-tundra to a mosaic of grasslands and *Salix* and *Juniperus* scrub with
251 scattered birch trees, in response to climate warming. The strong increase in pollen of juniper,
252 willow, and other shrubs is typical for the onset of the Bølling pollen zone in the Massif
253 Central and Jura Mountains (e.g. de Beaulieu et al., 1985, 1988, 1994a; Etlicher et al., 1987;
254 Magny et al., 2006; Cubizolle et al., This Issue). The Bølling warming phase is a general
255 warming observed on a global scale at the end of the glaciation and can be correlated (Table
256 3) with phase GI-1e in the oxygen isotope records in the Greenland ice cores (Johnsen et al.,
257 1992; Rasmussen et al., 2006, 2014).

258

259 **Zone 3** (502.5–512.5 cm depth; 14025–13904 cal yr BP): *Older Dryas*

260 Pollen of trees (~10%) and shrubs (~8%) decreased slightly, while NAP (~72.5%) increased.
261 The strong increase in Poaceae reflects a drying of the landscape with the expansion of dry
262 grassland with *Poa annua*, *Artemisia*, *Helianthemum*, *Campanula* cf. *linifolia*, *Centaurea*
263 *montana*, *Thalictrum*, and *Rumex* in the area. The assemblage resembles that of the previous
264 zone, with the difference that the values of sedges and *Ranunculus* subgen. *Batrachium*
265 strongly increased, suggesting shallower water. The expansion of other wetland taxa such as
266 *Carex*, *Hippuris vulgaris*, *Epilobium hirsutum*, *Filipendula*, *Caltha palustris*, and *Mentha*
267 suggests a decrease in lake water-level (compare Hannon and Gaillard, 1998) allowing an
268 expansion of fen vegetation into the lake. In the lake, the aquatic assemblage indicates
269 mesotrophic water. This short drier interval and regressive vegetation development can be
270 linked to the Older Dryas pollen zone (e.g. Lotter et al., 1992; de Beaulieu et al., 1988, 1994a;
271 Cubizolle et al., This Issue). It is correlated (Table 3) with phase GI-1d in the oxygen isotope
272 records in the Greenland ice cores (e.g. Johnsen et al., 1992; Rasmussen et al., 2006, 2014)
273 (Table 3).

274

275 **Zone 4** (442.5–502.5 cm depth; 13904–12846 cal yr BP): *Allerød*

276 Tree pollen, especially that of *Betula* and *Pinus*, increased strongly (up to ~25%). *Pinus*
277 values are just at or below the rational limit of pine of 20% (Lotter et al., 1992), which
278 indicates that pine was growing in the vicinity, but probably at slightly lower elevations.
279 Shrub pollen values are low (~2%), while NAP values are high (~72.5%). Plant diversity

280 increased, with an assemblage typical of subalpine meadows today. Main contributors to the
281 NAP and macrofossil assemblages are Poaceae, *Rumex*, *Artemisia*, *Plantago alpina*,
282 *Campanula*, *Trollius europaeus*, *Ranunculus*, *Sanguisorba officinalis*, *S. minor*, *Botrychium*,
283 and various Asteraceae, Brassicaceae, Fabaceae, and Apiaceae.

284 Development of open woodland is indicated by the (re-)appearance of macrofossils of
285 shrubs and trees like *Salix*, *Betula*, and *Populus*. Associated woodland taxa are *Phyteuma*
286 *spicatum*, *Chaerophyllum temulum*, *Anemone*, *Cyclamen purpurascens*, *Circaea*, *Luzula*
287 *sylvatica*, *Aconitum*, and *Stellaria nemorum*. *Calluna vulgaris* was probably present in open
288 woodlands or heaths on nutrient-poor soils. Open, mineral soils with *Juncus balticus*,
289 *Saxifraga granulata*, *Seseli libanotis*, *Sedum*, *Jasione*, *Lychnis alpina*, *Cerastium alpinum*,
290 *Draba fladnizensis*, *Herniaria*, Amaranthaceae, *Rumex acetosella*, *Polygonum viviparum*, and
291 *Peucedanum alsaticum* were still present in the area, probably more towards the summits.

292 At 490 cm depth the sediments change from gray/green sandy, clayey lake mud into
293 very organic gyttja, that becomes more silty, sandy and clayey again from 468 cm depth
294 upwards (Etlicher et al., 1987). The large increase of *Nitella* and decrease in macrofossils of
295 *Ranunculus* subgen. *Batrachium* and *Myriophyllum* indicate that the lake water-level rose
296 considerably (compare Hannon and Gaillard, 1998). The vegetation around the lake was still
297 relatively open, and mesotrophic to eutrophic fen with *Carex*, *Juncus*, *Galium*-type,
298 *Peucedanum*, *Filipendula*, *Caltha*, *Urtica dioica*, *Viola palustris*, and *Comarum palustre*
299 persisted.

300 The assemblage can be correlated to the Allerød pollen zone in the Massif Central (de
301 Beaulieu et al., 1985, 1988, 1994a; Etlicher et al., 1987; Cubizolle et al., This Issue). The
302 Allerød period is equivalent to phase GI-1abc (Table 3) in the oxygen isotope records of the
303 Greenland ice cores (e.g. Johnsen et al., 1992; Rasmussen et al., 2006, 2014).

304

305 **Zone 5** (422.5–442.5 cm depth; 12846–11653 cal yr BP): *Younger Dryas*

306 Tree pollen (especially *Pinus* and *Betula*) slightly decreases to ~18%, shrub pollen is ~1–5%,
307 while NAP increased to ~78% (especially *Artemisia* and Poaceae). Macrofossils of shrubs and
308 trees like *Salix* and *Betula* disappear from the record. Pollen of herbaceous taxa related to
309 woodland (e.g. *Anemone*, *Cynoglossum officinale*, *Cyclamen*) and to subalpine meadows also
310 disappears (e.g. *Trollius europaeus*, *Trifolium*, *Lotus*, *Pimpinella*, *Carduus*, *Aster*, *Anthriscus*,
311 *Scleranthus*, *Ranunculus*). Pollen re-appears of low and dwarf-shrubs (e.g. *Dryas octopetala*,
312 *Hippophae rhamnoides*, *Ephedra*) and various heliophilous herbs (e.g. *Artemisia*, *Centaurea*
313 *montana*, Amaranthaceae, *Seseli*, *Silene*, *Jasione*, *Saxifraga*, and *Armeria*).

314 Silty, sandy, clay-gyttja with lower organic content was deposited in the lake (Etlicher
315 et al., 1987). In the wetland flora, taxa such as sedges, *Juncus*, *Apium*, *Polygonum*
316 *amphibium*, *Ranunculus* subgen. *Batrachium*, and *Sparganium* are recorded. The botanical
317 assemblage suggests that water levels were fluctuating. The site was probably a mesotrophic
318 pool with a sedge fen on the shore.

319 The fossil assemblage in this zone indicates a landscape with much open ground, and
320 open vegetation reflecting colder climatic conditions. This second, more severe regressive
321 phase in the vegetation development suggests a correlation with the Younger Dryas pollen
322 zone (e.g. Lotter et al., 1992; de Beaulieu et al., 1985, 1988, 1994a; Cubizolle et al., 2014,
323 This Issue; Ponel et al., 2016). In the oxygen isotope records in the Greenland ice cores (Table
324 3), the Younger Dryas corresponds to GS-1 (e.g. Johnsen et al., 1992; Rasmussen et al., 2006,
325 2014).

326

327 **Zone 6** (387.5–422.5 cm depth; 11653– ca. 10200 cal yr BP): *Preboreal*

328 Tree pollen strongly increases (up to ~62%, especially *Pinus* and *Betula*) and NAP decreases
329 (especially *Artemisia* and Poaceae). Many shrubs and herbs typical of the Late Glacial are
330 absent or disappear soon after the start of the zone. *Juniperus* shows higher percentages at the
331 start of this zone. This is typical for the early Preboreal pollen zone (e.g. Etlicher et al., 1987;
332 van Geel et al., 1981; Hoek, 1997). These changes in the fossil assemblage reflect the climate
333 amelioration at the start of the Holocene, which Rasmussen et al. (2006, 2014) dated to 11653
334 cal yr BP (Table 3). This implies that zone 6 corresponds with the Preboreal of the Early
335 Holocene.

336 The abundant *Pinus* pollen may be largely long-distance transported from lower
337 elevations where pine woodlands strongly expanded (van der Knaap et al., This Issue), but
338 peak values to over 45% indicate that pine trees must have been growing around the lake
339 (Lutgerink et al., 1989; Lotter et al., 1992). A dip in pine percentages between 400 and 415
340 cm depth may reflect the Preboreal cool oscillation (PBO, *sensu* Lotter et al., 1992; Björck et
341 al., 1997). It seems likely that trees were initially scarce around the lake, but a few centuries
342 later woodlands with birch and some pine developed. *Sorbus* and *Rubus* shrubs and woodland
343 herbs such as *Cornus sanguinea* are also recorded. Taxa such as, *Alopecurus geniculatus*,
344 *Rumex*, Apiaceae, *Sanguisorba minor*, *Centaurea nigra*-type, *Galium*-type, and Poaceae
345 indicate the presence of herb-rich meadows on drier upland soils, and that the woodland was
346 open. In the upper part of the zone, *Betula* fruits are recorded again and *Corylus*, *Quercus*,
347 and *Ulmus* start continuous pollen curves and increase, suggesting the gradual development of
348 deciduous woodland.

349 *Potamogeton* fruits became abundant and *Ranunculus* subgen. *Batrachium* fruits show
350 a minimum. This may suggest an increase in lake level as the groundwater table rose. During
351 the Early Holocene, the lake expanded as temperature and precipitation increased after the
352 Younger Dryas. A rise in water level at the Late-Glacial/Holocene transition is widely
353 inferred in NW European records (e.g. Björck et al., 1996; Hoek and Bohncke, 2002; Bos et
354 al., 2007; Magny et al., 2007). Lake productivity also increased in the warmer climate. In the
355 lake, *Nitella*, *Schoenoplectus lacustris*, *Myriophyllum*, and *Isoetes* formed the aquatic
356 vegetation. *Nitella* and *Myriophyllum* usually grow in rather deep lakes, *Potamogeton* (most
357 species) and *Isoetes* in water up to 4 m deep, and *Schoenoplectus lacustris* in water up to 60
358 cm deep (Hannon and Gaillard, 1998), which indicates a maximum water depth of 4 m. The
359 lake was fringed by fen and wet grassland with sedges (*Carex* spp., *Eleocharis*), *Gentiana*,
360 *Galium*-type, *Sparganium* spp., *Caltha palustris*, *Filipendula* cf. *ulmaria*, *Peucedanum*,
361 *Hydrocotyle vulgaris*, *Lysimachia*, *Typha angustifolia*, ferns, and *Juncus*. The aquatic and
362 wetland taxa occur across a range of nutrient conditions.

363

364 **Zone 7** (321.5–387.5 cm depth; ca. 10200–9400 cal yr BP): Early Boreal

365 Tree and shrub pollen, especially *Corylus avellana*, *Quercus*, and *Ulmus* rises to 75%, while
366 *Betula*, *Pinus* and NAP decrease, suggesting an expansion of open deciduous woodland at
367 lower elevations and a correspondence with the Boreal pollen zone in the Massif Central (de
368 Beaulieu et al., 1988, 1994a; Etlicher et al., 1987; Cubizolle et al., 2014, This Issue). Taxa of
369 woodland undergrowth and edges include shrubs (*Corylus*, *Sambucus*, *Rhamnus*, *Cornus*
370 *sanguinea*, *Viburnum lantana*) and herbs (*Hedera helix*, *Humulus lupulus*, *Anthriscus*
371 *sylvestris*, *Chaerophyllum temulum*, *Heracleum sphondylium*, *Anemone*, *Mercurialis*
372 *perennis*, *Stellaria nemorum*). Many *Betula* fruits and macrofossils of taxa associated with
373 birch woodland (*Vaccinium myrtillus*, *Ranunculus polyanthemos*, *Actaea spicata*) were
374 recorded, which suggest the expansion of birch-dominated deciduous woodland in the
375 catchment. Many herbs re-appeared from the Allerød that had temporarily declined or were
376 not found during the Younger Dryas (Fig. 2b), indicating patches of subalpine meadow or
377 grassland at higher elevations.

378 Hydroseral succession and lake infilling is reflected in the gradual decline of aquatic
379 taxa and increase of *Carex* while the gyttja became richer in organic detritus. *Phragmites*
380 *australis* becomes more important in the wetland vegetation around the lake that also included
381 e.g. *Gentiana*, *Sparganium*, *Caltha palustris*, *Filipendula*, *Peucedanum*, *Lysimachia*, *Mentha*,
382 *Valeriana*, *Typha angustifolia*, *Juncus*, and ferns. *Menyanthes trifoliata* was present in
383 shallow water. *Phragmites* often grows in transitional situations where neutral and acid water

384 come in contact (Weeda et al., 1988). As the lake became shallower and poorer in nutrients,
385 peat started to accumulate locally.

386

387 **Zone 8** (290–321.5 cm depth; ca. 9400–9000 cal yr BP): *Late Boreal*

388 Pollen of *Quercus*, *Ulmus*, and *Corylus* increases further and percentages of *Betula*, *Pinus*,

389 and NAP (especially *Artemisia* and Poaceae) strongly decline. Tree and shrub pollen are

390 ~85%. Based on the high values of *Corylus*, *Quercus*, and *Ulmus*, we assign this zone to a

391 later part of the Boreal (de Beaulieu et al., 1988, 1994a; Cubizolle et al., 2014, This Issue).

392 The pollen assemblage indicates that the deciduous woodlands expanded to elevations above

393 the site. Mixed-oak woodlands occurred at slightly lower elevations. The reduction in the

394 number of woodland herbs implies that the woodlands became less open and hazel scrub was

395 probably present on woodland edges near the lake. Macrofossils of *Betula*, *Vaccinium*

396 *myrtillus*, and *Rubus* indicate birch woodland near the lake. *Anthriscus sylvestris*,

397 *Chaerophyllum temulum*, *Heracleum sphondylium*, and *Anemone nemorosa* may have grown

398 here. Meadows with Poaceae, *Ranunculus*, Asteraceae, Brassicaceae, *Rumex acetosa*,

399 *Campanula*, *Meum athamanticum*, *Sanguisorba minor*, and *Stellaria* cf. *uliginosa* still

400 occurred near the lake, probably in an intermediate zone towards the sedge vegetation on the

401 wetter soils.

402 The lake became overgrown and peat formation started. Macrofossils of mire plants

403 such as *Carex* spp., *Viola palustris*, *Comarum palustre*, *Juncus*, and *Eriophorum*, together

404 with *Sphagnum* and fern spores, indicate the development of nutrient-poor sedge fen at the

405 sampling site. *Sphagnum*-dominated fen and bog developed later, ca. 8400 cal. BP (Zone For-

406 7 in van der Knaap et al., This Issue). Later in this zone, *Potamogeton*, *Nitella*, and

407 *Ranunculus* subgen. *Batrachium* re-appeared, which suggests the occurrence of some pools

408 with open water and fluctuating water tables.

409

410 **4.3. Correlation of Gourds des Aillères within the Late Glacial of NW Europe**

411

412 The pollen zones of Gourds des Aillères (Figs. 2, 3) can be correlated with the

413 traditional Late-Glacial pollen zones (*sensu* Iversen, 1954) used for the Massif Central

414 (Etlicher et al., 1987, de Beaulieu et al., 1988, 1994a, Cubizolle et al., 2014, This issue)

415 (Table 3). They also correlate well with the biostratigraphy of other records from the Massif

416 Central, Jura Mountains, the French and Swiss Alps, and the Swiss Plateau (e.g. de Beaulieu

417 et al., 1985, 1988, 1994a,b; Reille and de Beaulieu, 1988; Ammann and Lotter, 1989; Lotter

418 et al., 1992; Wohlfarth et al., 1994; Magny et al., 2006; Ponel et al., 2016). Differences among

419 the records originate from differences in geographical location, vegetation settings, bedrock,
420 orographic situation, and meso-climate. This biostratigraphy is also recognised in the wider
421 context of northwest and central Europe (e.g. Hoek 1997; Bos, 2001; Mortensen et al., 2011;
422 Bos et al., 2017). We applied biostratigraphical correlation combined with radiocarbon dated
423 records from nearby areas such as the Jura Mountains and the Swiss Plateau (e.g. Lotter et al.,
424 1992, Magny et al., 2006; Ammann et al., 2013) to link our record (Table 3) to the major
425 climatic events during the Late Glacial and Early Holocene (*sensu* Björck et al., 1998)
426 identified in the Greenland oxygen isotope records (e.g. Johnsen et al., 1992; Lowe et al.,
427 2008; Rasmussen et al., 2014).

428

429 *4.4. Past vegetation in the Gourds des Aillères area*

430

431 After the Late Pleniglacial, the vegetation cover around Gourds des Aillères increased and the
432 vegetation changed from steppe-tundra to shrub tundra and then into boreal woodland with
433 birch and some pine, and eventually mixed-oak woodland. During the Bølling, Allerød and
434 Early Holocene, macrofossils in particular indicate that the tree-line rose above the elevation
435 of the lake (i.e. 1335 m a.s.l.) and scattered trees or open woodland surrounded the lake. The
436 macrofossil record clearly shows that during the Bølling and Allerød, a mosaic of shrubs and
437 woodland with willow and birch, and probably some *Populus*, was present in the extra-local
438 vegetation around the lake. Absence of *Pinus* macrofossils indicates that pine trees were not
439 growing in the lake catchment but at lower elevations. Local tree cover decreased during the
440 climate deterioration in the Older and Younger Dryas periods. During the Early Holocene,
441 woodland cover increased strongly in response to the higher temperatures and precipitation.
442 Mixed-oak forests and hazel shrubs replaced initial birch and pine woodlands during the
443 Boreal period after 10085 cal yr BP.

444 Of the two other pollen records from this area of the Monts du Forez, Gros Fumé (van
445 der Knaap et al., This Issue) contains part of the Late Glacial and Early Holocene. Gourd des
446 Aillères (Cubizolle et al., This Issue) is based on a different core from the Gourds des Aillères
447 mire and covers the same time interval. All three diagrams show similar biostratigraphy and
448 can be well correlated with each other. After deglaciation there was a very open landscape
449 with mineral soils supporting steppe-like grasslands around Gourds des Aillères. Both records
450 from the mire show the Older Dryas as a short drier phase with decreased AP values, when
451 grassland predominated and marsh vegetation extended into the lake. Strongly increased AP
452 values in both diagrams in the Allerød suggest the presence of shrubs and open woodland
453 around the site, composed of willow, birch, and possibly some aspen. During the Younger

454 Dryas, both sites record the disappearance of trees and the expansion of bare soils. Lower
455 water-levels allowed marsh vegetation to extend into the lake. The Early Holocene in both
456 records shows increasing AP percentages (especially birch and pine) and high values of
457 *Rumex* and Ranunculaceae pollen (probably *Ranunculus* subgen. *Batrachium* growing in the
458 lake; Fig. 3b). All three records show the Early Holocene development of pine-birch
459 woodland followed by mixed deciduous forest, bordered by hazel shrubs.

460 The two diagrams of Gourds des Aillères differ slightly. An Intra Allerød Cold Period
461 (IACP or GI-1b; Lotter et al., 1992; Lowe et al., 2008; Van Raden et al., 2013; Rasmussen et
462 al., 2014) was reported by Cubizolle et al. (This Issue) and also in the Aubrac Mountains
463 (Massif Central) by Ponel et al. (2016), but not in our record due to the lower sample
464 resolution. The Younger Dryas of Cubizolle et al. (This Issue) covers >1 m of sediment that is
465 mineral-rich with distinct gravelly and sandy layers in the upper part, suggestive of erosion in
466 an open landscape. In our core, the Younger Dryas sediments cover 20 cm and have an
467 elevated mineral content, but no erosional layers. Cubizolle et al.'s core may have been closer
468 to the influence of an inflow stream.

469 The pollen diagram from Gros Fumé (van der Knaap et al., This Issue) covers the late
470 Younger Dryas up to 7900 cal. yr BP. Gourds des Aillères and Gros Fumé lie only a few
471 hundred meters apart at similar elevation (1335 m and 1350 m respectively, Fig. 1) and are
472 about the same size (2 ha). They show similar regional vegetation development during the
473 Younger Dryas and Early Holocene, but differ in their local vegetation development. Gros
474 Fumé was a sedge–*Sphagnum* fen during the Younger Dryas, whereas Gourds des Aillères
475 was a pool with littoral vegetation. *Sphagnum* fen continued at Gros Fumé to the end of the
476 record (ca. 7900 cal yr BP), but was only initiated at Gourds des Aillères at ca. 8400 cal yr
477 BP. Between ca. 9250 and 8600 cal yr BP, *Betula* played a much larger role at Gros Fumé
478 than at Gourds des Aillères, suggesting that *Betula* may have been locally present at the edges
479 of the sedge–*Sphagnum* fen.

480

481 **4.5. Regional forest dynamics**

482

483 In both diagrams from the Gourds des Aillères mire, pine pollen dominates over birch from
484 the early Allerød but stagnates at the rational limit of 20% (Lotter et al., 1992). No
485 macrofossils were found, so we conclude that pine was growing at slightly lower elevations
486 and its pollen was blown upward. In most other records from the Massif Central, Jura
487 Mountains, French and Swiss Alps, and the Swiss Plateau, high *Pinus* pollen values are
488 recorded during the Allerød and Younger Dryas, and *Pinus* clearly dominated over *Betula*,

489 suggesting that pine was growing locally (e.g. de Beaulieu et al., 1985, 1988, 1994a,b; Reille
490 and de Beaulieu, 1988; Ammann and Lotter, 1989; Lotter et al., 1992; Wohlfarth et al., 1994;
491 Magny et al., 2006; Ponel et al., 2016). During the Early Holocene, high peaks in pine pollen
492 (to over 45%) in both Gourds des Aillères records indicate that pine trees must have been
493 growing around the lake (Lutgerink et al., 1989; Lotter et al., 1992).

494 In the southwestern Massif Central, De Beaulieu et al. (1982, 1984) and Reille and de
495 Beaulieu (1988) suggested that the Bølling climate warming probably contributed to an early
496 expansion of oak from its glacial refugia in the lower regions of the Massif Central. Ponel et
497 al. (2016) also recorded *Quercus* pollen throughout the Late-Glacial Interstadial and
498 suggested that oak woodlands developed at lower altitudes, but that oak was absent from the
499 Aubrac plateau. In the Early Holocene, oak woodlands probably expanded here from their
500 refugia in the warmer limestone valleys of the Cévennes, Quercy, and Périgord. In the
501 northeastern Massif Central, both Gourds des Aillères records show no evidence for an early
502 expansion of *Quercus* during the Late-Glacial Interstadial. *Quercus* pollen is recorded
503 regularly, but there is no macrofossil evidence and the low values probably originated from
504 mixed oak woodlands at much lower elevation. A rapid *Quercus* expansion was not recorded
505 in the Early Holocene diagrams from the Monts du Forez, in contrast to the southwestern
506 Massif Central and French Pyrenees (e.g. de Beaulieu et al., 1982, 1984, 1994b; Reille and de
507 Beaulieu, 1988; Ponel et al., 2016).

508 In the Monts du Forez, *Corylus* played an important role as a pioneer in the Early-
509 Holocene afforestation, as it did in the western Alps and northern and central Europe
510 (compare Tallantire, 2002; Finsinger et al., 2006; Theuerkauf et al., 2014). The expansion of
511 hazel in Europe was probably triggered by warming, favoured by a combination of high
512 seasonality, summer drought, and frequent fires, which helped hazel to out-compete oak (e.g.
513 Huntley, 1993; Tallantire, 2002; Finsinger et al., 2006; Theuerkauf et al., 2014).

514

515 **4.6. Taphonomy**

516

517 Pollen can be blown over long distances and can be derived from both the extra-regional,
518 regional, and local vegetation (*sensu* Janssen, 1973), whereas plant macro-remains in lakes
519 are usually deposited more locally (Birks, 1973). The effects of pollen transport in mountains,
520 however, differ from those in the lowlands. Mountain wind systems transport pollen upwards
521 to where clouds are formed and rain washes the pollen out to the soil (e.g. Kalis, 1984, 1985;
522 Lutgerink et al., 1989; van der Knaap et al., This Issue). In treeless areas, pollen blown in
523 from forests often exceeds the local pollen production and dominates a pollen diagram, which

524 makes interpretation difficult. The addition of pollen influx measurements and plant
525 macrofossil analysis can provide a more realistic interpretation (Birks and Birks, 2000;
526 Tamboer-van den Heuvel and Janssen, 1976; Janssen, 1981; Lutgerink et al., 1989). In
527 treeless areas, small plant remains can also be transported over long distances by wind,
528 meltwater, or streams (e.g. Birks, 1991, 2013; Bos et al., 2004).

529 Our record shows that during the Late Pleniglacial and Late Glacial, both pollen and
530 macrofossils are derived from (extra-) local and regional sources. During the late Pleniglacial
531 (GS-2a), the vegetation in the landscape around the site was very open, allowing pollen,
532 spores, and small seeds to be easily transported over long distances by wind, meltwater, and
533 streams into shallow pools in spring and summer and/or wind-blown over the snow on to the
534 frozen depressions in winter (Glaser, 1981; Birks, 1991, 2013). Although the landscape
535 around Gourds des Aillères became more vegetated during the Late Glacial, with even some
536 open woodlands close to the site during the Allerød, pollen and macrofossils still had regional
537 and local components. This changed during the Early Holocene when woodlands expanded
538 around the site and littoral vegetation filtered out remains from terrestrial plants, resulting in
539 local macrofossil assemblages that reflected the hydrosere succession in and around the lake
540 itself.

541

542 ***4.7. Past lake level changes and nutrient status of the lake***

543

544 Changes in lake-levels in our record and that of Cubizolle et al. (This Issue) were inferred
545 from shifts in the aquatic and semi-aquatic taxa and the sediment lithology. Also other lakes
546 in the Jura Mountains and French and Swiss Alps (Magny, 2001; Magny et al., 2006;
547 Ammann et al., 2013) and other parts of NW and central Europe (Bohncke and Wijmstra
548 1988; Bohncke et al., 1988; Bohncke and Vandenberghe, 1991; Hoek et al., 1999; Bos, 2001;
549 Bos et al., 2006; 2018) record changes in lake levels during the Late Glacial and Holocene.
550 The fact that many of these records show simultaneous major fluctuations in lake levels
551 suggests external forcing, *i.e.* climate.

552 Our data illustrate the varying nutrient availability within the lake during its
553 development. During the Late Pleniglacial (GS-2a) small pools were present in the glacial
554 depression of Gourds des Aillères, but during the Bølling (GI-1e) a wetter and warmer climate
555 caused the glaciers and permafrost on the slope above to melt and fill the depression, forming
556 a lake up to 5 m deep. Small inflowing streams and slope-wash transported minerals and clay
557 particles into the lake, which formed sandy and clayey sediment. *Nitella*, pondweed, and
558 water crowfoot grew in the water and species richness increased. They indicate that the water

559 was base-poor and oligotrophic to mesotrophic. During the Older Dryas (GI-1d), the drier
560 climate resulted in lake levels falling, which allowed an encroachment of marsh vegetation
561 into the lake. In the lake, base-poor mesotrophic conditions still prevailed, and species
562 richness slightly decreased.

563 The lake level rose again in the Allerød (GI-1abc), the water became
564 mesotrophic/eutrophic, and species richness increased. As the lake increased in size, aquatic
565 vegetation expanded again. Rich littoral vegetation developed. In The Netherlands and
566 Belgium, such a transition to more eutrophic conditions in lakes at the start of the Allerød is
567 often attributed to the final disappearance of permafrost (e.g. Bos 1998; Hoek et al., 1999;
568 Hoek and Bohncke 2002; Bos et al., 2006, 2017). This may also have occurred at Gourds des
569 Aillères. Lake productivity may also have increased in the early Allerød as a result of the
570 improved climatic conditions and increased precipitation (compare Ponel et al., 2016),
571 utilising the inwash of nutrients from Bølling soils that may have occurred during the drier
572 Older Dryas.

573 During the colder Younger Dryas (GS-1) lake levels fluctuated, initially increasing but
574 later falling again. In the lake, nutrient availability decreased, the water was mesotrophic, and
575 species richness became low. A twofold division of the Younger Dryas into an initially cold,
576 wet, and then a warmer and drier phase is also apparent in other records in NW Europe (e.g.
577 Lowe et al., 1994; Hoek, 1997; Brauer et al., 1999; Bos, 2001; Bos et al., 2006).

578 During the Early Holocene, the lake probably expanded in size again as the climate
579 warmed, snow and ice melted, and precipitation increased. A strong rise in water levels
580 typically occurs at the Late-Glacial /Holocene transition and is often inferred in NW European
581 records (e.g. Björck et al., 1996; Isarin et al., 1998; Hoek and Bohncke, 2002; Bos et al.,
582 2007; Magny et al., 2007). Aquatic and semi-aquatic taxa richness increased again, and the
583 assemblage suggests that the lake was less than 4 m deep at the sampling site. A range of
584 nutrient conditions prevailed (nutrient-poor to nutrient-rich). During the Boreal, hydroseral
585 succession progressed so that the lake became shallower with more neutral to acidic water
586 containing fewer nutrients. The sampling site was overgrown by a nutrient-poor sedge fen and
587 peat formation started. This was followed at ca. 8400 cal yr BP by the development of a
588 *Sphagnum* bog (van der Knaap et al., This Issue). Therefore, after deglaciation of the area, the
589 infilling of Gourds des Aillères from a lake to a peatbog took more than 6000 years.

590

591 **5. Conclusions**

592

593 The pollen and macrofossil record of Gourds des Aillères, a small palaeolake at 1335 m a.s.l.,
594 reveals a valuable archive of climate and environmental changes in the Monts du Forez
595 (Massif Central, France) for the Late Pleniglacial, Late Glacial, and Early Holocene.
596 Climatically induced changes in the regional and local vegetation inferred in the record could
597 be directly linked to the major climatic events identified in the Greenland oxygen isotope
598 records. The Late Pleniglacial steppe-tundra changed to shrub and open forest with birch and
599 pine in the Late Glacial and Preboreal. During the Boreal mixed-oak woodlands eventually
600 developed. This progressive vegetation development was briefly interrupted by changes to
601 drier and colder climates during the Older Dryas and Younger Dryas. The tree-line rose
602 around the lake during the Bølling and the Allerød, and the forest limit surpassed the lake
603 during the Early Holocene.

604 Climatically induced changes in the local fen or lake ecosystem, lake levels, and
605 nutrient availability were reconstructed. Meltwater from glaciers and permafrost filled the
606 basin to form a lake during the Bølling. Lake levels rose during the Allerød and Early
607 Holocene but fell during the drier and colder Older Dryas and Younger Dryas, allowing
608 swamp vegetation to encroach temporarily at the coring site. During the Early Holocene,
609 hydroseral succession resulted in infilling of the lake basin and the formation of a *Sphagnum*-
610 fen and the peatbog that occupies the site today.

611

612 ***Author contributions***

613 Bos: pollen and macrofossil analyses, writing the manuscript. Birks: macrofossil
614 identification, writing. Van der Knaap: writing, construction of diagrams, Van Leeuwen:
615 pollen analyses, Janssen: formulation and initiation of the project.

616

617 ***Data availability***

618 Pollen and macrofossil data from Gourds des Aillères will be deposited in the Neotoma
619 paleoecology database.

620

621 ***Declaration of competing interest***

622 No competing interest occurred.

623

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635

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932

933 ***Figure and Table captions***

934

935 Fig. 1.

936 The research area in the summit area of the Monts du Forez, Massif Central, France, with the
937 location of Gourds des Aillères mire sites (red dot) and Gros Fumé (red cross). The highest
938 mountain top Pierre-sur-Haute (1634 m a.s.l.) is indicated by a black triangle. Inset map of
939 France with the location of the Monts du Forez, Massif Central (after Eric Gaba, Wikimedia).

940

941 Fig. 2.
942 Pollen diagram from the Gourds des Aillères mire in the Monts du Forez (Massif Central,
943 France). The botanical taxa are grouped by habitats and arranged stratigraphically. The
944 zonation follows the known and calibrated chronozones *sensu* Iversen (1954). Microfossils
945 are shown as curves (%) with an exaggeration of 5x. Single occurrences of types have been
946 omitted.

947
948 Fig. 3.
949 Plant macrofossil diagram from the Gourds des Aillères mire in the Monts du Forez (Massif
950 Central, France). Macrofossils are seeds unless otherwise stated. The botanical taxa are
951 grouped by habitats and arranged stratigraphically. Macrofossils are shown as histograms
952 showing total numbers adjusted to a standard volume of 100 ml sediment. The zonation
953 follows the known and calibrated chronozones *sensu* Iversen (1954).

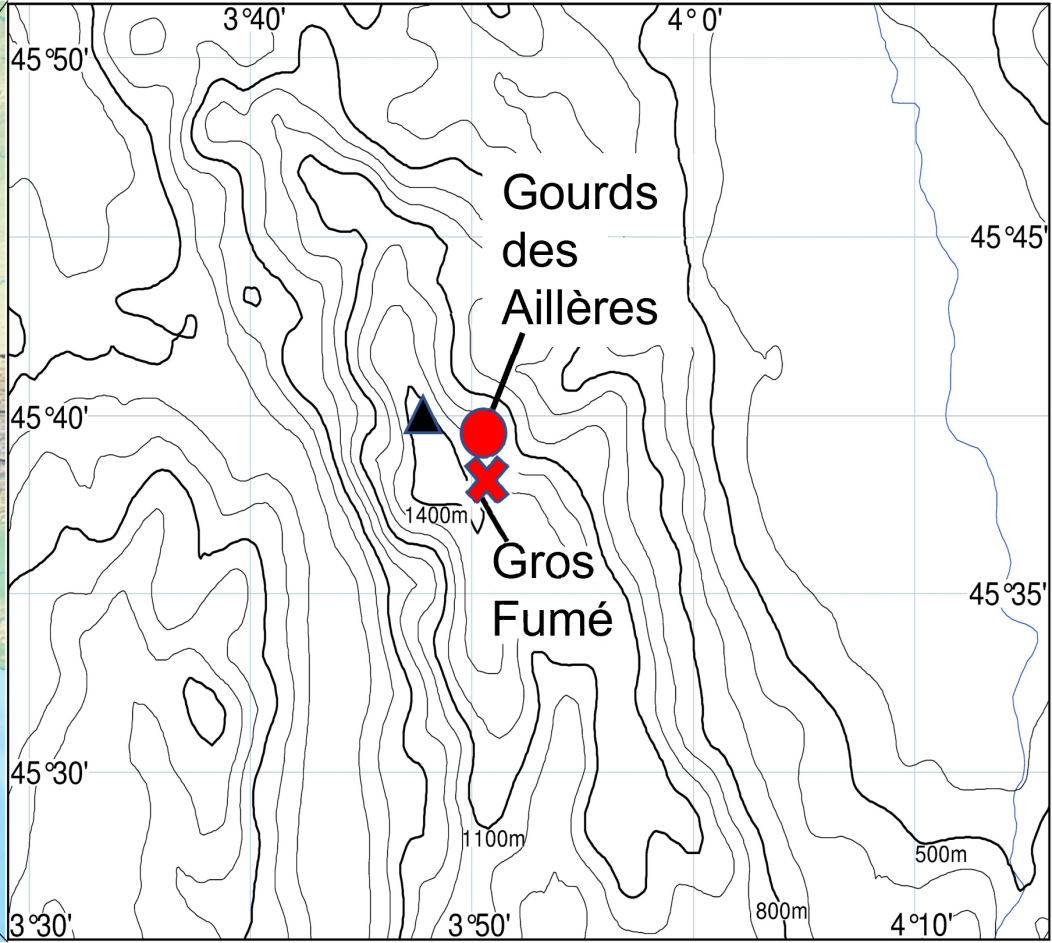
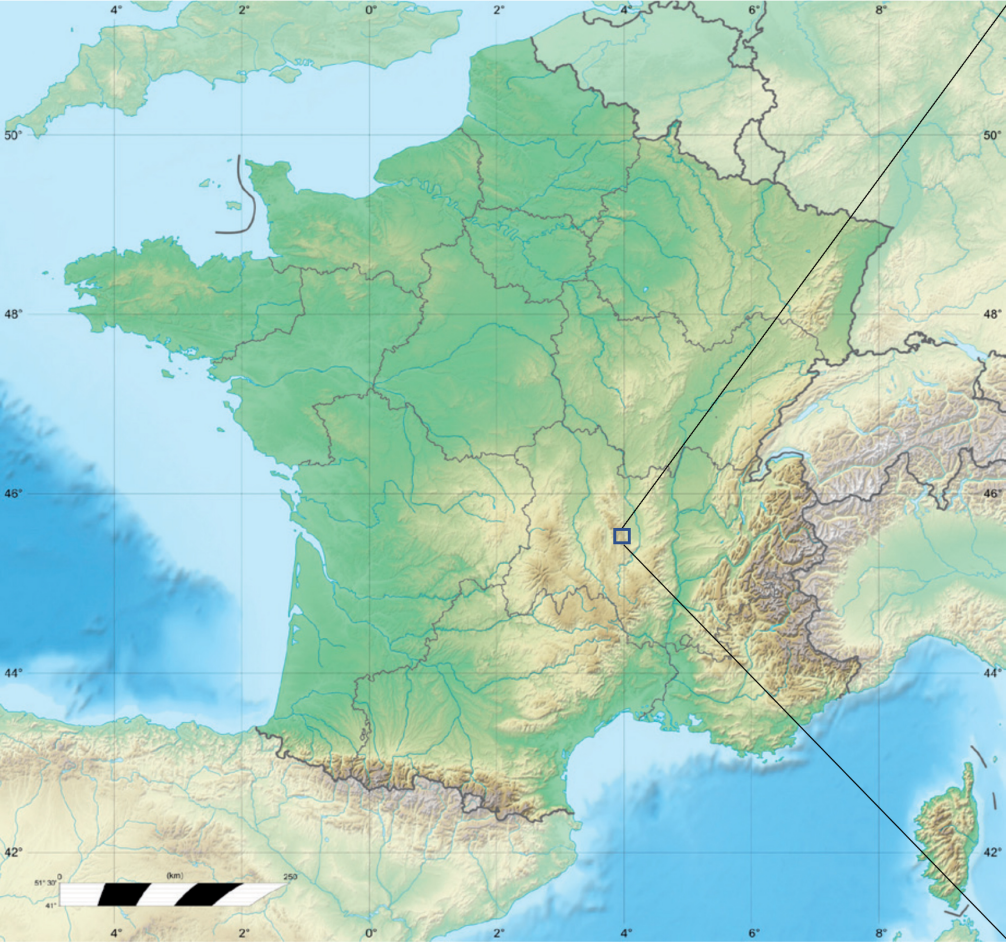
954
955 Table 1.
956 Radiocarbon dates of Late-Glacial bulk sediments from the Gourds des Aillères mire in the
957 Monts du Forez (Massif Central, France) (Etlicher et al., 1987), measured Groningen
958 Radiocarbon Laboratory (GrN; conventional measurements). Dates are calibrated using
959 IntCal13.

960
961 Table 2.
962 Late-Glacial and Early Holocene radiocarbon dates used in the age–depth model for the
963 Gourds des Aillères (GdA) mire stratigraphy (Monts du Forez, Massif Central, France). The
964 two dates from GdA are supplemented by dates and calibrated ages from Cubizolle et al.
965 (2014, 2017, This Issue) from the same mire and ice-core ages for the start of the Bølling
966 period and the Holocene from Rasmussen et al. (2006).

967
968 Table 3.
969 Comparison of the Gourds des Aillères pollen zones with the traditional Late-Glacial pollen
970 stratigraphy (Iversen, 1954), the chronozones for the Massif Central (Cubizolle et al., 2014
971 after Richard, 1999), the event stratigraphy of the INTIMATE group (Björck et al., 1998), and
972 ice-core years in the Greenland oxygen isotopes records (Rasmussen et al., 2006, 2014).

973 Abbreviations: GS = Greenland Stadial, GI = Greenland Interstadial.

974



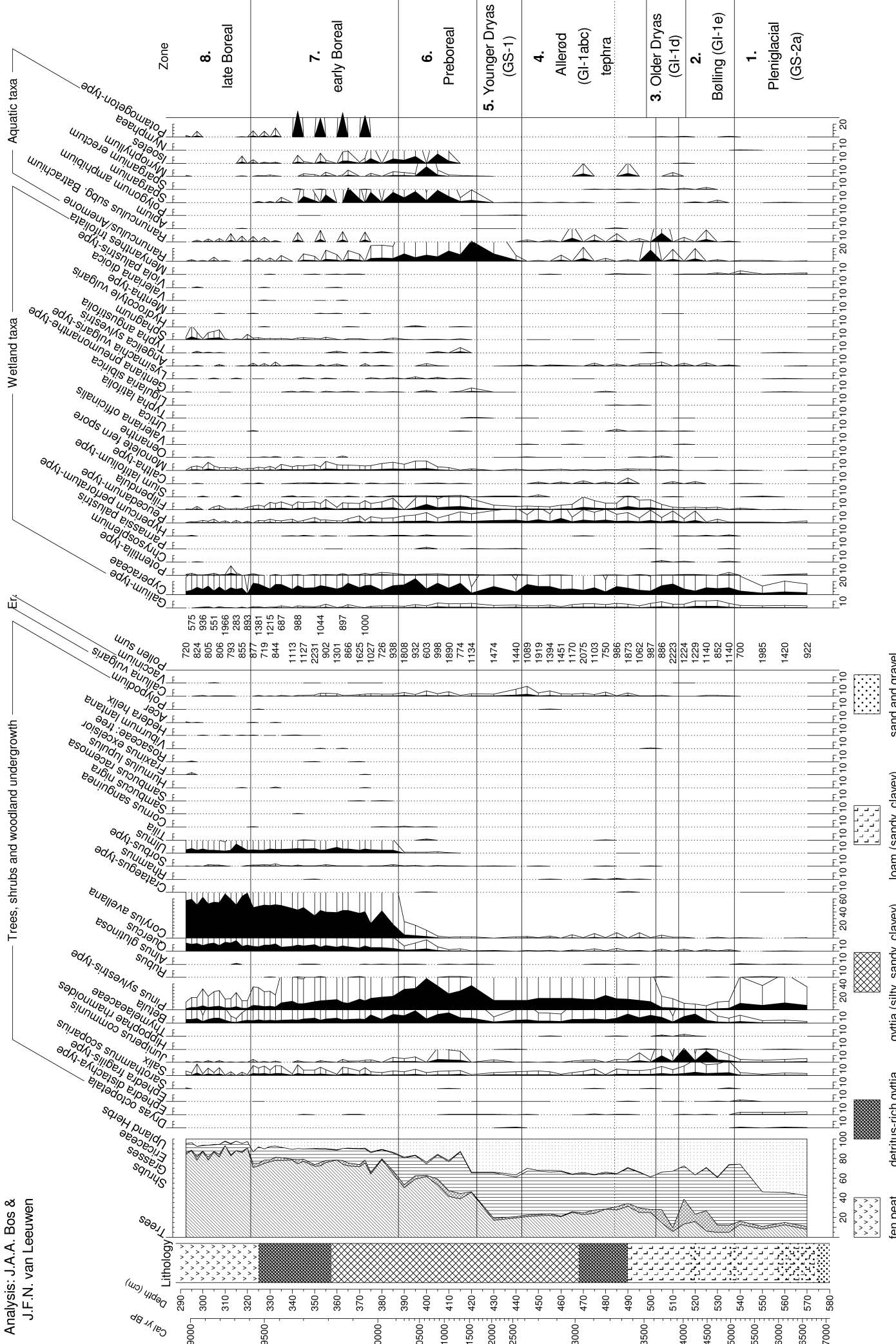
Depth (cm)	Material	Radiocarbon age	Cal yr BP	Laboratory number
481.75 ± 2.5	Bulk	11340 ± 100 BP	13489–13238	GrN-12642
487.75 ± 2.5	Bulk	11490 ± 60 BP	13430–13093	GrN-12643

Depth (cm)	Provenance	Type	Rationale & Chronozones	Pollen features at lower zone boundary	Age cal yr BP
387.5	Cubizolle et al. (2014)	Pollen	Preboreal/Boreal transition	<i>Pinus</i> ↓, <i>Corylus</i> ↑	10085
422.5	Rasmussen et al. (2006)	Marker horizon	Younger Dryas/Preboreal transition	<i>Pinus</i> , <i>Betula</i> ↑ at end of <i>Artemisia</i> maximum	11653
442.5	Cubizolle et al. (2014)	Pollen	Allerød/Younger Dryas transition	<i>Artemisia</i> , NAP ↑	12710
481.75	Etlicher et al. (1987)	¹⁴ C date	Dating above tephra layer at 484 cm at GdA		13238–13389
487.75	Etlicher et al. (1987)	¹⁴ C date	Dating below tephra layer at 484 cm at GdA		13093–13430
502.5	Cubizolle et al. (2014)	Pollen	Older Dryas/Allerød transition	<i>Pinus</i> , <i>Betula</i> ↑, Poaceae, Cyperaceae ↓	13600
512.5	Cubizolle et al. (2014)	Pollen	Bølling/Older Dryas transition	<i>Pinus</i> , <i>Plantago</i> , Poaceae, Cyperaceae ↑, <i>Betula</i> ↓	13900
537.5	Cubizolle et al. (2014)	Pollen	Late Pleniglacial/Bølling transition	<i>Pinus</i> , <i>Helianthemum</i> , Amaranthaceae, Caryophyllaceae ↓, Apiaceae, <i>Juniperus</i> , <i>Salix</i> ↑	15075
537.5	Rasmussen et al. (2006)	Marker horizon	Late Pleniglacial/Bølling transition		14650
560	Cubizolle et al. (2017)	¹⁴ C date	Pleniglacial		15269–15652
	Cubizolle et al. (2022) (621 cm)	¹⁴ C date	Late Pleniglacial/Bølling transition		14765–14168

Pollen zone Gourds des Aillères	Late-Glacial palynostratigraphy	Chronozones Massif Central Age cal yr BP	Event stratigraphy INTIMATE	Ice-core years Age cal yr BP
6	Preboreal	11490	Holocene	11653
5	Younger Dryas	12710–11,490	GS-1	12846–11653
4	Allerød	13600–12,710	GI-1abc	13904–12846
3	Older Dryas	13900–13,600	GI-1d	14025–13904
2	Bølling	15075–13,900	GI-1e	14642–14025
1	Late Pleniglacial/Oldest Dryas boundary	15075	GS-2	14642

Gourds des Aillères, Pollen, Late Glacial and Early Holocene

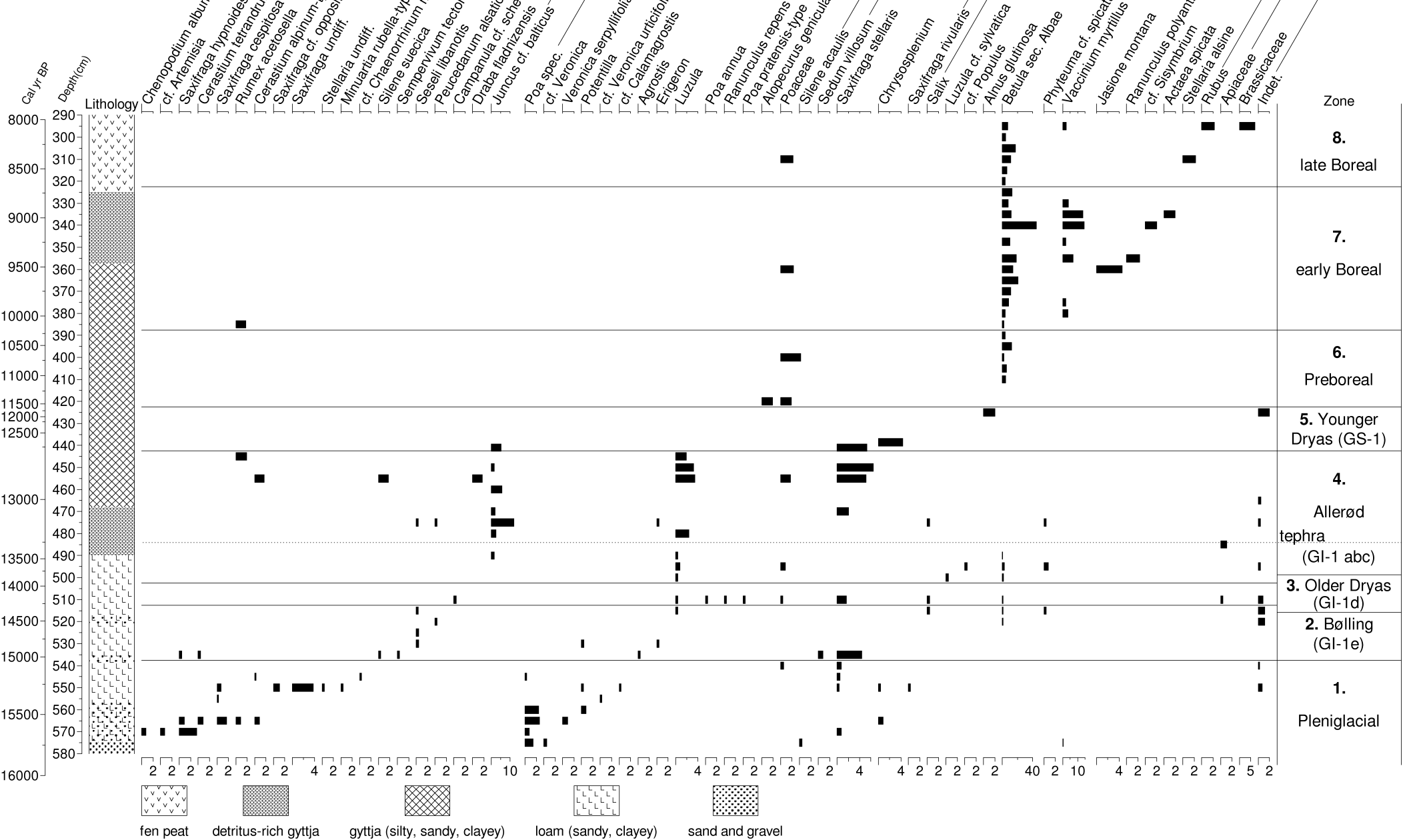
Analysis: J.A.A. Bos & J.F.N. van Leeuwen



Gourds des Aillères, Macrofossils, Late Glacial and Early Holocene

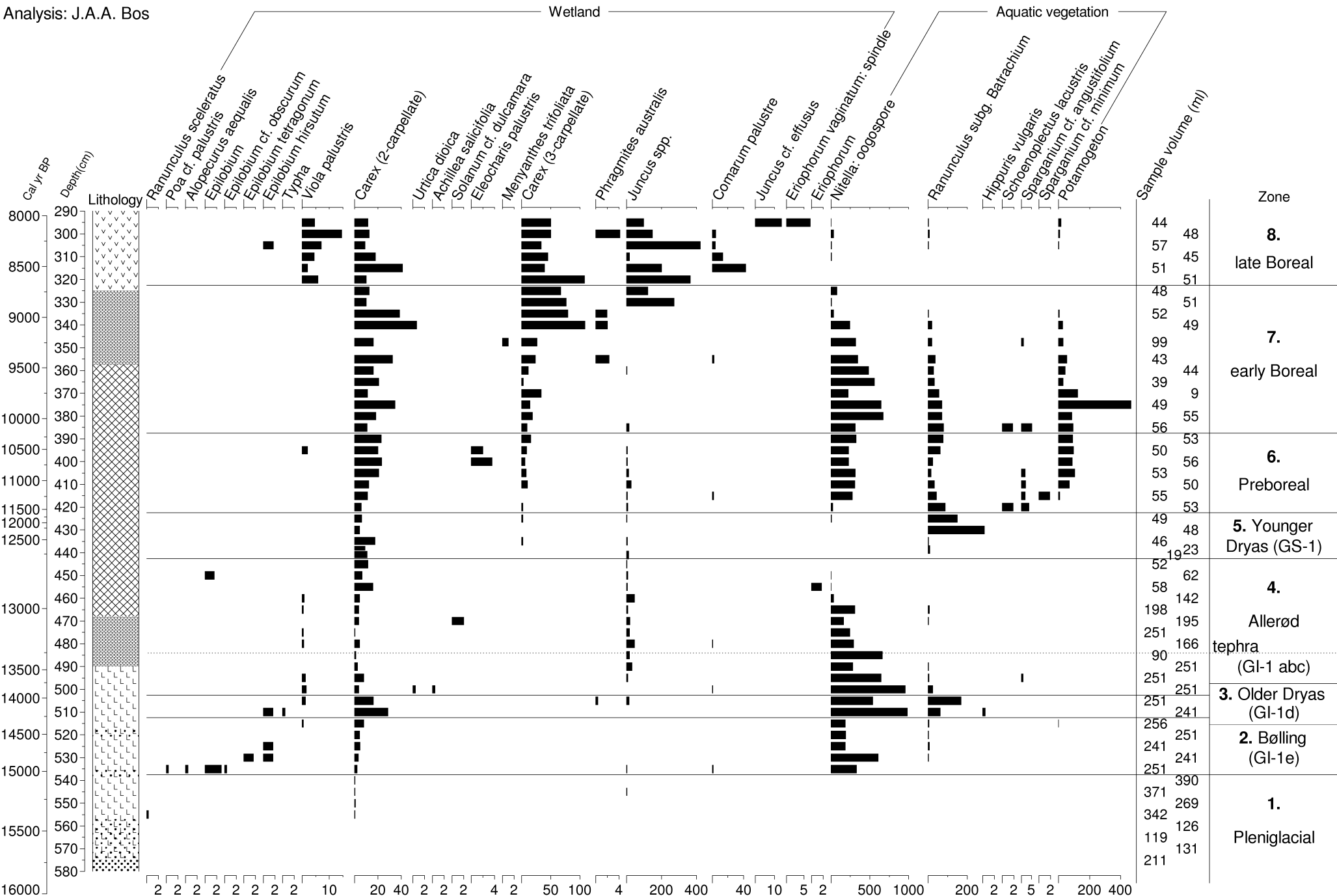
Terrestrial taxa

Analysis: J.A.A. Bos



Gourds des Aillères, Macrofossils, continued

Analysis: J.A.A. Bos



Pollen and microfossil data from Gourds des Aillères will be deposited in the Neotoma paleoecology database.

Bos: pollen and macrofossil analyses, writing the manuscript. Birks, macrofossil identification, writing. Van der Knaap, writing, construction of diagrams. Van Leeuwen, pollen analyses. Janssen, formulation and initiation of the project.

No competing interest occurred.