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1 **Palaeoecological response to Greenlandian (Early Holocene) climatic changes: Insight**  
2 **from an abandoned-channel sequence of the Meuse River at Autrecourt-et-Pourron**  
3 **(Ardennes, France)**

4

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19

20 **ABSTRACT**

21 A Greenlandian (Early Holocene) palaeochannel of the Meuse River is described from  
22 Autrecourt-et-Pourron in the Ardennes region of northern France. During the Younger Dryas,  
23 fluvial deposits represent a high-energy, sinuous palaeochannel, but at the onset of the  
24 Holocene, progressive channel abandonment resulted in the establishment of a low-energy  
25 meandering river system. Well-dated studies using palynology, carpology, malacology and  
26 geomorphology reveal a Greenlandian succession of changes in fluvial dynamics and  
27 vegetation. Between 11,700 and 11,400 cal yr BP, warmer temperatures led to the development  
28 of a birch community (*Betula* sp.) within an open grassland, dominated by herbaceous cold-  
29 adapted plants (*Linum alpinum*, *Plantago montana*, *Artemisia* sp., *Juniperus* sp.). Between  
30 11,400 and 11,100 cal yr BP, the river and the vegetation dynamics reflected two short-term

31 climate events. Around 11,400 cal yr BP, the palaeochannel became separated from the active  
32 channels of the Meuse River but remained dominated by waterlogged wetlands. This cold and  
33 wet phase represents the “Preboreal Oscillation” also referred as the “11.4 ka event”. Around  
34 11,300 cal yr BP, the records suggest that fire frequency increased close to the channel, and  
35 may indicate a dry episode that reflects a sharp, short-lived rise in temperature. Between 11,100  
36 and 10,700 cal yr BP (Late Preboreal phase), the channel received flood deposits again. *Salix*  
37 and helophytes developed while *Populus* colonised the riverbank. From 10,700 cal yr BP, at  
38 the beginning of the Boreal phase, the palaeochannel was finally abandoned and dense  
39 temperate woodland with *Corylus avellana* and *Quercus* spp. became established. Based on its  
40 high chronological resolution, Autrecourt-et-Pourron represents a key locality in north-western  
41 Europe to investigate environmental change in connection with Early Holocene short climate  
42 variations. In addition, the results highlight the valuable contribution of carpological analyses  
43 in improving the spatial resolution of reconstructions of vegetation cover.

44

45 Keywords: Palaeoenvironment; Palaeochannel; Preboreal; Multiproxy investigation; Plant  
46 macrofossils; Short climate variation

47

## 48 **1. Introduction**

49 Valley floor wetlands from northern Europe can provide valuable palaeoecological  
50 archives that preserve information regarding environmental changes in several biotic and  
51 abiotic proxies. Such studies have been conducted in Northern France (Antoine, 1997; Antoine  
52 et al., 2003b, 2003a; Coutard et al., 2010; Le Jeune et al., 2005; Limondin-Lozouet, 1998;  
53 Limondin-Lozouet and Antoine, 2001; Pastre et al., 2003, 1997), in Belgium (Deforce et al.,  
54 2014; Meylemans et al., 2013; van der Sloot et al., 2014), in Netherlands (Bos, 2001, 1998; Bos  
55 et al., 2018, 2007, 2006, 2005; Bos and van Geel, 2017; Huissteden et al., 1986), and in Poland

56 (Kołaczek et al., 2018a, 2018b). Holocene warming in northern Europe was prone to several  
57 climate fluctuations (Magny, 2019, 2004; Rasmussen et al., 2014a, 2014b). In valley floors, the  
58 beginning of the Preboreal was characterised by an intense fluvial activity, the cutting of large  
59 palaeomeanders and avulsions. However, an increase in temperature ( $10\pm 4^{\circ}\text{C}$ ) and precipitation  
60 (Hoek and Bos, 2007; Kobashi et al., 2008; Magny, 2013) was interspersed with a brief cooling  
61 due to melting ice and a change in the thermohaline circulation. This cooling phase, called the  
62 "11.4 ka event", has been observed all over North-western Europe: in the GRIP and NGRIP  
63 Greenland ice cores (Björck et al., 1997; Rasmussen et al., 2014b), in French and Swiss lakes  
64 (Arbogast et al., 2006; Magny, 2004; Magny et al., 2006; Magny and Ruffaldi, 1995), in  
65 Norway (Birks et al., 2000; Birks and Ammann, 2000) and the British Isles (Lowe et al., 1999).

66 In this framework, the French Meuse Valley (Northern France) provides the opportunity  
67 to study climate changes and landscape evolution at the beginning of the Holocene (11,700 –  
68 10,700 cal yr BP) especially during the Preboreal. So far, the French part of the Meuse valley  
69 (Ardennes region) has had only one palaeoenvironmental investigation published, at Mairy site  
70 (Lefèvre et al., 1993). A multidisciplinary approach (morphosedimentary, palynology and  
71 malacology) was undertaken in two palaeochannels (My87 and My90), which characterised the  
72 Greenlandian dynamics of the sedimentary and biological environments (Lefèvre et al., 1993).  
73 In 2012, we had the opportunity to excavate the Autrecourt-et-Pourron site (Ardennes, France),  
74 and we detected an extremely thick sedimentological sequence spanning from the beginning of  
75 the Holocene at ca. 11,700 up to 10,200 cal yr BP. As a result, this unique high-resolution  
76 sequence is shed light on the interactions between climate, vegetation and the river. This paper  
77 discusses significant variations in fluvial and environmental dynamics, using a  
78 multidisciplinary palaeoecological approach. We aim to describe Greenlandian environmental  
79 changes and investigate their links with climate variations. The patterns observed at Autrecourt-  
80 et-Pourron are compared with regional and global climate trends in order to characterise the

81 palaeohydrological and palaeoenvironmental events related to the Preboreal. Special attention  
82 is given to the 11.4 ka event and its effects on river dynamics and the local environment.

83

## 84 **2. Study area**

85 The fluvio-palustrine sequence of Autrecourt-et-Pourron (49°36'57,391" N /  
86 5°2'53,781" E/ altitude ca. 155 m a.s.l.) is located in the Meuse Valley, about 30 km upstream  
87 from Charleville-Mézières in the Ardennes hilly region (Fig. 1). The Meuse River flows in a  
88 northwesterly direction across Jurassic (Late-Lias) marly bedrock, following the Jurassic cuesta  
89 scarp of the Eastern Parisian Basin. Airborne imagery and LIDAR-DEM from the 2018  
90 copyrighted IGN (Institut Géographique National) resources provide a comprehensive  
91 overview of the present-day alluvial landscape, which includes a low sinuosity channel (Canal  
92 de l'Est), partly-located on the north-western border of the valley floor and a ~ 2 km-wide  
93 floodplain. This floodplain was shaped by both recent meandering planforms and older irregular  
94 palaeochannels with narrowing expansion. Such palaeochannels of the PalaeoMeuse river  
95 system were incised in a ca. 4 m-thick layer composed of fluvial gravels corresponding to the  
96 Pleniglacial valley infilling of Weichselian age (Lefèvre et al., 1993). The study carried out  
97 here was undertaken at the same time archaeological excavations (2008 and 2012). Both field  
98 surveys uncovered several palaeochannels of the PalaeoMeuse River, with the last field survey  
99 in 2012 revealing a cross-section of a well-preserved palaeochannel sequence (Fig. 2). Its  
100 continuous vertical succession (Section 3-6) exposed from the bottom of Trench N°6 has  
101 allowed us to define stratigraphical units (SU) and undertake continuous sampling for  
102 palaeoecological reconstruction.

103

## 104 **3. Materials and methods**

### 105 *3.1. Radiocarbon dating*

106 Samples were directly collected from a 160 cm thick section comprising a fluvio-palustrine  
107 deposit with organic horizons. Based on the different lithostratigraphic units and organic  
108 material availability, 10 samples of wood and terrestrial plants were dated by the AMS  
109 radiocarbon method ( $^{14}\text{C}$ ) in the Beta-Analytic (US) and Poznan-Radiocarbon (Poland)  
110 laboratories (Table 1). Oxcal 4.3 (©Christopher Bronk Ramsey 2018) was used to calibrate the  
111 AMS  $^{14}\text{C}$  ages based on the Northern Hemisphere terrestrial IntCal13 calibration curve (Reimer  
112 et al., 2013). Calibrated radiocarbon dates are expressed as cal yr BP, while the absolute  
113 chronology based on an age-depth model was constructed with a  $2\sigma$  confidence envelope using  
114 the CLAM package (Blaauw, 2010). Linear interpolation between the dated intervals was  
115 applied taking into account the main changes in the sedimentation rate in yr/cm (Fig. 3).

### 116 *3.2. Geochemical analyses*

117 For each sediment sample, the mineral sediment grain-size range was assessed with a  
118 laser granularity analyser (Coulter LS 230). Samples were prepared by decarbonation ( $\text{H}_2\text{O}_2$ )  
119 and dissolution of the organic matter (HCL). They were first sieved using a 2 mm mesh and  
120 afterwards deflocculated with a few millilitres of sodium hexametaphosphate ( $\text{Na}_6\text{O}_{18}\text{P}_6$ ). After  
121 homogenisation, the samples were introduced gradually using an eyedropper, and the  
122 concentration values were checked. The different granulometric fractions of the sample were  
123 measured by laser sensor. The analyser measured, with an accuracy of <1%, the relative  
124 proportions of clay (0.04-2  $\mu\text{m}$ ), silt (2-50  $\mu\text{m}$ ) and sand (50-2000  $\mu\text{m}$ ).

125 Using 100 mg samples of dry sediment, analyses of Total Organic Carbon (TOC) were  
126 carried out with a CNS analyser. The TOC content was measured by thermocatalytic oxidation  
127 (Elementar, Vario TOC cube analyser).

128

### 129 *3.3. Palaeozoological analysis*

130           Within the context of an exploratory analysis, 11 samples were studied to assess the  
131 malacological preservation potential. Shells were sieved and sorted by the carpologist. Only the  
132 fraction between 0.5 and 2 mm (the most abundant in malacological remains) was studied,  
133 which was a bias compared to the methodological standards of malacology (Limondin-Lozouet,  
134 2002). Another bias was that the volume of sieved sediments (between 2 and 4 litres) was  
135 insufficient to reach the minimum number of 200 shells required for a malacological analysis  
136 (Evans, 1972). Despite these biases, shells were determined in order to estimate the major  
137 changes in the composition of the malacofauna within the sequence. This qualitative approach  
138 was intended both to estimate the ratio between freshwater and terrestrial species, which is  
139 important for assessing the palaeochannel dynamics, and to determine whether species used as  
140 biostratigraphic markers on a northern French scale were identifiable at Autrecourt-et-Pourron.

141           In addition, as part of the exploratory analysis, microfaunal, micromammal and fish  
142 remains found in 29 carpological samples were handpicked and counted. Although no  
143 identification was undertaken, it seemed relevant to present the total abundances of microfaunal  
144 and ichthyofaunal remains as these might also reflect environmental changes.

145

#### 146 *3.4. Palaeobotanical analysis*

147           Palynological samples were extracted from cores with a sampling interval of 5 cm, and  
148 34 sediment samples of 1 cm<sup>3</sup> volume were prepared following standard pollen analytical  
149 procedures (Faegri and Iversen, 1989), with chemical treatments (NaOH, HCl, HF, ZnCl<sub>2</sub>)  
150 followed by acetolysis. Pollen preservation was sufficient and between 250 and 800 pollen  
151 grains were counted in each slide. Pollen types were identified using determination keys (e.g.  
152 Beug, 2004), pollen reference guides (Moore, 1991; Reille, 1992-1998) and comparison with  
153 the reference collection of the Chrono-environnement Laboratory (Besançon, France). The  
154 identified species were sorted according to their morphological type (trees, herbaceous) and the

155 herbaceous taxa were categorised as ecological groups: heliophilous (*Artemisia*,  
156 *Chenopodiaceae*, *Thalictrum*, *Helianthemum*, *Potentilla*, *Plantago*, *Centaurea*, etc.),  
157 mesohygrophilous (*Filipendula*, *Equisetum*, *Sanguisorba officinalis*, *Polemonium*, *Lythrum*)  
158 and aquatic (*Typha/Sparganium*, *Potamogeton*, *Myriophyllum*).

159         The 29 carpological samples with a thickness of 5 centimetres and a volume of 10 to 20  
160 litres were extracted continuously on a stratigraphic column 85 cm wide. After sampling,  
161 sediments were water-sieved with several meshes (2, 1, 0.5 and 0.25 mm). Sieved macrofossils  
162 were fully sorted under a stereomicroscope with a magnification of 2x to 60x. Extracted  
163 elements were seeds, bryophytes, buds, vegetative parts (internodes, leaf abscission scars),  
164 twigs larger than 2 mm in diameter, whole leaves, needles, and charcoal over 1 mm in diameter.  
165 Plant macrofossils were identified using standard specialised literature (Beijerinck, 1976;  
166 Berggren, 1969; Cappers et al., 2006; Tomlinson, 1985) and on the basis of the reference  
167 collections from the Chrono-environnement Laboratory and GéoArchÉon company. The  
168 remains were counted according to the principle that a whole macrofossil equalled one  
169 specimen. The fragments were also counted and then converted into an estimated whole  
170 (minimum number of individuals) using the «judgmental method» (Pradat, 2015). All data were  
171 recorded in the AGAM database (Schaal, 2019a). To measure functional diversity, the  
172 ecological requirements (Ellenberg, 1992; Julve, 1998) of species were averaged and weighted  
173 by the abundance of fossil remains. As a result, a hierarchical cluster analysis was constructed  
174 to categorise groups of samples.

175         For plotting all the stratigraphic diagrams, the C2 program (©2014 Steve Juggins) was  
176 used and we have defined the local pollen assemblage (LPAZ) from the botanical data.

177

## 178 **4. Results**

### 179 *4.1. Lithostratigraphy*



180 The detailed stratigraphic study of the section 3 (Trench N° 6), described in Table 2, showed  
181 an alluvial sequence including an abandoned channel-fill, which was observed to be over 2.5 m  
182 thick and composed of 22 stratigraphic units (SU). Those units have been grouped into main  
183 associations of facies corresponding to Lateral-accretion Deposits (Element LA), Sandy  
184 Bedforms (Element SB), Abandoned Channel Fills (Element FF(CH)) and Floodplain Fines  
185 (Element FF) sensu Miall (1996). From a sedimentary point of view, the sequence corresponds  
186 to contrasting depositional settings related to the fluvial history of a palaeochannel in the Meuse  
187 Valley. It is proposed that the basal units (i.e. SU 301, SU 339, SU 341,) were formed in a  
188 fluvial bar domain composed of lateral accretion structures (LA) and sand bars (SB). Indeed,  
189 we suggest a south-western lateral adjustment of a low to moderate sinuosity stream within a  
190 multi-channeled river (i.e. the Palaeo-Meuse River system). According to the age-depth model,  
191 we consider that these Late-Glacial fluvial macroforms (LA and SB) were the result of a  
192 transitional river system at the expense of a previous braided-plain, as observed over the  
193 Weichselian Pleniglacial period (Antoine et al., 2003a, 2003b; Coutard et al., 2010; Limondin-  
194 Lozouet and Antoine, 2001; Pastre et al., 2003). Field observations of the SU 326a/b, SU 327,  
195 SU 328 and SU 329 support the progressive burial of the preexisting lateral bars by  
196 sedimentation of suspended-load deposits with varying amounts of sand (overbank to  
197 backswamp deposits). We interpret this fine-grained sediment deposition as the result of  
198 channel plugging (CH-FF) controlled by a diminishing flow regime. At the supra-regional scale,  
199 the large valleys from the Parisian Basin showed a reduction in the number of channels with  
200 generalised clogging and subsequent peat infilling from the Lateglacial (Pastre et al., 2000). At  
201 Autrecourt, the floodplain reworking process of the PalaeoMeuse River was characterised by  
202 the slow abandonment of its secondary channels followed by vegetated swamp development  
203 (CH-FF), with local peat bogs, as observed in SU 330 to SU 332. The upper part of the alluvial  
204 sequence was dominated by vertical accretion of floodplain fines (FF), with the occurrence of

205 an embryonic humic soil (SU 334), interbedded with clayey silts units (SU 333 to SU 335). The  
206 overlying SU 336 is part of 1.5 m-thick subsurface alluvial clay deposits which exhibited  
207 reworking evidence, including protohistoric (308-184 BC dendrochronological date on  
208 *Quercus* sp.) remains (which were not sampled, and thus not described in this paper). Finally,  
209 the current soil (ca. 0.5 m) covered alluvial deposits.

210

#### 211 4.2. Microfaunal data

212 In sedimentary units SU 326, SU 327 and SU 328, an average of 5 fish remains/litre  
213 (scales and vertebrae) were found (Fig. 4). In SU 329, fish remains were scarce. In SU 330, few  
214 fish remains were recorded while an average of 6/litre of micro-mammal remains were found.  
215 No fish remains were observed in SU 331, SU 332 and SU 333.

216 Malacological samples provided assemblages that reflected two environmental phases.  
217 First, in SU 326, terrestrial molluscs were dominant (Table 3). Almost half of the specimens  
218 belonged to a single species: *Trochulus hispidus*. Besides this mesophile species, the open-  
219 ground species *Pupilla muscorum* and the marshland species *Oxyloma elegans* were the most  
220 common. In addition, two terrestrial species indicative of cold environments, were listed during  
221 this first environmental phase: *Pupilla alpicola* and *Columella columella*, which are mainly  
222 restricted today to boreo-alpine areas (Welter-Schultes, 2012). The list of freshwater species,  
223 with *Pisidium subtruncatum* as the main taxon, suggested permanent water in the palaeochannel  
224 (Welter-Schultes, 2012). In SU 327 and SU 328, terrestrial molluscs virtually disappeared. The  
225 species composition of freshwater mollusc assemblages changed with *Valvata macrostoma*,  
226 characteristic of periodic pools in floodplain contexts (Horsák et al., 2013), which was observed  
227 as the main taxon. The upper sedimentary units were devoid of any malacological remains,  
228 probably because of the acidity of peat deposits, which prevented the development of molluscs  
229 and/or the preservation of their shells.

230

231 4.3. Palaeobotanical data

232           **In SU 326, SU 327 and SU 328** (local pollen assemblage zone **LPAZ AUT.1**), NAP  
233 values (> 60%) are high, which suggest an open landscape, dominated by Poaceae and  
234 heliophilic taxa (*Artemisia*, *Thalictrum*, *Helianthemum* and Chenopodiaceae). *Pinus* (20% of  
235 records) and *Betula* (not exceeding 10%, with a peak in layer SU 327) represent woodland (Fig.  
236 5). Taxa from wet meadows are also well represented with Cyperaceae (30%) and *Filipendula*  
237 (20 %). The carpological diagram (Fig. 6) specifies the composition of the herbaceous  
238 assemblage with some taxa representative of cold climates such as *Linum alpinum*, which is  
239 found today at high altitudes (Alps Mountain). Carpological results also give accurate  
240 information about ecology, particularly for mesohygrophilic and aquatic plants. The plant  
241 macrofossil assemblage is composed of some algae (*Nitella* sp.), submerged plants  
242 (*Myriophyllum spicatum*) and floating leaf plants (*Potamogeton* sp.). Hygrophytes and seasonal  
243 amphibious vegetation complement the aquatic spectrum (*Carex rostrata*, *Rorippa palustris*  
244 and *Phragmites australis*). Riparian and wet meadow plants also occur (*Carex elata*,  
245 *Filipendula ulmaria*, *Geum rivale*, *Viola* cf. *palustris*, *Stellaria palustris* and *Peuceodanum*  
246 *officinale*). Some weed species (*Oxybasis rubra*, *Urtica dioica* and *Ranunculus repens*) and  
247 *Cenococcum geophilum* sclerotia have been found. In the carpological diagram, trees are  
248 represented by macrofossils of *Betula* sp. and *Salix* sp. (seeds and buds).

249           **In SU 329 (LPAZ AUT.2)**, the percentage of *Pinus* pollen increases slightly, while  
250 *Betula* pollen and macrofossils decreased (Figs. 5 and 6). At the same time, oogonia from *Chara*  
251 algae sharply increase, as well as the seed densities of *Potamogeton*, *Carex rostrata*, *Rorippa*  
252 *palustris* and *Veronica longifolia*. The riparian vegetation is imperceptible and taxa from  
253 meadow environments decline.

254           **In SU 330 (LPAZ AUT.3)**, numerous wood charcoal fragments (between 100 and 200  
255 > 1mm per litre of sediment) were recovered. Carbonised seeds of wetland plants, such as  
256 *Carex*, were also found with an average of 5 seeds per litre. Macrofossils of aquatic plants  
257 almost disappeared whereas seasonal amphibious and hygrophilous plant remains such as  
258 *Sparganium erectum*, *Carex elata*, *Filipendula ulmaria*, *Ranunculus repens* and *Thalictrum*  
259 *flavum* increased. The first riparian forest indicators are *Stachys sylvatica*, *Prunus spinosa* and  
260 *Rhamnus cathartica*, while at the top of this pollen zone the end of the *Juniperus* phase is  
261 recorded.

262           **In SU 331 (LPAZ AUT.4)**, charcoal and carbonised seeds were still recovered but in  
263 far less abundances (Fig. 4). *Pinus* pollen reaches its maximum percentages between 40 and  
264 60% (Fig. 5). The main components of the aquatic environment change with *Myriophyllum*  
265 *spicatum* and *Ranunculus aquatilis* agg. being recorded as the dominant species. Helophytic  
266 vegetation decreases despite the presence of *Sparganium erectum* seeds. Riverside vegetation  
267 with *Salix*, *Solanum dulcamara* and *Filipendula ulmaria* expand, while taxa indicative of  
268 alluvial forest develop (*Prunus spinosa*, *Rhamnus cathartica* and *Origanum vulgare*).

269           **In SU 332 (LPAZ AUT.5)**, high percentages of *Betula* and *Salix* pollen and  
270 macrofossils characterize this phase, while Cyperaceae and *F. ulmaria* gradually decline (pollen  
271 and seeds). High abundances of *Hippuris vulgaris* and *R. aquatilis* agg. correlate with the  
272 aquatic environment of the channel. The riparian vegetation shows a diverse spectrum including  
273 *Lycopus europaeus* and *Valeriana officinale*.

274           **SU 333 (LPAZ AUT.6)** is marked by a *Pinus* decline (13%) and the development of  
275 *Corylus*, comprising 45% of the pollen assemblage, together with the appearance of  
276 mesothermophilic taxa, such as *Quercus* (2.5%) and *Ulmus* (2%). Forest herbs such as  
277 *Origanum vulgare*, *Stachys sylvatica* and *Valerianella dentata* are also important. This last  
278 phase is highlighted by a strong decrease in Cyperaceae (3%) and mesohygrophilous taxa (e.g.

279 *Filipendula* and *Equisetum*). With the presence of *Ranunculus aquatilis* and *Hippuris vulgaris*  
280 in both palynological and carpological diagrams, increasing drier conditions can be  
281 reconstructed within the channel. The occurrence of *Lycopus europaeus* and *Eupatorium*  
282 *cannabinum* indicate a wet meadow environment in its vicinity.

283

## 284 **5. Discussion**

285

### 286 *5.1. Palaeoenvironmental succession at Autrecourt-et-Pourron*

287         The phase AUT.0 was defined from the current landforms and the lithostratigraphy since  
288 no samples were taken within the gravels and sands of the excavation floor (SU 301, SU 339  
289 and SU 341). The depositional settings observed at the base of the section 3-6 are characterised  
290 by lateral bar deposits and sandy bedforms recorded along the course of a narrow channel (ca.  
291 5 to 10 m-width). Thus, it appears that this palaeochannel probably occurred in a relatively  
292 stable multi-channeled floodplain as a wandering gravel-bed river controlled by both high  
293 hydrodynamic conditions and lateral accretion processes. It is assumed that this transitional  
294 river pattern, including several channels with such geometry, incised the underlying pleniglacial  
295 gravels. An age of between 12,377 and 11,626 cal yr BP is supported by two radiocarbon  
296 measurements on waterlogged wooden twigs (Table 1). This time-span covers the Younger  
297 Dryas period, reported in the GRIP isotope record as the last cold phase before the postglacial  
298 warming (Ammann et al., 2007; Rasmussen et al., 2014b). A succession of silt, clay and peat  
299 dated between c. 11,700 and c. 10,200 cal yr BP, then slowly filled the channel with the low  
300 sedimentation rate being of an oxbow lake type (Fig. 3). The phases established from the age-  
301 depth model were very accurate in comparison with other alluvial plain or down slope records.  
302 Six environmental phases (AUT.1 to AUT.6) were defined in this time frame spanning the first  
303 half of the Greenlandian.

304

305 5.1.1. AUT.1: a cold steppic environment recording backswamp deposits

306 The phase AUT.1 covers sandy and clayey silts (SU 326, 327 and 328) deposited in low  
307 sedimentation dynamics. In the pollen assemblages, herbaceous plants such as *Artemisia* and  
308 *Helianthemum* are dominant and, in the carpological assemblages, taxa from basophilic  
309 grassland vegetation (such as *Linum alpinum*, *Scabiosa columbaria* and *Knautia arvensis*) show  
310 occurrences restricted to the phase AUT.1. The record of *Linum alpinum* in SU 326 is of  
311 significance in terms of palaeoclimatic interpretation, as this species only grows today in  
312 subalpine areas, above 1500 m a.s.l. (Julve, 1998). In the whole SU, the presence of cold-  
313 tolerant molluscs in an assemblage dominated by *Trochulus hispidus* and the absence of  
314 thermophile species from woodland environments are consistent with such a reconstruction of  
315 cold climate conditions. In SU 327, the decline or disappearance of these cold-tolerant plants  
316 and molluscs suggests warmer conditions c. 11,600-11,500 cal yr BP. In the carpological  
317 analysis, *Pinus* is absent, as is *Juniperus*, which are both adapted to poorly developed and thin  
318 soils, as probably occurred on the valley's slope. Meanwhile *Salix* is the dominant tree, as it  
319 grew directly in the vicinity of the palaeochannel. In addition, characteristic plants of eroded  
320 sandy and stony soils (such as *Arenaria serpyllifolia* and *Linaria supina*) together with the  
321 recorded fungal species *Cenococcum geophilum*, indicative of short environmental stress (Eide  
322 et al., 2006; Kroll, 1988; van Geel et al., 1989; Walker et al., 2003), suggest erosion of soil and  
323 organic matter in the floodplain. Sporadic fluvial inputs observed as overflow facies in SU 327  
324 and SU 328 are in agreement with such biological features. The increasing proportions of the  
325 freshwater mollusc *Valvata macrostoma*, indicative of standing water, would be consistent with  
326 a decline in hydrodynamics. The notable abundances of *Urtica dioica*, *Chenopodium rubrum*,  
327 *Ranunculus repens* and *Prunella vulgaris* might suggest the presence of large herbivores (Bos  
328 et al., 2006) since coprophilous fungi (Sordariaceae and *Sporormiella*), which could be

329 indicators of grazing pressure (Gauthier et al., 2010; van Geel and Aptroot, 2006), have been  
330 observed in the pollen samples (E. Gauthier, personal communication). The slow change in  
331 vegetation in the Greenlandian at Autrecourt-et-Pourron might have favoured the Lateglacial  
332 megafauna, which eventually disappeared from the region with the subsequent disappearance  
333 of the steppes.

334

#### 335 5.1.2. AUT.2: a well-vegetated abandoned channel-fill under cold conditions

336 The phase AUT.2 covers SU 329. *Pinus* forests developed gradually while a decline of  
337 *Betula* sp. was observed in both the palynological and carpological diagrams, suggesting a  
338 greater distance from wooded areas in the valley. A decrease in *Salix* sp. macro-remains was  
339 also detected in the floodplain, while Poaceae steppe, *Thalictrum* and *Filipendula* wet meadows  
340 were significantly well-represented. Plant macrofossils assemblages were strongly dominated  
341 by *Chara oogonia* and *Carex rostrata*, indicative of aquatic environments. This sudden change  
342 in the vegetation composition together with the development of organic mud in SU 329 suggest  
343 that channel abandonment was occurring away from the active river system. A water depth of  
344 two metres could be estimated on the basis of the formation of calcium carbonate encrusting  
345 the *Chara oogonia* (Pełechaty et al., 2013). Furthermore, the presence of aquatic and helophytic  
346 plants, such as *Myriophyllum spicatum* and *Carex rostrata*, indicate slightly colder average  
347 temperatures than during the end of phase AUT.1. The list of plant taxa has enabled an  
348 estimation of the minimum mean July temperatures to be between 8 and 10 °C (Bos et al.,  
349 2007).

350

#### 351 5.1.3. AUT.3: development of marshland environment and fire activity

352 Whereas in the silts (SU 326 to SU 329), the moisture content was rather stable and  
353 provided a suitable environment for the preservation of organic material, the plant macrofossils  
354 in the peat layers (SU 330 to SU 332) were more deteriorated (Schaal and Naton, submitted).

355 This taphonomic bias, even if low, should be carefully considered in palaeoecological  
356 interpretations.

357 This environmental phase AUT.3 covers peats from SU 330. In the carpological  
358 diagram, aquatic plants from AUT.2 virtually disappeared and were replaced by plants from  
359 marshland environments, especially *Carex elata*, *Filipendula ulmaria* and *Thalictrum flavum*.  
360 The numbers of plant macrofossils from arboreal taxa were low. In addition, the biodiversity of  
361 terrestrial grasses sharply decreased. In the pollen diagram, at the transition between AUT.3  
362 and AUT.4, *Pinus* sp. decline while *Betula* sp. and *Salix* sp. increase in proportion. This  
363 decrease in *Pinus* sp. was identified in only one sample. However, it was observed shortly  
364 before the disappearance of *Juniperus* in the pollen diagram and in connection with a peak in  
365 charcoal and carbonized seeds (Fig. 4).

366

#### 367 5.1.4. AUT.4: a riparian vegetation development in an abandoned channel-fill

368 In SU 331, described as dark peat, the specific composition of marshland plants  
369 changed. In the carpological diagram, *Carex elata* and *Thalictrum flavum* were replaced by  
370 *Sparganium erectum* and *Filipendula ulmaria* as the main species. Large helophytic plants with  
371 rhizomes, such as *Typha* and *Sparganium*, developed in connection with the nutrient-rich peat.  
372 The proportions of arboreal pollen increased in the valley and, in the floodplain, *Salix* sp.  
373 showed a higher density of macro-remains. On the basis of their ecological requirements, the  
374 appearances of the tree species *Prunus spinosa* and *Rhamnus cathartica*, and the herbaceous  
375 forest plants *Stachys sylvatica* and *Luzula* sp. were favoured by the soil texture and its organic-  
376 rich content (Ellenberg, 1992; Julve, 1998). The abandoned channel was colonised by trees and  
377 grasses that composed the riparian vegetation.

378

#### 379 5.1.5. AUT.5: development of an alluvial forest and hydrodynamic changes



380 This phase was defined according to the palaeobotanical assemblages of SU 332. *Betula*  
381 sp. and *Salix* sp. showed higher proportions in the pollen diagram. In the carpological sequence,  
382 *Betula* sp. was barely noticeable, while a high density of *Salix* sp. macro-remains was observed  
383 together with the first occurrence of *Populus*. The results reveal that an alluvial forest developed  
384 in the floodplain. Changes in the composition of the aquatic community (*Ranunculus aquatilis*  
385 and *Hippuris vulgaris* as the main species) provide evidence of hydrodynamic fluctuations.  
386 Therefore, we conclude that the abandoned channel was flooded by water estimated at 40 to  
387 100 cm-depth. These wetter and more anoxic conditions favoured the conservation of the  
388 organic remains. The occurrence of *Typha latifolia* in the pollen assemblage is of climatic  
389 significance since this species requires minimum mean July temperatures of 13°C to develop  
390 (Bos et al., 2007).

391

#### 392 5.1.6. AUT.6: a temperate woodland in an alluvial plain setting

393 During AUT.6, which covers SU 333, mesothermophilic taxa (*Corylus*, *Quercus*,  
394 *Ulmus*) characteristic of the temperate woodland develop, while *Pinus*, *Betula* and *Salix*  
395 decline. Heliophilous taxa (*Artemisia*, *Thalictrum*, *Helianthemum* and Chenopodiaceae) are  
396 virtually absent. The wetland considerably changed as well, with a mesohygrophilous  
397 community of *Eupatorium cannabinum* replacing the wet meadow composed of Cyperaceae.  
398 The swampy area shrank and only a few patches of sedges remained. The alluvial sedimentation  
399 also changed with massive clay deposition as observed in SU 333. These facies settled out from  
400 suspension in a backwater area of the floodplain, thus in the distal part of the fluvial distributary  
401 system. This upper layer of grey clay was strongly subjected to erosional factors, resulting in  
402 the carpological material being most likely moved and reworked, causing fragmentation and  
403 even destruction. Given the absence of fossil remains of aquatic plants and ichthyofauna, it can

404 be assumed that the channel was definitely abandoned (Bogaart et al., 2003; Martín-Closas and  
405 Gomez, 2004).

## 406 5.2 Palaeoenvironmental links with regional reference series

### 407 5.2.1. A useful record of the first centuries of the Holocene (11,700-11,400 cal yr BP)

408 At Autrecourt-et-Pourron, the base of the alluvial sequence was dated from the Younger  
409 Dryas phase of the Lateglacial on the basis of radiocarbon dating. A multi-channel floodplain  
410 environment was proposed based on the evidence of a sinuous and a gravel-bed palaeochannel  
411 deposit (Fig. 7A). The Younger Dryas period was characterized by glaciers advancing,  
412 significant temperature reduction (below  $-20^{\circ}\text{C}$ ) and the replacement of pine forests by  
413 herbaceous steppe (Bos et al., 2018; Kasse et al., 2017; Renssen, 2001). The PalaeoMeuse River  
414 has evolved towards a low-energy fluvial system from the onset of the Holocene. Based on the  
415 section 3-6, fluvial sedimentation tends to be finer-grained than the sediment found with the  
416 preexisting channel. In numerous alluvial series from northern France (e.g. Antoine et al., 2000;  
417 Le Jeune et al., 2005; Orth et al., 2004; Pastre et al., 1997; Guélat and Richard, 2014) and north-  
418 western Europe (e.g. Bogaart et al., 2003; Tebbens et al., 1999; Vandenberghe, 2002), the first  
419 centuries of the Holocene were marked by an incision phase. This erosive period was not  
420 recorded in the section 3-6 of Autrecourt-et-Pourron. In the Netherlands, while the transition  
421 between the Younger Dryas and the onset of the Holocene (Friesland phase *sensu* Behre, 1966)  
422 was reported as dating from c. 11,500 cal yr BP (Bos et al., 2007; Bos and van Geel, 2017), the  
423 Lateglacial/Holocene transition was interpreted as occurring around 11,700 cal yr BP in the  
424 GRIP and NGRIP Greenland ice cores (Björck et al., 1997; Rasmussen et al., 2014b).  
425 Autrecourt-et-Pourron thus provides a valuable insight of the transition between the Lateglacial  
426 and Holocene conditions in the Meuse valley. The cold-tolerant plants (such as *Linum alpinum*)  
427 and molluscs (such as *Columella columella*), observed at the base of phase AUT.1, are likely  
428 relics of colder Lateglacial conditions.

429 In the Dutch section of the middle Meuse River valley, the preservation of various  
430 biological archives in Younger Dryas deposits have enabled an accurate environmental  
431 reconstruction of the composition and distribution of vegetation (synthesised in Bos et al.,  
432 2007). Whether the absence of biological samples in the Lateglacial coarse sediments from  
433 Autrecourt-et-Pourron precludes any paleoenvironmental discussion, an open landscape most  
434 likely developed. One could assume that the relative instability of the river might have formed  
435 patches of gravel bars in the floodplain, while small-vegetated mid-channel islands developed  
436 between the wandering channels. With the warming temperatures of the Greenlandian and the  
437 changing style of the river, heliophilous herbs and trees became far more widespread in the  
438 floodplain (phase AUT.1, Fig. 7B). In the Netherlands and Belgium, the Friesland Phase was  
439 characterised by the full development of *Betula* woodland, while the open herbaceous  
440 vegetation of the Younger Dryas became scarce (Bos et al., 2007; van Geel et al., 1980). This  
441 phenomenon was not fully perceived in the carpological assemblages from Autrecourt-et-  
442 Pourron since *Betula* remains were quite low in comparison with the Dutch plant assemblages.  
443 It can be assumed that different edaphic conditions or geomorphological settings may explain  
444 the relative scarcity of *Betula* at Autrecourt-et-Pourron.

445 *5.2.2. Highly fluctuating humidity and temperature conditions over a short period (11,400-*  
446 *11,100 cal yr BP)*

447 At Autrecourt-et-Pourron, a sudden change was observed in the lithostratigraphy with  
448 the occurrence of peats c. 11,400 cal yr BP (Fig. 3). The development of these organic-rich  
449 sediments was observed in connection with a decline of *Betula*, an increase in Poaceae and the  
450 appearance of taxa from cold (*Ephedra*) and wet (*Equisetum*) environments during the phase  
451 AUT.2 (Fig. 5). In the phase AUT.3, despite rather poor conservation of plants macro-remains,  
452 a decline of aquatic plants was observed (Fig. 6) together with an increase in charcoal (Fig. 4),  
453 suggesting that a dry phase occurred c. 11,300 cal yr BP. One could hypothesize that the drying

454 of the valley bottom induced an increase in fire activity at the transition between phases AUT.3  
455 and AUT.4. In Germany, an increase in fires has been reported as being connected with the  
456 presence of Mesolithic settlements (Bos and Urz, 2003). However, at Autrecourt-et-Pourron,  
457 there is no evidence to distinguish whether the fires were of natural or anthropogenic origin.  
458 Nevertheless, the drier conditions reconstructed around 11,300 cal yr BP were *per se favourable*  
459 to fires, as observed elsewhere in Europe (Doyen et al., 2015; Rius et al., 2014; Tinner and  
460 Lotter, 2001). During the first part of the phase AUT.4, marshland vegetation developed, but  
461 trees still showed poor assemblages until c. 11,100 cal yr BP (at 250 cm in Fig. 3).

462         This short period, spanning 200 years, was thus marked by highly fluctuating humidity  
463 and temperature conditions. Each of these environmental phases lasted a few decades, or a  
464 century at the most.. In the Netherlands, this period has been considered as the Rammelbeek  
465 phase (between c. 11,400 and c. 11,250 cal yr BP), which was characterized by a decrease in  
466 *Betula* in favour of herbaceous steppe assemblages (Behre, 1978; Bos et al., 2007; van Geel et  
467 al., 1980). As a result, these changes in the plant cover led to the reconstruction of a dry climate  
468 phase with hotter summers and colder winters. Indeed, Autrecourt-et-Pourron provides a  
469 detailed and original record, far more complex than previously described for this period. The  
470 cold and wet phase described in AUT.2 (Fig. 7C) would be coincident with the "Preboreal  
471 Oscillation" (PBO), which was characterised by a gradual cooling over 100-150 years. This  
472 cold event, reported as the "11.4 ka event", was widely observed in the GRIP and NGRIP  
473 Greenland ice cores (Björck et al., 1997; Rasmussen et al., 2014b), in French and Swiss lakes  
474 (Arbogast et al., 2006; Magny, 2004; Magny et al., 2006; Magny and Ruffaldi, 1995), in  
475 Norway (Birks et al., 2000; Birks and Ammann, 2000), and in the British Isles (Lowe et al.,  
476 1999). The dry phase observed in AUT.3 and AUT.4 (Fig. 7D) would be coincident with an  
477 abrupt warming of  $4 \pm 1.5^{\circ}\text{C}$  observed in the Greenland ice cores (Kobashi et al., 2008). The  
478 authors suggested that the climate transition could have occurred within a few years given the

479 rapid increase in snow accumulation, and they compare this sudden warming with the  
480 Dansgaard–Oeschger (D/O events), which consisted of several abrupt warming phases that took  
481 place in a matter of decades (Bond et al., 2013).

482 Based on this high chronological resolution, Autrecourt-et-Pourron has become a  
483 regional key sequence in north-eastern France to investigate these Greenlandian short climate  
484 oscillations.

485

#### 486 5.2.3. *The wet Late Preboreal phase (11,100-10,700 cal yr BP)*

487 At Autrecourt-et-Pourron, AUT.5 was marked by the development of alluvial forest and  
488 a new fluvial input in the palaeochannel (Fig. 7E), both indicative of wetter conditions. Our  
489 French series closely corresponds with the Dutch records from the Late Preboreal (11,250-  
490 10,700 cal yr BP), which was considered as a wet climate phase (Bos et al., 2007; van der Plicht  
491 et al., 2004). In addition, the appearance of *Populus* in AUT.5 is consistent with its colonisation  
492 during the Late Preboreal phase further downstream.

493

#### 494 5.2.4. *Temperate forest development of the Boreal phase*

495 At Autrecourt-et-Pourron, the vegetation composition sharply changed in AUT.6,  
496 especially with the development of temperate woodlands (Fig. 7F). The development of *Corylus*  
497 *avellana* woodland, inferred from it being the main tree species in the pollen assemblage  
498 appeared as a strong marker of the Boreal phase in north-western Europe (e.g. Giesecke et al.,  
499 2011). In the Netherlands, the appearance of *Corylus avellana* was dated c. 10,700 cal yr BP  
500 (Bos et al., 2007). Similarly, the modelled age of the appearance of *Corylus avellana* at  
501 Autrecourt-et-Pourron is consistent with such an assumption (transition between SU 331 and  
502 SU 332 in Fig. 3). In addition, as in the Dutch Meuse River section, *Quercus* and *Ulmus*  
503 appeared shortly after *Corylus* (Fig. 5).

504 At the onset of the Boreal, the palaeochannel was reduced to a very shallow stream with  
505 stagnant water. In the French Ardennes, paleoenvironmental studies in fluvial contexts show  
506 significant hiatus for the Boreal phase (Lefèvre et al., 1993). As such, well-preserved sequences  
507 are still lacking to better characterise the fluvial dynamics and palaeoenvironmental  
508 development during this phase.

509

## 510 **6. Conclusions**

511 A multiproxy investigation of a Greenlandian palaeochannel located in north-eastern  
512 France has provided a good reconstruction of the river dynamics and environmental changes in  
513 the Meuse River. The Meuse River showed several narrow and sinuous channels over the Late  
514 Glacial, probably flowing in a mobile gravel-bed river system. At the onset of the Holocene,  
515 such a depositional setting, based on the well-developed sequence of Autrecourt (section 3-6),  
516 recorded a slowly infilling sequence before leaving behind an abandoned and vegetated channel  
517 on the floodplain. Three steps are proposed as the response of the Preboreal climate variations:

- 518 1. The Early Preboreal (11,700-11,400 cal yr BP): silty inputs characterise the beginning of the  
519 Preboreal at 11,700 cal yr BP. Subsequently, the flow regime of the channel slowly declined  
520 for 300 years. Aquatic plants colonised in and around the area of the channel, which became  
521 marshy. The speed of the current was slow enough for floating vegetation to colonise, which  
522 suggests calm conditions. The slow infilling dynamics were interrupted by the "11.4 ka event".
- 523 2. The "11.4 ka event": during this very brief phase, lasting less than a century, the temperature  
524 dropped sharply by 4°C. At the same time, groundwater levels remained very high. The water  
525 in the channel remained deep and calm and the lowland vegetation continued to grow. Separated  
526 from the main active river, the water-saturated area was covered with floating vegetation.  
527 Amphiphytes, which benefit from high water levels, colonised. The "11.4 ka event" was  
528 immediately followed by a rapid rise in temperature at around 11,300 cal yr BP, and channel

529 cut-off occurred suddenly. During this phase, lasting about a century or less, the water table  
530 level decreased, the land dried up, and the wet vegetation disappeared and gave way to extensive  
531 grasslands. As a result, these large areas of dry grass were able to catch fire

532 3. The Late Preboreal (11,100-10,700 cal yr BP): after these two oscillations of cold and warm  
533 conditions, the vegetation dynamics were unstable for a century. For the next four hundred  
534 years, the relatively high water table allowed aquatic and riparian vegetation to colonise and  
535 the abandoned channel had a new fluvial input. Nevertheless, during the Boreal (10,700/10,600  
536 cal yr BP), the channel was abandoned.

537         According to studies in the southern Netherlands, Bohncke et al. (1991) concluded that  
538 during the Preboreal the vegetation phases were not so much related to thermal phenomena, but  
539 to humidity variations and water conditions governing the observed palynological changes. The  
540 carpological analysis of Autrecourt-et-Pourron not only confirms this hypothesis but also adds  
541 detail to it as plant macrofossils provide information for characterizing river flows and water  
542 levels in palaeochannels. The data presented in this study shows that the identification of a large  
543 number of wetland species is a major step for improving the understanding and accuracy of past  
544 climate and hydrological phenomena in North-East France (Schaal, 2019b), but also may be  
545 useful for predicting future patterns.

546

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818 **Tables and figures**

819

820 Table 1. AMS radiocarbon dates, depth and dated material of Autrecourt-et-Pourron section

821 3-6 as indicated in Fig. 2. The shaded line was not considered in the age model.

822 Table 2. Stratigraphy of the channel-fill sequence of Autrecourt (section 3-6).

823 Table 3. Molluscs: list of species and number of specimens.

824 Fig. 1. Location of Autrecourt-et-Pourron sites (red rectangle), IGN-France map with altitude.

825 Fig. 2. Section 3-6 stratigraphy based on 2012 excavations at Autrecourt-et-Pourron. **A** -

826 Location of 3-6 profile on the Meuse River valley. **B** - Detailed Cross-section 3-6 of

827 Autrecourt-et-Pourron. 301: Alluvial plain with overbank fines deposits and pedogenesis,

828 339: Sandy gravels, 341: Gravelly sands with calcareous granules, 326a: Homogeneous grey

829 sandy silts, 326b: Grey Sandy silts, 327: Grey sandy silts and with wood debris, 328a&b:

830 Light grey clayey silts with sandy beds, 328c: Light grey clayey silts, slightly sandy, 328d:

831 Homogeneous yellowish sands, 329a: Brown silts, slightly organic and bioturbated, 329b:

832 Grey clayey silts, 329c: Mottled clayey silts with root traces, 330a: Light-brown peat, 330b:

833 Grey clayey silts, 331: Dark-brown peat, 332: Light-brown peat affected by desiccation

834 cracks topward, 333a: Grey to greenish-grey clay, 333b: Mottled light clay with sandy beds,

835 334: Dark-grey humic horizon, 335: Gray clay, 336: Light-grey clay with hydromorphic

836 features. **C** – Section's picture, yellow rectangle = sediment sampling area.

837 Fig. 3. Age-depth model in calibrated yr BP and lithology of the Autrecourt-et-Pourron,

838 section 3-6 sequence. Radiocarbon dates (Table 1) were calibrated using Oxcal 4.3

839 (©Christopher Bronk Ramsey 2018) based on the Northern Hemisphere terrestrial IntCal13

840 calibration curve (Reimer et al., 2013). The absolute chronology based on an age-depth model

841 was produced with a  $2\sigma$  confidence envelope using the CLAM package (Blaauw, 2010). The

842 Bayesian age-depth model is presented with its median (middle grey line) and its associated

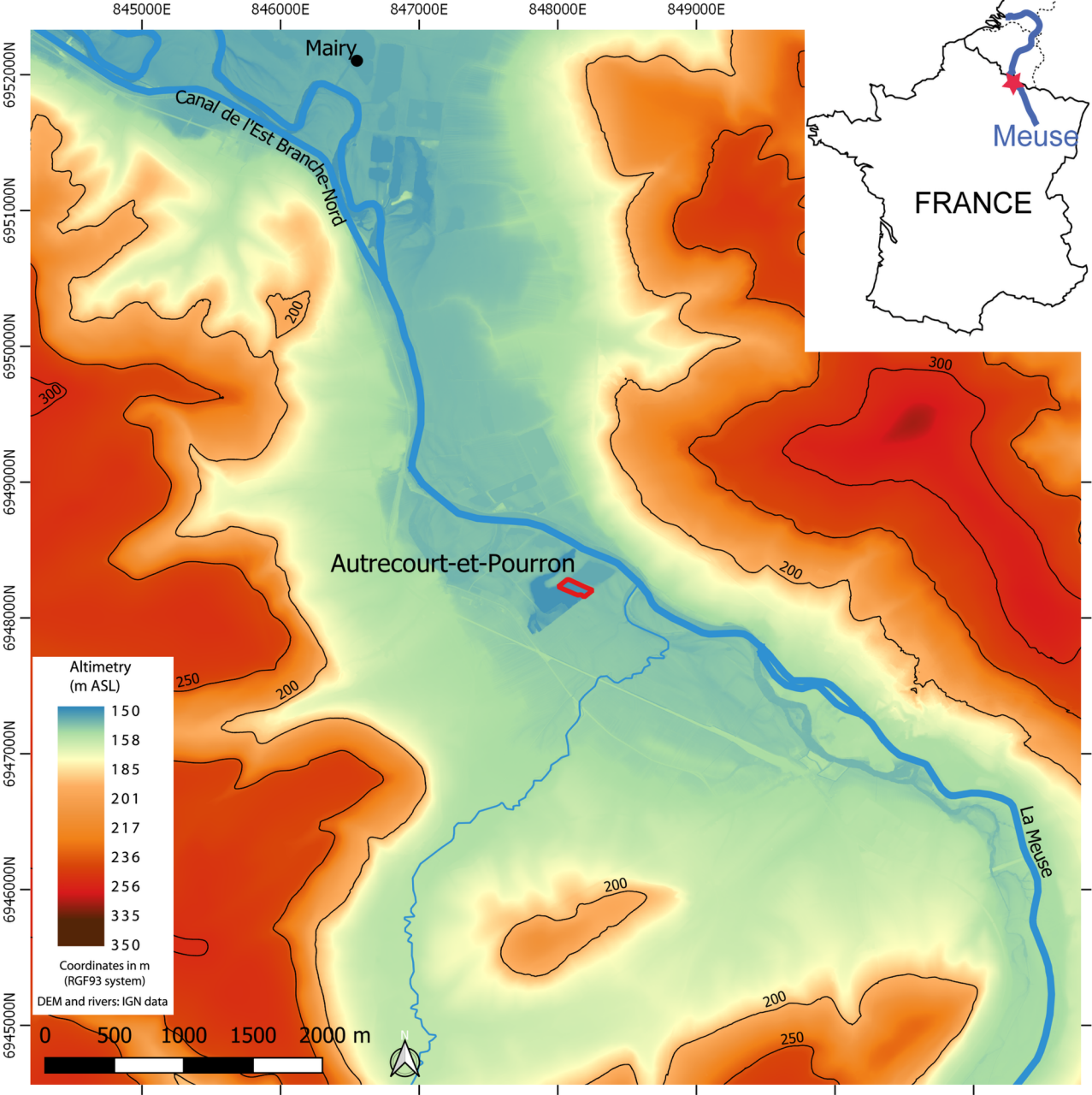
843 95 % confidence interval (grey area). The calibrated age range of dated samples is indicated  
844 in blue and the dates excluded from model in red (outlying). Two dates were rejected after  
845 age-depth modelling and outlier analysis, primarily because of age reversals.

846 Fig. 4. Diagram with grain size (%), organic carbon (%), charcoal (number/litre), carbonized  
847 seed (number/litre) and aquatic and terrestrial fauna (number/litre) data. Ecological values  
848 (moisture, reaction, nitrogen and organic matter), of the identified taxa at the species level,  
849 were averaged and weighted by the abundance of plant fossil remains. Depth below ground  
850 level. LPAZ: Local Pollen Assemblage Zone.

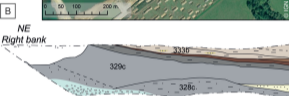
851 Fig. 5. Simplified pollen diagram (%). Depth below ground level. Exaggeration curve x5.  
852 LPAZ: Local Pollen Assemblage Zone.

853 Fig. 6. Carpological diagram showing the abundances of plant remains/litre of sediment.  
854 Depth below ground level. LPAZ: Local Pollen Assemblage Zone.

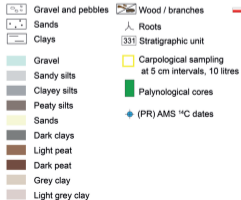
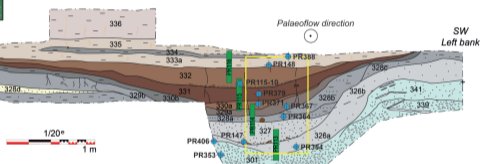
855 Fig. 7. Conceptual diagram of palaeoenvironment dynamics of the Autrecourt-et-Pourron  
856 channel during the Early Holocene. Exaggerate scales.

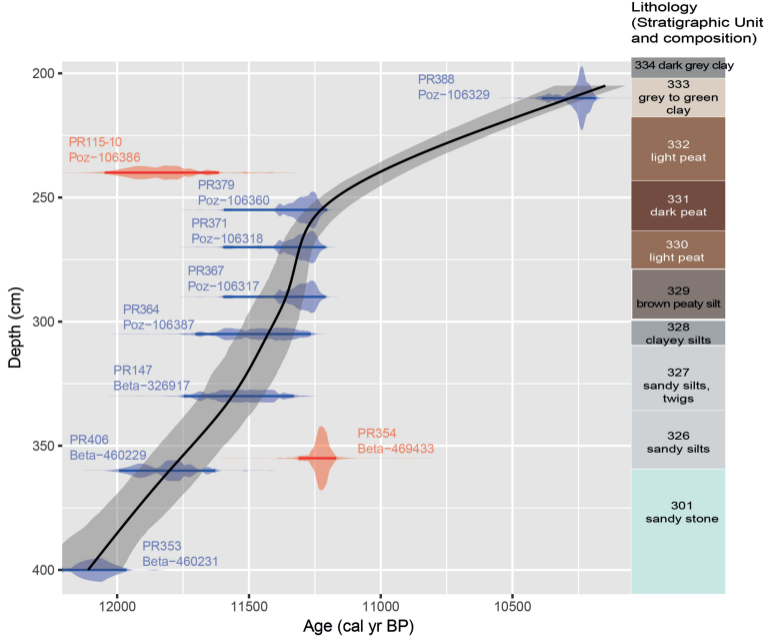


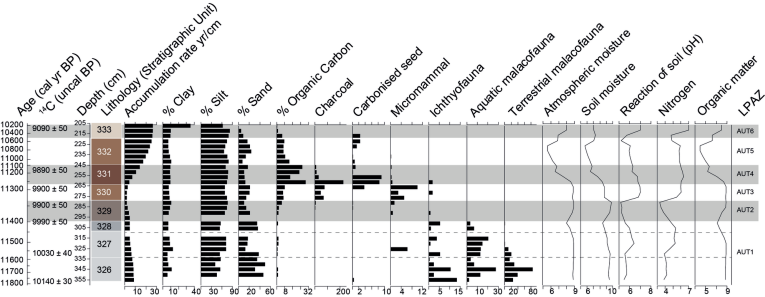




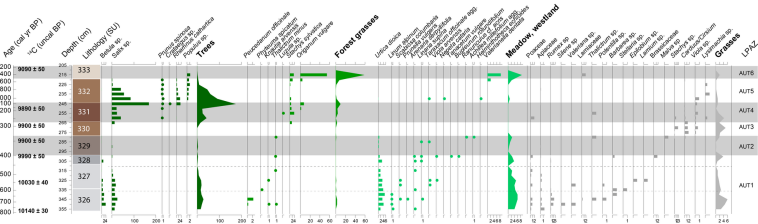
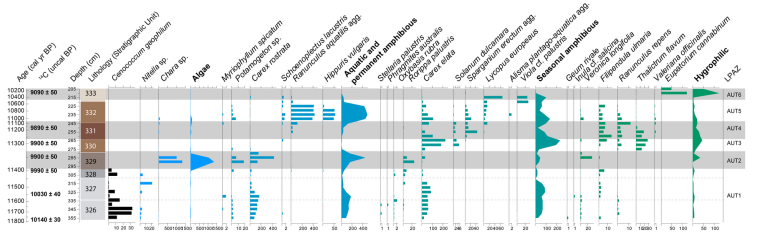
**Autrecourt - Section 3-6**

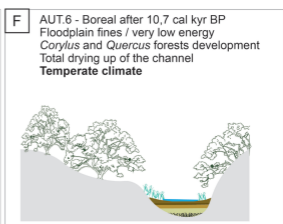
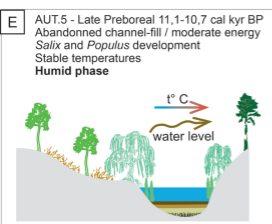
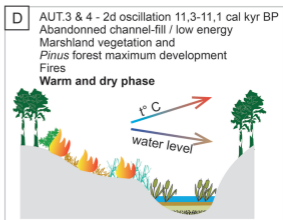
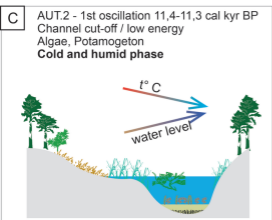
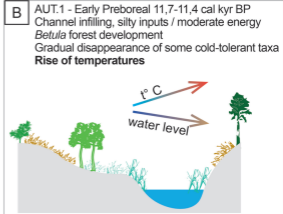
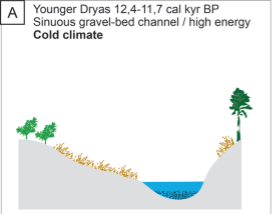












Legend



Autrecourt sample	Depth cm	Laboratory N°	Dated material	$\delta^{13}\text{C}$ (‰)	Age $^{14}\text{C}$ yr B.P. without d13C correction	Conventional Age $^{14}\text{C}$ yr B.P. with d13C correction	Calibrated age (cal yr B.P. 2 $\sigma$ ) INTCAL13 (95.4%)	Calibrated age (cal yr B.P. 2 $\sigma$ ) INTCAL13 (68.2%)	Calibrated age (cal yr B.C. 2 $\sigma$ ) INTCAL 13 (95.4%)
2018-PR388-US333	210	Poz-106329	waterlogged <i>Eupatorium cannabinum</i> seeds (174 fgt)		9,090 $\pm$ 50		10,396 - 10,182	10,271 - 10,200	8,447 - 8,233
2012-PR148-US333a	215	Beta-326918	waterlogged root	-29.3	4,750 $\pm$ 40	4,680 $\pm$ 40	5,577 - 5,5315	5,467 - 5,323	3,628 - 3,366
2018-PR115-10-US332	240	Poz-10386	waterlogged <i>Hippuris vulgaris</i> (4) + <i>Carex</i> (1) seeds		10,160 $\pm$ 50		12,053 - 11,511	11,974 - 11,750	10,104 - 9,562
2018-PR379-US331	255	Poz-106360	waterlogged <i>Thalictrum flavum</i> seeds (20)		9,890 $\pm$ 50		11,597 - 11,202	11,336 - 11,230	9,648 - 9,253
2018-PR371-US330a	270	Poz-106318	waterlogged <i>Thalictrum flavum</i> seeds (20)		9,900 $\pm$ 50		11,600 - 11,208	11,385 - 11,236	9,651 - 9,259
2018-PR367-US329	290	Poz-106317	waterlogged <i>Carex rostrata</i> seeds (30)		9,900 $\pm$ 50		11,600 - 11,208	11,385 - 112,36	9,651 - 9,259
2018-PR364-US328	305	Poz-106387	waterlogged <i>Carex</i> seeds (20)		9,990 $\pm$ 50		11,705 - 11,263	11,603 - 11,322	9,756 - 9,314
2012-PR147-US327	330	Beta-326917	charred wooden twigs	-28.2	10,030 $\pm$ 40	9,980 $\pm$ 40	11,620 - 11,264	11,620 - 11,398	9,671 - 9,315
2017-PR354-US326	355	Beta-469433	waterlogged <i>Linum alpinum</i> seeds (3)	-26.0	9,810 $\pm$ 50	9,790 $\pm$ 50	11,287 - 11,126	11,242 - 11191	9,338 - 9,177
2012-PR406-US326a	360	Beta-460229	waterlogged wooden twigs	-27,6		10,140 $\pm$ 30	11,998 - 11626	11,941 - 11,715	10,049 - 9,977
2012-PR353-US303	400	Beta-460231	waterlogged wooden twigs	-27.9		10,310 $\pm$ 30	12,377 - 11,962	12,156 - 12,011	10,428 - 10,013

Stratigraphic units (SU)	Description (field & grain-size)	Thickness (in m.)	Sedimentary interpretation (depositional setting)
336	Light-grey clay with hydromorphic features	0.85	Alluvial plain with overbank fines deposits and pedogenesis (humic horizon and redoxic soil) (FF : floodplain fines sensu Miall, 1996)
335	Grey clay		
334	Dark-grey humic horizon		
333 a	Grey to greenish-grey clay		
333 b	Mottled light clay with sandy beds		
332	Light-brown peat affected by desiccation cracks topward	0.3	Vegetated swamp deposits with Histosol development (3 soils) (CH-FF sensu Miall, 1996)
331	Dark-brown peat (reworked to the North-East direction)	0.22	
330 a	Light-brown peat	0.12	
330 b	Dark-grey clay (progressive transition with 330a)		
329 a	Brown silts, slightly organic (peat) and bioturbated	0.2	Vegetated swamp deposits (a) with overbank fines (b) and incipient soil (c) (CH-FF sensu Miall, 1996)
329 b	Grey clayey silts		
329 c	Mottled clayey silts with root traces		
328 a & b	Light grey clayey silts with sandy beds	0.5	Backswamp to overbank deposits in a channelized area (CH-FF sensu Miall, 1996)
328 c	Light grey clayey silts, slightly sandy		
328 d	Homogeneous yellowish sands		
327	Grey sandy silts and with wood debris		
326 a	Homogeneous grey sandy silts		
326 b	Grey Sandy silts		
341	Gravelly sands with calcareous granules	1 min.	Lateral accretion macroform & cross-bedded silty sands (Lateral accretion: LA ; Sandy bedforms : SB sensu Miall, 1996)
339	Sandy gravels		
301	Cross-bedded polygenic gravels with silty sand beds organized in fining upwards (Clast size : 2 – 50 mm, sub-rounded clasts, moderately sorted, openwork texture and normal grading )		



Sedimentary units		SU326				SU327					SU328	
Taxa/Samples		Pr354	Pr355	Pr356	Pr357	Pr358	Pr359	Pr360	Pr361	Pr362	Pr364	Pr365
Terrestrial fauna	<i>Clausilia rugosa</i>	3	2	12	6	3	4	2				1
	<i>Cochlicopa lubrica</i>		1	3								
	<i>Columella columella</i>		1									
	<i>Euconulus fulvus</i>			1								
	<i>Nesovitrea hammonis</i>		2				1					
	<i>Oxyloma elegans</i>	4	2	23	8	4				1		
	<i>Punctum pygmaeum</i>			1								
	<i>Pupilla alpicola</i>	2										
	<i>Pupilla muscorum</i>	2	14	23	7	7	7	2				1
	Slugs		3				1	2	6			2
	<i>Succinella oblonga</i>					3	8	3				7
	<i>Trochulus hispidus</i>	39	53	99	39	15	22	16	3		3	
	<i>Vallonia costata</i>	1	2	5								
	<i>Vallonia</i> sp.	1	4	2	1	1	2	1				
<i>Vertigo pygmaea</i>		1	1									
Freshwater fauna	<i>Ancylus fluviatilis</i>	1		2	1							
	<i>Anisus</i> sp.	1	1	2			1			1		2
	<i>Pisidium amnicum</i>							1	1	3	2	
	<i>Pisidium subtruncatum</i>	1	15	24	11	4	22	18	6	14	2	
	<i>Radix</i> sp.	1	2	11						2		13
<i>Valvata macrostoma</i>	1	8	17	2	4	3	8	23	63	25	26	
Total number of specimens		57	108	229	75	41	70	52	35	90	32	52
Volume studied (in litres)		2	2	2	2	2	2	2	2	4	4	4