Small headwater stream evolution in response to Lateglacial and Early Holocene climatic changes and geomorphological features in the Saint-Gond marshes (Paris Basin, France)

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Abstract

The study focuses on river dynamics and vegetation changes during the last Glacial-Interglacial transition from a headwater stream located in the eastern part of the Paris Basin. We adopt a spatial multiproxy approach combining image analyses, geophysical surveys, sedimentary and pollen record analyses to document the impact of Lateglacial climate changes and geomorphological features on vegetation and fluvial dynamics in the small Boitet catchment (ca. 20 km²). Our results show that the sedimentary record is organized into six successive alluvial sequences reflecting changes in discharge and channel morphology in response to short phases of climate oscillations during the Lateglacial and Early Holocene periods. The Boitet alluvial sequences present some similarities with other NW European rivers that are interpreted as large-scale fluvial system evolution to climate changes. However, some local differences have also been highlighted partly related to the upstream position of the catchment. Among them, two distinctive features of the Boitet catchment are 1) the preservation of the Oldest Dryas deposits, which have been rarely described in this area, and 2) the recognition of multichannel river dynamics during the Oldest Dryas and Younger Dryas. We demonstrate that the fluvial evolution is firstly triggered by climate changes and that land surface features may also influence specifically upstream areas revealing contrasting responses of the river system.

Keywords: Lateglacial; anastomosed system; headwater catchment; climate changes; Saint-Gond marshes; Paris Basin

1 Introduction

In NW Europe, the Last Glacial Maximum (LGM), reached at ca. 22.1 ± 4.3 ka, was followed by a Lateglacial interstadial during which glaciers retreated and temperatures increased (Shakun and Carlson, 2010; Clark et al., 2012). Over the last three decades, numerous paleoclimate records based on marine and continental sedimentary archives from the North Atlantic realm, indicate a non-linear warming punctuated by prominent abrupt climate changes (Björck et al., 1996; NGRIP members, 2004). The failure of the North Atlantic thermohaline circulation caused by freshwater inputs is supposedly partly responsible for these cooling events (Barber et al., 1999; Teller et al., 2002; Alley and Agustsdottir, 2005; Fleitmann et al., 2008), and these have been well documented in the Greenland ice cores. At the transition from the LGM to the Lateglacial, analyses of oxygen isotope ratios in ice cores have allowed the identification of two stadials associated with cold conditions (GS-2 and GS-1), interspersed with one interstadial displaying milder conditions (GI-1) (Björck et al., 1998). In terrestrial records from northern Europe, these abrupt cooling events were firstly recognised from pollen analyses by Jessen (1935) and Iversen (1954). An inferred Lateglacial biostratigraphy zonation was defined by a conventional sequence (Oldest Dryas, Bølling, Allerød and Younger Dryas), which is often used in a chronostratigraphic and/or climatostratigraphic sense (Litt et al., 2001; Rasmussen et al., 2014). Sedimentary records from European rivers have been widely studied in order to document these periods, as in northern France (Antoine et al., 2003; Pastre et al., 2003; Deschodt et al., 2004), but also in the Netherlands (Vandenberghe et al., 1987), in the United Kingdom (Brown, 2001; Bridgland, 2010; Macklin et al., 2010; Walker et al., 2012), in Germany (Kasse et al., 2005), or in Poland (Vandenberghe et al., 1994). They all highlight that NW European river morphodynamics evolve in response to the short-term climate changes and follow broadly similar fluvial evolution patterns. During the colder period, e.g. during the Upper Pleniglacial or Younger Dryas period (respectively GS-2 and GS-1), fluvial dynamics are generally characterized by the development of braided channels in a steppe environment (Vandenberghe, 2003). Conversely, a warmer climate, e.g. the Bølling-Allerød (GI-1), induces a water discharge decrease and a temperature increase and favours conditions for organic deposition in channels and floodplains of NW European rivers (Antoine, 1997; Pastre et al., 2000). However, if isotopic analyses on ice cores provide direct records of climatic oscillations, sedimentary archives are rather controlled by local hydrological events, which means that climate changes are indirectly recorded in the sedimentary archives, with possibly some delays and under various preservation potential conditions. This also implies that the chronology defined by the reference conventional sequence may not be entirely preserved, and if preserved may be temporally shifted. For instance, among all of the studies performed in NW European rivers, only a very few of them have been able to describe Oldest Dryas deposits even though it is a well-known cooling climate period in ice cores. Therefore, there is a need to study environmental and fluvial morphodynamics changes in various catchments throughout Europe to better conceive the responses of rivers to climate changes and the spatial variability of the conventional chronostratigraphic sequence.

In this paper, we document the morphosedimentary dynamics and the vegetation cover evolution during the last Glacial-Interglacial transition of a small headwater basin located in eastern part of the Paris Basin (Saint-Gond marshes, NE France) where no previous studies have been carried out. We first present our results obtained from a multidisciplinary approach combining both spatial and temporal data: sedimentological and pollen analyses supplemented by aerial image processes and sub-surface geophysical surveys. Then, considering the geomorphological context and climate reconstructions from other alluvial sequences in NW Europe, we discuss the preservation potential of the sedimentary archives and the local geomorphological features as key factors for recording Lateglacial alluvial deposits.

2 Study area

The Boitet catchment (48°846 N, 3°92 E) belongs to a large peatland called "Marais de Saint-Gond", located in the eastern part of the Paris Basin (Marne, France), at the foothills of the Brie plateau (Fig. 1). These peatlands have developed over a Late Cretaceous chalky substrate in the alluvial valley of the Petit-Morin River which is the trunk drainage of the catchment. The Boitet River is a small low-gradient tributary river draining a 20 km² catchment in the upstream part of the Saint-Gond marshes. The present-day mean slope is less than 1 ‰ and the mean annual water discharge is estimated at 2 $m^3.s^{-1}$ in the Montmirail hydrological station, which is located 20 km downstream.

The Saint-Gond marshes are bordered to the west by an upland plateau characterized by a cuesta morphology where chalky slopes are covered by Mesozoic and Cenozoic deposits, composed of clays, silts and sands. The present-day morphology of the investigated catchment has been shaped during the Quaternary period. Periglacial processes favoured the weathering of the chalky substrate, delivering sediments consisting of chalky cryoclasts and flints to the valley floor. On the hillslopes, Cenozoic formations are overlain by colluvial deposits containing chalky cryoclasts packed into a silty matrix. Close to the peatlands, the core drillings performed by the French geological survey (BRGM) indicate that the chalky substrate is covered by Weichselian colluvial-alluvial deposits, whose thickness may reach up to 10 -15 m, and that are related to a terrace system associated with the Petit-Morin drainage network (Hatrival et al., 1988) (Fig. 1). During the Pleistocene, the drainage basin of the Saint-Gond marshes was modified to its eastern and upstream part by the hydrographic captures of the Somme-Soude and the Vaure rivers. These captures have induced a major disruption causing possibly a water discharge decrease and the alluvial aggradation of the Petit-Morin valley (Tricart, 1949).

Since the Pleniglacial, the Petit-Morin catchment did not experience any other significant landscape transformation apart from those let by anthropogenic activities. The surface of these peatbogs were broadly exploited from the 17^{th} century as combustible fuel or fertilizer, as evidenced by the numerous traces of extraction pits of several meter thick (Salaün and Marre, 2005). Large drainage operations were carried out. The hydrographic network has been modified and regularly cleaned. As a result, in some areas, these anthropogenic activities have possibly provoked the destruction of the superficial layers of sedimentary sequence. Therefore, it is expected that Petit-Morin catchment hosts well-preserved sedimentary records for the Late Pleniglacial-Holocene transition period.

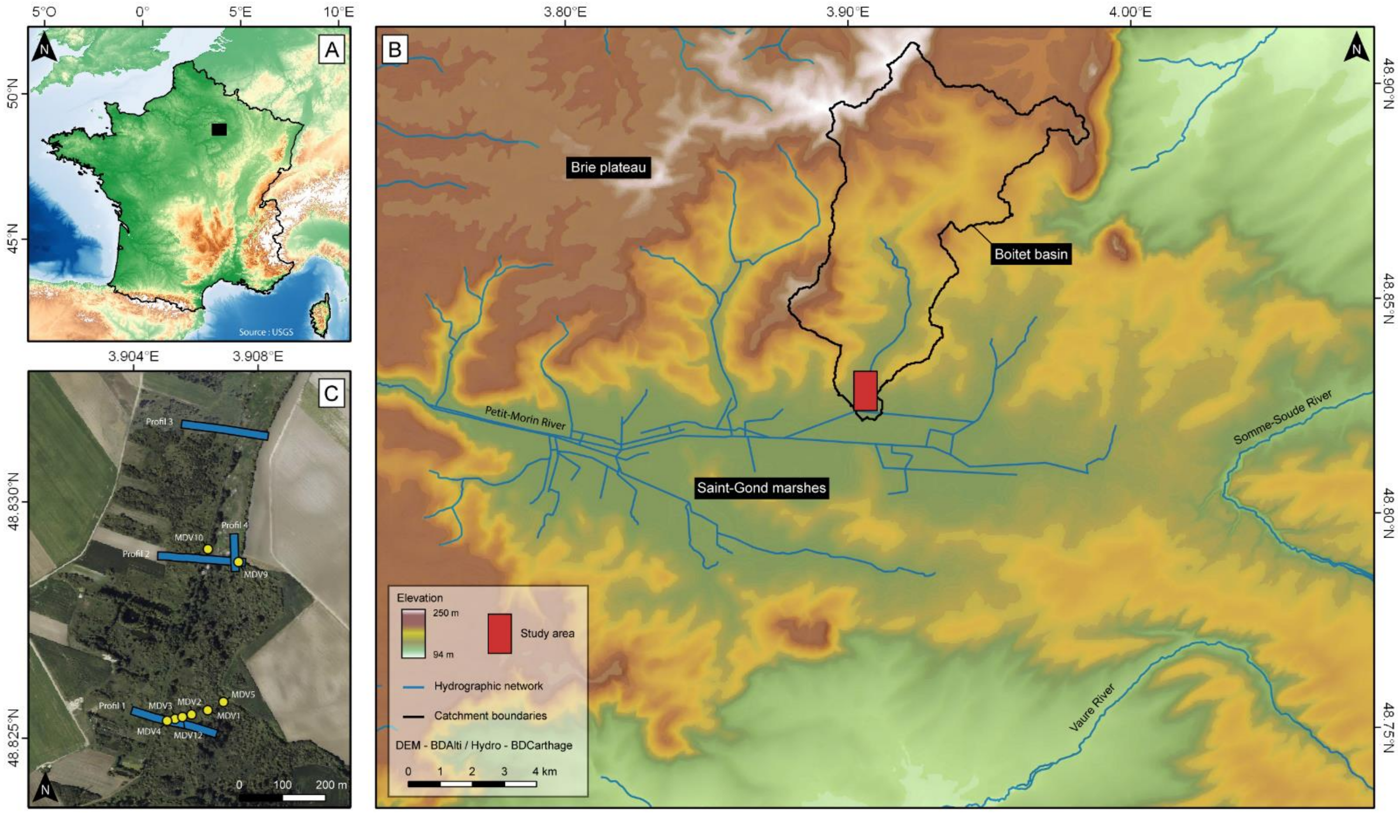

Fig. 1. Study area location maps. A: Area of interest in France. B: Topographical map of the Saint-Gond marshes region and location of the study area at the mouth of the Boitet River. C: Location map of the coring transects (yellow circles) and the geophysical profiles (blue lines).

3 Material and Methods

The morphosedimentary dynamics of the valley has been investigated by combining geophysics, geomorphology, sedimentology and palynology in the central part of the Boitet valley.

3.1 Planimetric analysis of the floodplain from image processing

A geomorphological study combining field surveys (core drilling and geophysical investigations) with image analysis techniques have been performed in order to obtain a synoptic view of the morphodynamics of the valley. We have used historical aerial images supplied by the French Geographic National Institute (IGN) (1946, 1969 and 1974) and historical maps, i.e., the cadastral plan called “Napoleonic cadastre” (1830) and the map of “Etat-Major” produced by the French army (1832). Images and maps have been georeferenced and also processed with ENVI/IDL (2018) remote sensing software to better reveal spectral anomalies linked to alluvial formations. We have reconstructed a diachronic image in which each spectral band is composed respectively of the aerial images of 1946, 1969 and 1974. Then, a Principal Component Analyses (PCA) have been performed to highlight spectral anomalies linked to channel systems, and then digitize the detected traces (Fig. 3).

3.2 Geophysical investigations

We used a shallow geophysical method to reconstruct the geometry and thickness of the fluvial depositional system and to define the drilling location. To this end, four electrical resistivity tomography (ERT) profiles have been undertaken using a multimode resistivity imaging system (Syscal Pro Switch, Iris Instruments©). This method is widely employed in alluvial system (Vandenberghe and Desmedt, 1979; Vandenberghe, 1981; Van Huissteden et al., 1986; Chambers et al., 2012; Laigre et al., 2012; Hausmann et al., 2013; Rey et al., 2013; Matys Grygar et al., 2016; Bábek et al., 2018). The survey positioning was chosen in such a way that the paleochannels identified by aerial imagery were intersected. The profiles 1-3 were acquired perpendicularly to the river flow direction in order to image the sedimentary filling of alluvial valley where the valley was the widest (Fig. 4). We have positioned a longitudinal profile, parallel to the valley axis, to investigate spatial lateral variation of the sedimentary records. The 192 m long profiles were acquired surveys with 2 m-electrode spacing using a Wenner-Schlumberger array to maintain both a sufficiently high horizontal resolution and restrict sensitivity to vertical variations. Investigation depths, that reach 20 m for the profiles 1-3, respectively 8 m for the profile 4, are deep enough to attain the horizontal calcareous substrate and reconstruct the geometry of the alluvial record of the valley.

3.3 Core sedimentology

A total of eight cores, named MDV-1 to MDV-5, MDV-9, MDV-10 and MDV-12, were collected as close as possible to the geophysical profiles. However, for reasons of accessibility in the field, the geophysical profile and the coring locations were sometimes slightly shifted (Fig. 1). The cross-section consists of six cores, spaced 20 m apart in the central part, and spaced 40 m apart near the edges (Fig. 6).

Sediment cores were described on the basis of lithology and sediment grain-size characteristics. Lithology is dominated by the presence of clayey, silty chalky layers in which some cherts were identified and peaty sediments. According to the Udden-Wentworth Scale, sediment grain size ranges from clays, to silt to silty sand to pebbles. The sediment color, on the basis on the Munsell Colour Chart, can reflect either the lithology and/or the degradation of the organic content, and was used as a complementary parameter to define sedimentary facies. Using these criteria, ten major sedimentary facies (F1 to F10) were identified with their characteristics summarized in Table 1.

Table 1. Synthetic classification of the sedimentary facies and units of the Boitet River.

Sedimentary Unit (SU)	Sedimentary facies	Texture	Munsell color
SU 1	F1	clayey sand	2.5 Y 8/4 pale yellow
SU 2	F2	silty clay	10 YR 7/1 light gray
	F3	silty sand	10 YR 7/1 light gray
	F4	clayey-sandy silt	2.5 Y 8/1 white
	F5	silty-sandy clay	2.5 Y 6/4 light yellowish brown
	F10	sandy silt	10 YR 6/3 pale brown
SU 3	F6	clayey peat	10 YR 2/1 black
	F2	silty clay	10 YR 7/1 light gray
	F8	silty clay	7.5 YR 3/3 dark brown
SU 4	F2	silty clay	10 YR 7/1 light gray
	F3	silty sand	10 YR 7/1 light gray
	F7	sandy silt	10 YR 5/2 grayish brown
	F8	silty clay	7.5 YR 3/3 dark brown
SU 5	F6	clayey peat	10 YR 2/1 black
	F8	silty clay	7.5 YR 3/3 dark brown
SU 6	F9	silty clay	2.5 Y 2.5/1 black

3.3.1 Laboratory sedimentary analyses

A maximum thickness of 4 m was obtained on MDV-4 in the central part of the Boitet valley. Therefore, we have chosen two reference cores (MDV-4 and MDV-1 near the geophysical profile 1), to be representative of the hydro-sedimentary dynamics of the river and on which complementary laboratory analyses (magnetic susceptibility, loss on ignition, pollinic spectra) were performed.

Magnetic susceptibility was measured in SI unit with Bartington MS2E sensor, to detect any presence of detrital colluvial materials (Vannière et al., 2004). Organic matter or calcite will lead to very low negative values, oxides and clays will have slightly positive values and ferrimagnetic materials, such as iron oxides will display high values (Dearing, 1999).

Loss on ignition (LOI) method was used in order to determine organic matter (OM) and carbonate contents. The values of these contents are expressed in percentage of the mass of bulk. Samples were dried 12h at 105°C then burned in a muffle furnace in two steps. First, OM content was measured under oxidising conditions at 550°C during 5h. Then, carbonate content was obtained under pyrolysis conditions at 950°C during 2h (Heiri et al., 2001).

3.3.2 Chronostratigraphic framework

Seven ^{14}C ages were carried out on three samples in the MDV-4 core and four samples in the MDV-1 core, using AMS method in organic levels (Table 2) to propose chronostratigraphic framework and constrain the temporal evolution of the depositional environment. The age-depth model was established on organic material using the R package 'clam' (Fig. 2). No material was available to date the bottom of the sequence. Calibration was performed by using the CALIB programme version 7.1 (Stuiver and Reimer, 1993) with the IntCal13 calibration curve (Reimer et al., 2013). In the MDV-1, ^{14}C ages extend from 12460 ± 70 BP (15024-14220 cal. BP) at a depth of 191 cm to 10220 ± 50 BP (12131-11752 cal. BP) at the depth of 70 cm. In the MDV-4, the older ^{14}C dating is of 12140 ± 70 BP (14184-13779 cal. BP) at about 127 cm, and the younger ^{14}C dating is of 10110 ± 60 BP (11993-11400 cal. BP).

Thus, these ^{14}C ages span the Lateglacial period, from the Oldest Dryas – Bølling transition to the Younger Dryas – Preboreal transition. In this paper, we employ the term ‘Oldest Dryas’, which encompass ca. 18 – 14.7 cal. BP, as a chronostratigraphic period, such as the associated conventional nomenclature (Bølling, Allerød and Younger Dryas) (Alley and Clark, 1999; Ivy-Ochs et al., 2005; Shakun and Carlson, 2010; Clark et al., 2012).

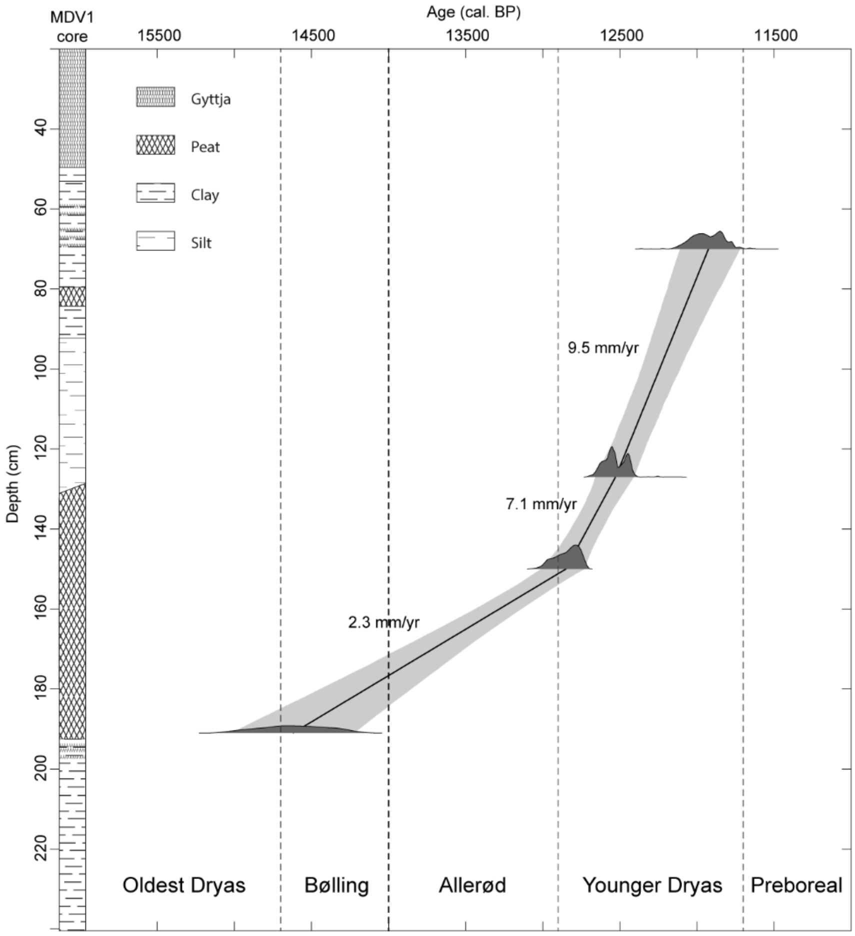

Fig. 2. Age-depth model of the MDV1 core. Age spectra (grey shading) correspond to the 2σ ranges.

Table 2. AMS radiocarbon dates from the Boitet River. Calibration with IntCal13 (Reimer et al., 2013).

Lab. code	Core	Depth (cm)	^{14}C yr BP	Cal. BP (2σ)	Biozones
Poz-70902	MDV-4	68-69	10110 ± 60	11993-11400	Younger Dryas
Poz-70901	MDV-4	91.5-92.5	10890 ± 60	12905-12688	Allerød
Poz-70903	MDV-4	126.5-127.5	12140 ± 70	14184-13779	Bølling
Poz-86926	MDV-1	70	10220 ± 50	12131-11752	Younger Dryas
Poz-86927	MDV-1	127	10560 ± 50	12661-12410	Younger Dryas
Poz-86928	MDV-1	159	10970 ± 60	12993-12718	Allerød
Poz-70904	MDV-1	191-192	12460 ± 70	15024-14220	Bølling

3.4 Palynology

Pollen analysis was carried out on 60 samples collected at four centimetres intervals from the MDV1 core. Around 1 g of fresh matter was prepared using the standard method established by Faegri and Iversen (1989). Material was filtered to 200 µm, then treated with HCl 10%, HF 40%, NaOH 10% and acetolysis to colour the pollen grains. A minimum of 300 pollen grains were counted from each sample. Pollen grains were identified using a light microscope (magnification 250x and 400x) with comparison to modern material and the standard identification keys of the Central

European pollen flora (Beug, 1961; Punt, 1976; Punt and Clarke, 1980, 1981, 1984; Punt et al., 1988; Faegri and Iversen, 1989; Moore et al., 1991; Reille, 1992, 1995).

The construction of the pollen diagram was performed using the program TILIA 1.5.12 (Grimm, 1991). The main pollen sum includes all pollen types excluding spores. Six pollen assemblage zones (PAZ) were identified according to the changes on trends in the percentages of the main taxa.

4 Results

4.1 Mapping the traces of paleochannels from aerial images and geophysical investigation

Aerial image processes reveal the presence of numerous linear and sinuous spectral anomalies in the floodplain, displaying straight, to sinuous, to meandering geometries and that may intersect themselves. These detected anomalies could be indicative of an alluvial history of the valley before the development of the marshes (Fig. 3) and are interpreted as remnant palaeochannels. To test this hypothesis, the positioning of geophysical profiles 1 to 4 were chosen in such a way that some of the possible palaeochannels identified by aerial image processing were crossed, and this, where field condition accessibility in the marsh was possible (dense shrub vegetation, open water patches).

The low resistivity values, ranging from 15 to 107 Ω.m, suggest a mixture of clay, silt, and sand deposits within a water-saturated context (Fig. 4). In all ERT profiles, it is possible to distinguish a basal homogeneous unit defined by a tabular geometry and the relatively highest resistivity values (> 50 Ω. m). This basal unit is overlain by a 1-4 m thick heterogeneous unit, displaying the lowest resistivity values (< 20 to 50 Ω.m). This unit exhibits some gully morphologies, symmetrical or asymmetrical, that can be recognized by their low resistivity (< 35 Ω.m).

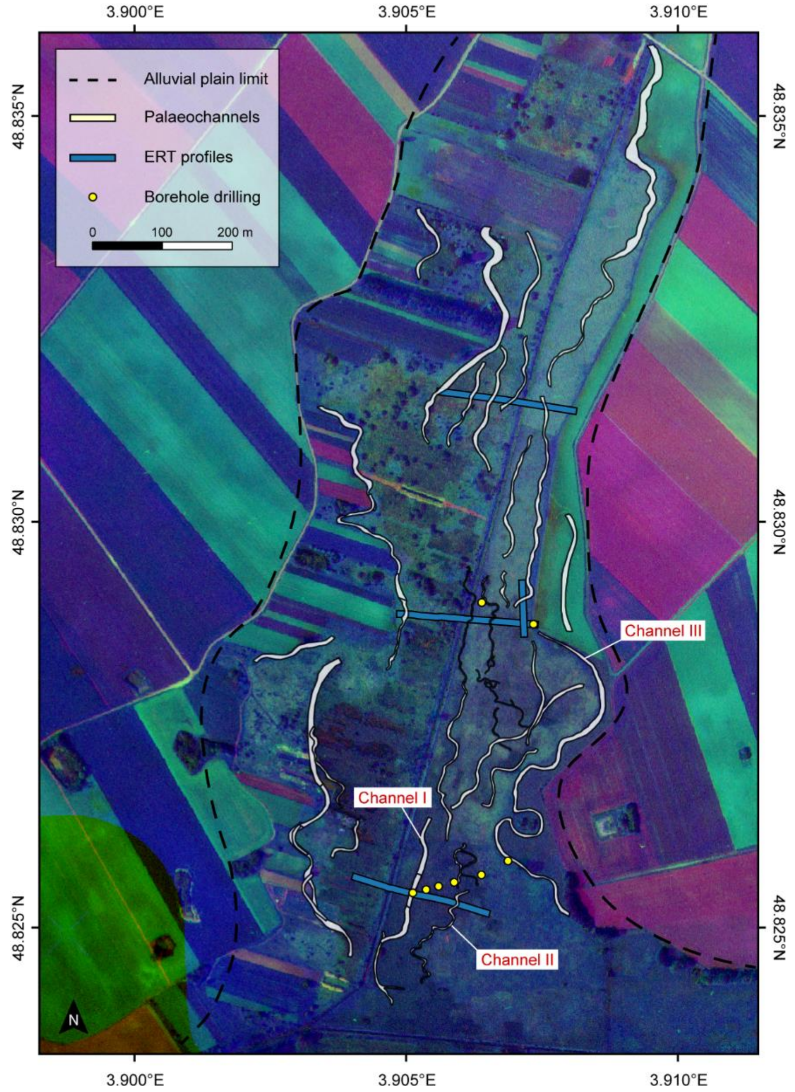

Fig. 3. Network of multiple palaeochannels revealed by the PCA of the historical aerial images performed in 1946, 1969 and 1974.

In this alluvial context, the geometries and the resistivity values of the basal unit are consistent with deposits, composed of gravel, sand and silt. The low-resistivity gully morphologies identified in the upper geophysical unit are located just below the traces of palaeochannels that were detected by the aerial images. The geometries and low resistivity values are consistent with paleochannels filled by organic and silty-clayey deposits.

The results of photo-interpretation and geophysics highlight a fluvial system dominated by multiple channels exhibiting various shapes, ranging from meander to slightly sinuous to straight channel. Morphology of the channels has been estimated by the width/depth ratio that is indicative of the energy of the river regime. In our case, we have estimated these values on the conductive sedimentary bodies, identified in the geophysical profiles for depth of less than 2 m. The Wenner-Schlumberger array, as it sounds the sub-surface horizontally and vertically, makes it possible to assess the channel morphology, and give some estimation of the depth by the contrast between high and low resistivity values. Smith and Smith (1980) have shown that values ranging from 7 to 20 are indicative of an anastomosed fluvial system.

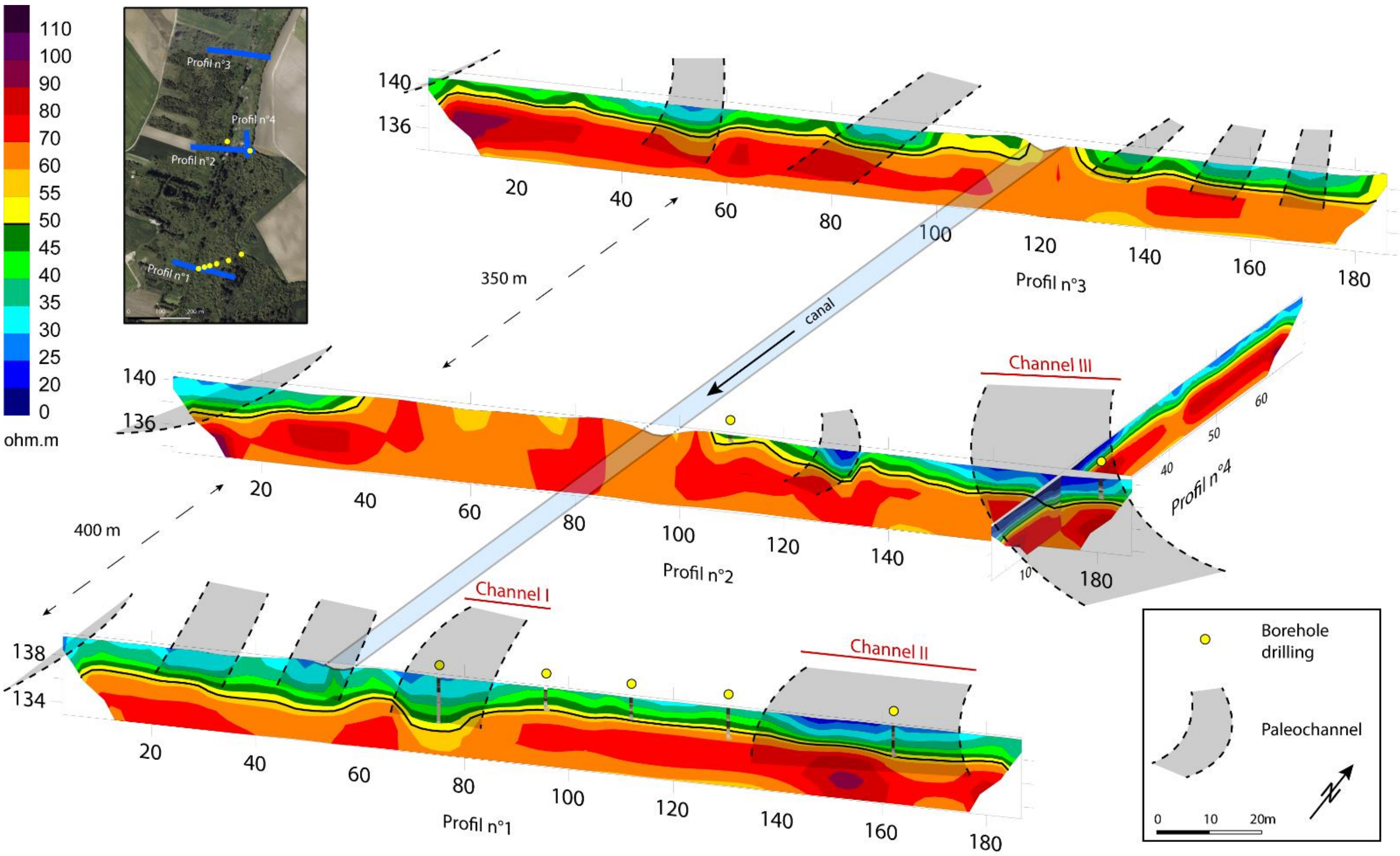

Fig. 4. Reconstruction of the Lateglacial multichannel river network from geophysical and coring surveys.

4.2 Sedimentology, palynology and chronostratigraphic framework

Here, we describe the sedimentary and palynological record subdivided respectively into six sedimentary units (SU) and five pollinic units (PAZ) on the basis of (i) the ten sedimentary facies defined previously, (ii) the sedimentary analyses (grain size, magnetic susceptibility, carbonate and organic contents), (iii) the palynological analyses and (iv) the age constraints. The chronostratigraphic framework was constrained by ^{14}C ages, by relative chronology between the different units, and/or by comparison to facies defined by the BRGM (Hatrival et al., 1988). The depositional geometry of the cross-section has been reconstructed from the correlation of six SU.

Unit 1 (SU 1 / PAZ 1)

Sedimentology: The base of the sedimentary record begins with a yellow oxidised clayey sand (F1) overlaying the Campanian chalks. This bed contains angular chalky gravel layer and abundant flints, coming from the erosion of Campanian chalky bedrock. The top of SU is delimited by an undulating erosional surface, forming a topographic depression of more than 1 m between the MDV-3 and MDV-2 cores (Fig. 66).

Palynology: This zone corresponds to a very low pollen concentration with much of the pollen being eroded and not identifiable. Levels at 246 and 250 cm depth do not contain any pollen. The spectra is dominated by Poaceae, Cyperaceae, *Betula* and *Juniperus* (Fig. 77).

Chronostratigraphic constraints: A lack of organic matter does not permit any ^{14}C dating of Unit 1. However, since this unit displays similar characteristics to the Weichselian facies described by the BRGM (Hatrival et al., 1988), we propose to attribute Unit 1 to the Late Pleniglacial period.

Interpretation: The coarse texture of the deposits and the presence of abundant flint slivers suggest a periglacial environment dominated by cryoclastic processes and a sediment transport governed by high-energy braided rivers. The incision phase results from a change in the river discharge occurring at the end of the Pleniglacial period.

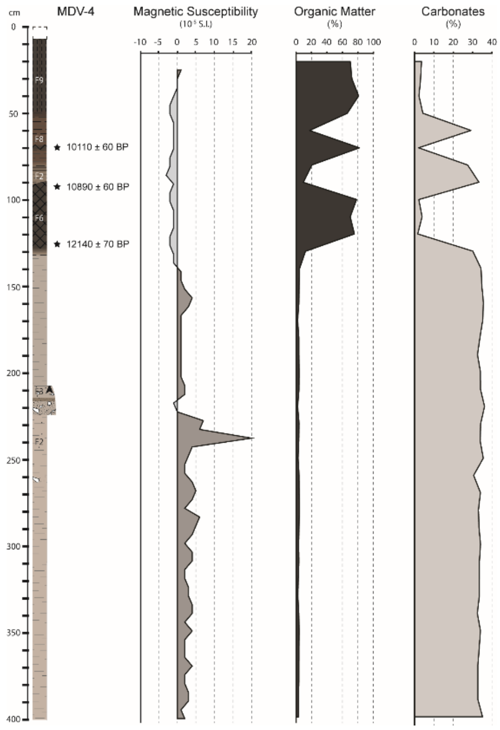

Fig. 5. Magnetic susceptibility, organic matter and carbonates contents from MDV4 core.

Unit 2 (SU 2 / PAZ 2)

Sedimentology: The thickness and the facies of the SU 2, overlaying the erosional surface, differ from one core to the other (Fig. 66). The unit is the thickest in the MDV-4 core (> 3 m thick since the SU 1 has not been reached) and the thinnest in the MDV-1 core (only about 50 cm). In all of the cores where the unit base was attained, the basal deposits consist of yellowish-grey silty clay beds (F2) that have weakly positive magnetic susceptibility values (1 to 5 × 10^{-5} SI). In the lowermost part of this unit, some greyish silty sand beds (F3) displaying a null to weakly negative signal (-3 to 50 × 10^{-5} SI) have been encountered in the MDV-3 and MDV-4 cores (Fig. 5). In the upper deposits of the unit, several facies evolutions have been observed. In the MDV-2, MDV-1 and MDV-12 cores, some colour changes, from yellow-brown to grey-blue towards the top, suggest an evolution towards a reducing environment. At the uppermost part of the cores, some thin organic-rich beds have been encountered. In these cores, the transition towards Unit 3 is gradual. Conversely, the MDV-5 core consists of a whitish clayey-sandy silt facies (F4). In the MDV-4 and MDV-5 cores, no increase in the organic content has been observed and the uppermost part of the unit is marked by a second incision surface that also was identified in the MDV-3 core. Sedimentological analyses show that SU 2 displays a very low organic matter content (about 4 %), and a high content of silicates and oxides (63 %). The carbonate content represents about a third of the total composition (Fig. 5).

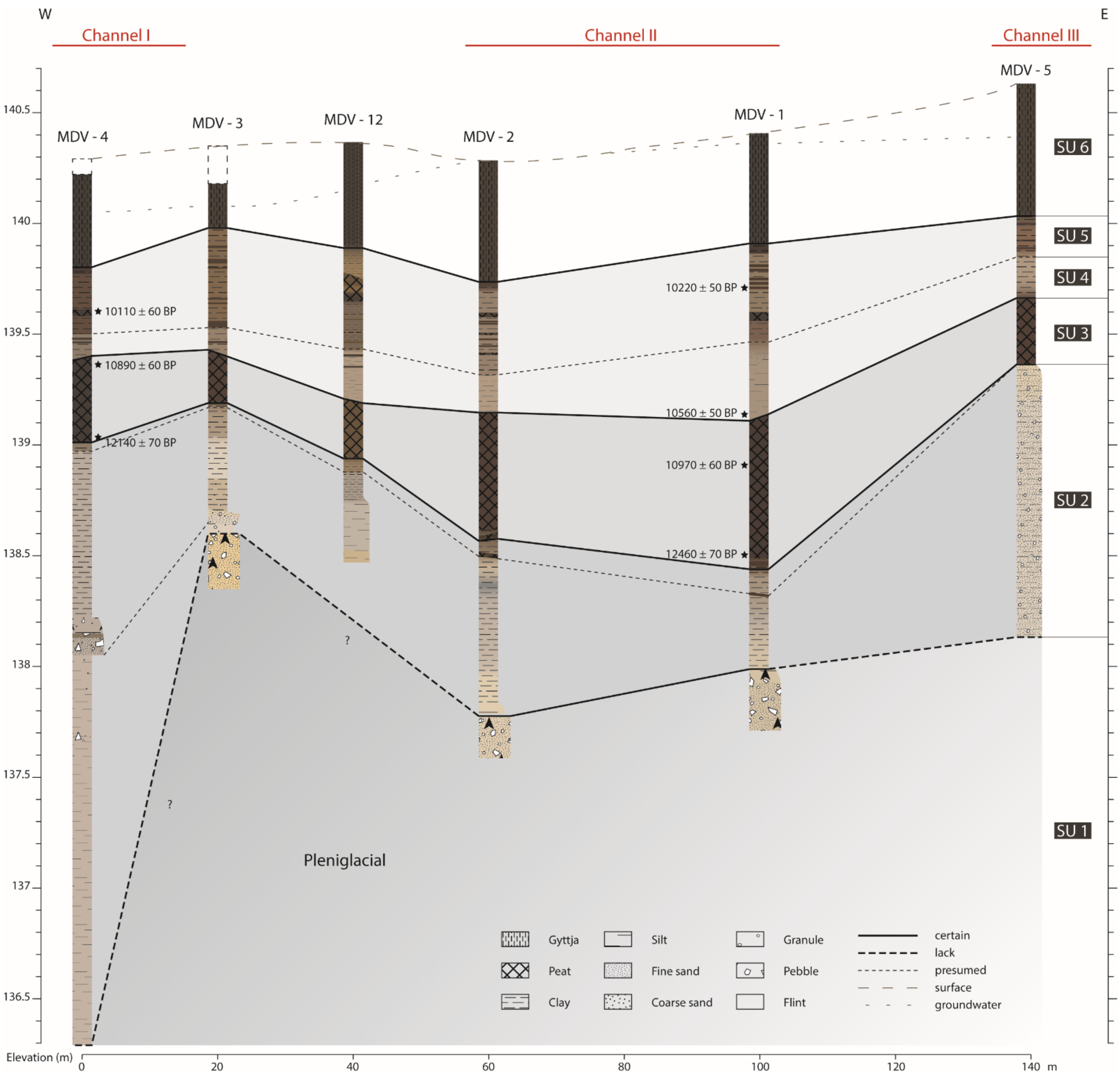

Fig. 6. Cross-section of the Lateglacial and Early Holocene sequence from the Boitet valley with the sedimentary units and the radiocarbon dates.

Palynology: The pollen composition of this zone indicates a large open herbaceous landscape with dominance of sedge communities, probably linked to swamp soils where important shrub vegetation with willow and birch can grow (Fig. 77). Standing water is assumed because of consequent pollen percentages of aquatic plants at the end of the zone, between 222 cm and 198 cm. The extension of local dry habitats was limited as it was reflected by low representation of steppe vegetation but nevertheless more significant at the beginning of the zone with the development of *Ephedra* and *Hippophae*.

Chronostratigraphic constraints: The radiocarbon dates performed at the base of the Unit 3 corresponds to the onset of the Bølling. It is likely that Unit 2 records the Oldest Dryas period and partly an early phase of the Bølling.

Interpretation: This assumption seems to be confirmed by the pollen assemblages of treeless vegetation which can be compared with the Oldest Dryas of the Lateglacial stratigraphy of higher altitude areas although the percentages of *Artemisia* were relatively low. The silty-clayey sequence suggests a gradual filling of the channels by a fine alluvial load. A significant river and sediment discharge change has possibly occurred between the Pleniglacial period and the Oldest Dryas to explain the absence of a gradual evolution of the sediment supply from coarse to fine load. The high silt/clay percentage, the low width/depth ratio and the aggradation geometry of the deposits are all consistent with a low-energy system of anastomosed channels. We note a peculiarity of channel III: where the whitish clayey-sandy silt (F4) of the MDV-5 core, which is also observed in MDV-9 further upstream, could correspond either to lateral bank deposits or to the infilling of another channel. This singular deposit may correspond to a distinctive channel at the east of the alluvial plain, as these cores are exactly located on a wide meandering channel observed on aerial images and geophysical surveys (Fig. 3). Nevertheless, we are unable to link this channel to the chronostratigraphic framework to fully confirm this hypothesis.

In the MDV-1 and MDV-2, the colour, evolving from yellow-brown to grey-blue towards the top, is indicative of a transformation from oxidised towards reducing conditions. The reducing environment, the preservation of muddy organic deposits and the gradual facies transition towards the Units 3 suggest that these muddy organic-rich deposits accumulated in a channel that was abandoned. In contrast, MDV-4 and MDV-5 document the functioning of active channels. On the whole, our data suggest that the landscape is a marshy expanse with a low-energy multichannel system running through it with some abandoned and active channels. These hypotheses are consistent with geophysical and image data that highlight a multichannel river system, although it cannot be totally excluded that some of the channels in the floodplain are more recent.

Unit 3 (SU 3 / PAZ 3)

Sedimentology: The base of the unit presents some differences of facies and thicknesses between the abandoned channel (MDV-1 and MDV-2) and the active channels (MDV-3, MDV-4 and MDV-5). The peat thickness varies between the cores: the thickness is highest in the MDV-1 and MDV-2 cores, and thinnest in the MDV-5 and MDV-3 cores (Fig. 66). In the MDV-1 and MDV-2, the unit starts with thin organic centimetre thick layers that are interbedded with silty beds. These deposits evolve towards a highly-decomposed black clayey peat (F6) that fills the space available left by a channelized topography. In the MDV-3, MDV-4 and MDV-5, no silty beds have been observed in the lowermost part of the unit, leaving only the black peaty layer (F6) that overlays directly the incision surface. This facies is composed of 75 % of organic matter, 2-3 % of carbonate content and 20 % of silicates and oxides (Fig. 5). The susceptibility values are weakly negative to null, which is consistent with the presence of a high organic matter content. The top of the unit is truncated by a sharp undulating erosional surface that is observed in all cores.

Palynology: This zone corresponds to the pioneer shrub colonization (PAZ3a) which continues with the installation of pine (PAZ3b) in or near the investigated area (Fig. 77). In PAZ3a, the first stage of dynamic is characterized by an increase of *Juniperus* rapidly followed by a rise in *Betula*. *Salix* communities remain locally in the surrounding wet areas. The depletion of pollen from aquatic plants with simultaneous and continuous increase of hygrophilous taxa like *Filipendula* and *Equisetum* indicates the paludification, i.e., the peat initialisation, of the area probably also linked with the augmentation of *Poaceae* and *Cyperaceae*. In PAZ3b, the continuous representation of *Pinus* percentages of around 30% signals the forest development of the surrounding area. The intensification of tree cover has led to a decline of heliophilous shrubs like *Betula* and *Juniperus* and herbaceous taxa like *Artemisia* and *Helianthemum*.

Chronostratigraphic constraints: Four radiocarbon dates have been performed in this unit: 12460 ± 70 (15024-14220 cal. BP), 12140 ± 70 (14184-13779 cal. BP), 10970 ± 60 (12993-12718 cal. BP) and 10890 ± 60 (12905-12688 cal. BP). The oldest dates at the base of the peaty Unit 3 coincide with the Oldest Dryas-Bølling transition (Fig. 2). Since the younger dates at the top of the unit are concomitant with the Allerød-Younger Dryas transition, we suggest that Unit 3 was deposited during the Bølling-Allerød period.

Interpretation: The increase in shrub representation is consistent with the vegetation changes recorded in Western Europe as "The Bølling biozone" corresponding to the GI-1e of the event stratigraphy (Lowe et al., 2008). The consistent increase in *Pinus* percentages is probably linked to the development of mixed pine forest and is assigned to the Allerød biozone in NW Europe. The deposits are defined by the presence of a homogeneous peat layer and a low abundance of a clay fraction. These characteristics are indicative of a phase of decreasing river dynamics that evolves towards a swamp environment. The peaty F6 probably developed under water-saturated and anaerobic conditions. The evolution from silt to organic-rich sediment could record a decrease in sediment supply due to soil stabilization linked to a densification of the vegetation cover induced by the temperature increase and wetter conditions during the Bølling-Allerød period.

The difference of facies observed in the lowermost part of Unit 3 in MDV-1 and MDV-2 (absence of erosion surface, differential preservation of silty beds, thick peat layer) and MDV-3, MDV-4 and MDV-5 (erosion surface, thinner peat layer) could reflect a differential response during the climate transition depending of the channel activity. In the abandoned channel, no erosion has occurred and the silt to organic-rich deposits evolution may reflect some delay, *i.e* the time required for the vegetation to develop. In the active channel, the decrease in sediment supply and the increase of the water table would have favoured a brief erosion phase in the channel. The only preserved deposits are the peaty deposits. We suggest that the incision phase in the peaty deposits of the Unit 3 could be attributed to the climate change from the Allerød to the Younger Dryas period.

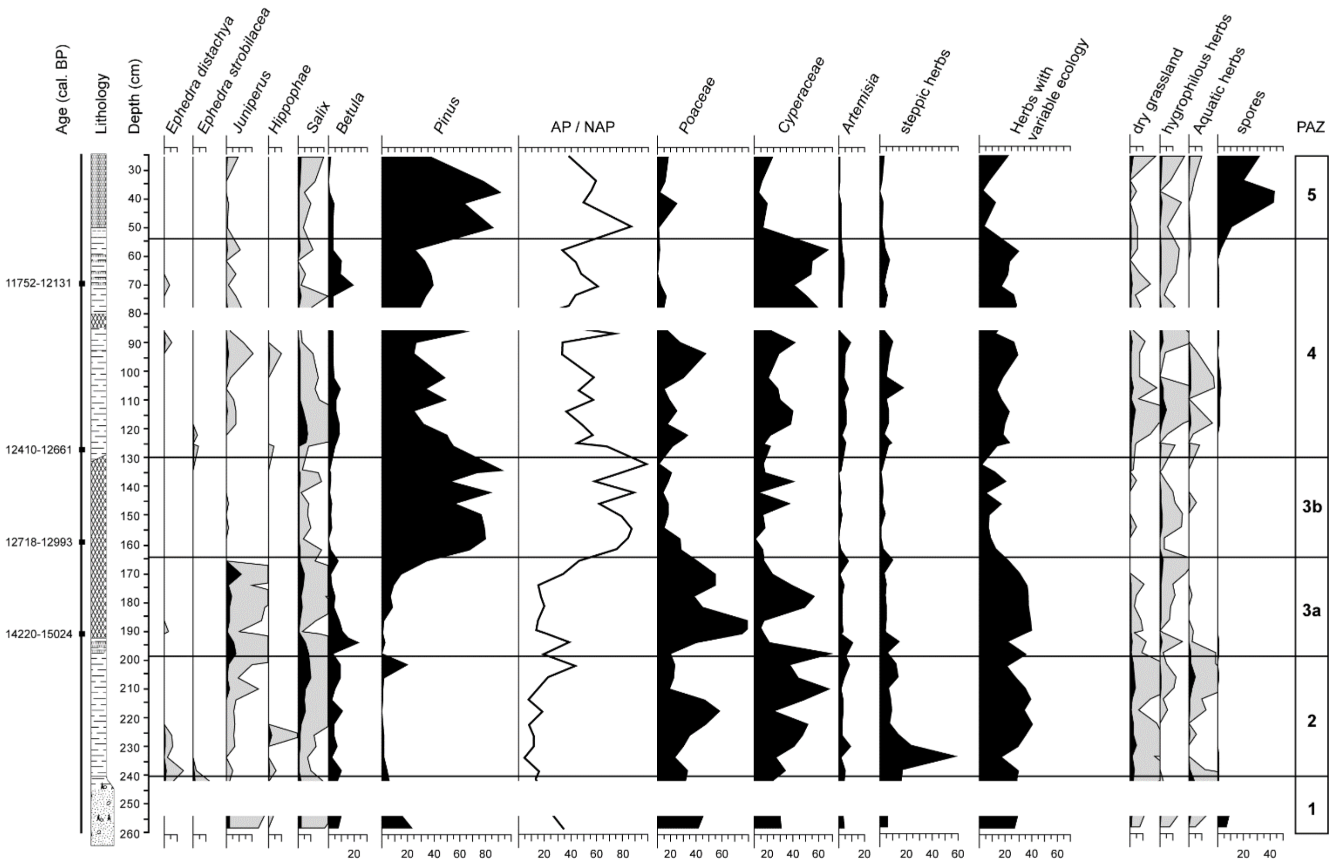

Fig. 7. Pollen diagram from MDV1 core. AP: arboreal and shrub pollen; NAP: non-arboreal pollen (herbaceous pollen); PAZ: pollen assemblage zone. Values are presented as percentages (black curves) and with a 10-times exaggeration (grey curves).

Unit 4 (SU 4 / PAZ 4)

Sedimentology: The base of SU 4 starts with a homogeneous greyish clay (F2) intercalated with few organic thin layers that fill the undulating topography formed during the previous incision phase. The unit thickness varies laterally from a few centimetres (MDV-1) to a few ten centimetres (MDV-4). The organic matter content remains very low (only a few %), as observed in Unit 2.

Palynology: The pollen changes indicate the return to open herbaceous communities with the extension of steppe taxa, especially *Artemisia* (Fig. 77). The presence of the low competitive taxa *Ephedra* indicates the emergence of coversand and full sun exposure areas. The openness of the forested landscape explains the increase in other heliophilous shrubs of *Juniperus* and *Hippophae* and even *Betula*. The occurrence of pollen of *Potamogeton sp*. can be explained only by the presence of standing water near the place of the core. We can detect a partition of this zone with a first part characterized by a greater pollen percentage of steppe taxa-Poaceae and aquatic plants and a second part with greater pollen percentages of Cyperaceae and *Betula* and a strong drop in Poaceae. These two biozones are separated by a sterile level.

Chronostratigraphic constraints: One radiocarbon date from the base of the unit returns an age of around 10560 ± 50 (12661-12410 cal. BP) and confirms that U4, which follows stratigraphically the Bølling-Allerød period, is attributed to the onset of the Younger Dryas.

Interpretation: The preservation of silty deposits (F2) reveals an increase in sediment supply, a fluvial aggradation, and thus the reactivation of a low-energy river system. We suggest that a rarefaction of the stabilizing vegetation cover and a lowering of the water table have occurred to explain the record of detrital silty sediments that feed the channels. Therefore, it is supposed that Unit 4 records the functioning of low-energy channels in colder conditions during the Younger Dryas period.

Unit 5 (SU 5 / PAZ 5)

Sedimentology: This unit consists of a clay layer interbedded with frequent organic-matter rich beds (F8), displaying between 15 to 60% of organic matter content. Some peaty layers, containing up to 75 %, can been identified in MDV-1, MDV-2, MDV-4 and MDV-12 cores (Fig. 5). The top of the unit is truncated by an incision surface observed in all cores (Fig. 66).

Palynology: The sharp increase in *Pinus* pollen and spore monolete curves indicates a marked environmental change where the development of large forested areas caused the quasi disappearance of herbaceous and shrubs heliophilous taxa (Fig. 77). The strong decrease of Cyperaceae percentages is notable. The stable presence of taxa linked to wet soils like *Salix* and *Filipendula* shows however the persistence of swampy areas.

Chronostratigraphic constraints: Two radiocarbon dates have been performed in the Unit 5: 10220 ± 50 (12131-11752 cal. BP) and 10110 ± 60 (11993-11400 cal. BP). These confirm that the U5 is dated to the end of the Younger Dryas.

Interpretation: The succession of detrital layers intercalated between the organic layers may reflect some fluctuations of the water table and the return to a marshy landscape. Clay deposits mark flood events in a low-energy river system whereas peaty layers reflect a water table increase. The sharp erosion observed at the top of the unit could record the transition between the Younger Dryas and the Holocene. The disappearance of cold-adapted species and the forest recovery correspond to the Younger Dryas-Holocene transitional phase.

Unit 6 (SU 6)

Sedimentology: It corresponds to a gyttja deposit that can be observed up to the ground surface. This non-cohesive facies (F9) is composed of clay and organic matter which can reach up to 75 % (Fig. 5). The heterogeneous and non-cohesive sediments appear fairly reworked. Magnetic susceptibility presents slightly negative values.

Chronostratigraphic constraints: No ^{14}C dating have been performed. However, the gyttja deposits and the ^{14}C dating in the Unit 5 are consistent with an Early Holocene record.

Interpretation: The gyttja deposit is indicative of a wet environment similar to the current fen, which signifies that the environmental conditions have not significantly evolved since the beginning of the Holocene. The hiatus highlighted between Units 5 and 6 could be either attributed to Holocene climate change or to more recent anthropogenic activity. Indeed, we cannot exclude that the industrial exploitation of the peat has contributed to the erosion and reworking of the gyttja (Salaün and Marre, 2005).

4.3 Morphodynamic evolution and climatic cycles

The combination of data coming from the image analyses, the geophysical acquisitions and the sedimentary and palynological records have highlighted changes in discharge and channel morphology in response to short phase climate oscillations. We observed (1) a multi-channel network that has developed in the alluvial plain, (2) the record of successive cut-and-fill phases in the sedimentary record, (3) a sedimentary filling mainly composed of clay, silts and peats. All these data allow us to define periodic fluctuations of the water level, with six successive phases of river dynamics in the Boitet catchment during the Lateglacial and Early Holocene periods.

Pleniglacial (Unit 1)

During the Pleniglacial period, the landscape is dominated by high-energy braided rivers transporting coarse sediments. Pollinic data indicate both wet conditions (Cyperaceae) and steppe environment with sparse dwarf-birchs and grass vegetation. The transition from the Pleniglacial to the Oldest Dryas appears to be marked by an incision phase potentially attributed to a climate change, but it cannot be totally excluded that the channel morphology filled by the Oldest Dryas deposits was inherited from the Pleniglacial.

Oldest Dryas (Unit 2)

The hydro-sedimentary dynamic of the river evolves during the Oldest Dryas. The image analyses and geophysical prospection reveal a river system consisting of low-energy multiple channels. In this river system, the main active anastomosed channels display a silty-clayey sedimentation, which may have occurred partly during an early phase of the Bølling period as evidenced by Pastre et al. (2003), while abandoned channels are filled by organic deposits. Indeed, several gullies were visible on the orthophotographs and/or on the coring transect that indicated a complex network of palaeochannels. Besides, one larger meandering channel with a coarser sedimentation seems to flow along the easternmost part of the valley. Palynological data suggests a landscape dominated by steppe meadows (*Poaceae*, *Helianthemum*) in which some anastomosed channels bordered by shrubs (dwarf-birchs and willows) develop. The deposition of a new sedimentary unit (SU2) without any gradual transition with the former Pleniglacial coarse deposits (SU1) indicates a significant change of the sediment discharge and of the Boitet River morphodynamics, which occurred between the Last Glacial Maximum and the Oldest Dryas. The timing of this change is not clear; it could be marked and occurred in a short time period, but also, the lack of constraint on the chronology of this phase does not allow us to exclude the possibility of a long time gap between the incision of SU1 and the aggradation of SU2.

Bølling-Allerød (Unit 3)

After the cold episode of the Oldest Dryas, the detrital sedimentation disappears at the onset of the Bølling, suggesting a decline of the fluvial activity. The sedimentation, dominated by organic matter rich deposits, is indicative of a significant change in terms of fluvial processes, sedimentary supply and vegetation cover at the catchment scale. This is reflected by warmer conditions favouring vegetation colonisation by shrubs and willow trees and soil stability. The presence of more aquatic vegetation suggests a mean water table rise coeval with the climatic amelioration of the Bølling period. In the second part of the Allerød, the amount of pines increases to replace an open forest vegetation cover.

Younger Dryas (Units 4/5)

A new incision phase is recorded at the end of the Allerød or at the onset of the Younger Dryas. The Younger Dryas period is marked by detrital sedimentation composed of silty-clayey load and the reactivation of a multi-channel system. The fluvial activity and the disappearance of the vegetation cover indicate both a lowering of the water table, that could be induced by climate changes, tectonics and any eustatic processes (Vandenberghe, 2015). The vertical deformation rate of the Paris Basin (0.01 m/1kyr) are too low to explain the observed base-level fall (Briais et al. 2016), and we suspect that this incision phase results from climate change, evolving towards cooler and drier conditions that characterized the Younger Dryas period. The vegetation is dominated by a steppe environment and a decrease of the amount of the pines. In the second period of the Younger Dryas, the increase of the organic matter beds in the sediment record suggests a recolonization of the vegetation. The landscape evolves towards an open birch-pine woodland in which sinuous rivers flow.

Holocene (Unit 6)

The general incision observed in all cores suggests a climate change occurring at the transition between the Younger Dryas and the Holocene. Abrupt changes both in vegetation and in the fluvial dynamics take place. Detrital sedimentation disappears to be replaced by gyttja deposits. A new phase of water table rise is recorded. The landscape is dominated by a marsh and the densification of a pine forest.

5 Discussion

Hereafter, we will compare successively the six phases of river dynamics observed in the Boitet catchment to those described in NW Europe during the Lateglacial and Early Holocene periods. Ensuingly, the preservation potential and geomorphological features as key factors for recording Lateglacial alluvial deposits will be discussed.

5.1 Climate changes and river adjustments: an interregional analysis

In NW European rivers, many studies have shown that the Oldest Dryas cooling period has been poorly preserved in fluvial deposits. In most channels located in lowland areas of northern France, Lateglacial sedimentary records have been incised at the beginning of the Bølling (Antoine, 1997; Pastre et al., 2000). Just prior to this major incision phase, a few relics of fluvial deposits reworking the former Pleniglacial loess have been noticed in the Oise and Marne valleys of the Paris Basin (Antoine et al., 2003; Pastre et al., 2003), in which Upper Palaeolithic Magdalenian sites of Etiolles, Verbrerie and Pincevent are interstratified and dated from 13000 to 12000 BP (Valladas, 1994). These deposits are similar to the silty fluvial sequence (SU2) described in this paper, although the latter is well developed. Therefore, the Boitet River provides a rare case of Lateglacial sedimentary archives in northern France marked by a marked incision phase followed by an Oldest Dryas – early Bølling alluvial deposit (Fig. **8**8).

In the Boitet catchment, the onset of Bølling warming period is closely correlated to the storage of organic infilling. Ages obtained at the very bottom layer of the channels around 14612 cal. BP (15024-14220 cal. BP) and 14009 cal. BP (14184-13779 cal. BP) are consistent with the oldest Lateglacial peaty deposits of the Selle and the Thérain rivers of the Paris Basin, respectively dated from 14472 cal. BP (14827-14150 cal. BP) and 14748-14081 cal. BP (Antoine et al., 2003; Pastre et al., 2003), making the Boitet sequence the oldest alluvial record from Lateglacial in northern France. Our dates also indicate that the shift from cold to warmer climate at the very early beginning of the Bølling may have provoked the re-incision of some of the inherited channels to explain the presence of gyttja deposits around 14.6 cal. BP. Similar incision surfaces have been broadly illustrated elsewhere in NW and Central Europe (Vandenberghe, 1995; Huisink, 1999) and interpreted as a response to climate warming at the Oldest Dryas-Bølling transition. However, in our case, the wide standard deviation does not allow us to date precisely the onset of the incision. Moreover, the preservation of organo-clastic deposits prior to this peat accumulation in some channels of the Boitet River may indicate a minor incision phase which predates the main temperature increase ca. 14.7 cal. BP. Such an assumption has already been suggested in the Somme valley of the Paris Basin (Antoine et al., 2003), in the Jeetzel River in northern Germany (Turner et al., 2013) or in the Dordogne River in SW France (Bertran et al., 2013), where river incision occurred before the main climate warming in response to seasonality changes, e.g. a subtle increase in vegetation cover (Wagner-Cremer and Lotter, 2011). Vegetation cover is indeed perceived as a direct and key control mechanism on river morphodynamics (Vandenberghe, 2003).

During the Bølling-Allerød, no evidence of changes in the river morphodynamics have been detected. However, pollen analysis highlights a clear division of the peat accumulation which is defined firstly by a prevailing of pioneer shrub vegetation marked by an increase of *Juniperus* and *Betula*, secondly, after a transitional layer, by a sharp rise of *Pinus* leading to the high amount of AP grains (80%). This abrupt change in vegetation cover, usually characterised by a crossing-over of the *Betula* and *Pinus* curves, is commonly recognised in NW Europe and occurred within the Allerød biozone (Hoek, 1997; De Klerk, 2008). Indeed, in the Paris Basin, the vegetation was largely dominated by *Betula* before being replaced by *Pinus* (Leroyer, 1997; Pastre et al., 2000), and the same trend has been observed in lowland areas of northern regions, e.g. in Belgium (Mullenders et al., 1972; Munaut and Paulissen, 1973; Crombé et al., 2013) or in the Netherlands (Bohncke, 1993; Hoek, 1997; Bos, 2001). Overall, the biozones defined from our palynological data are in accordance with regional synthetic studies from east (Turner et al., 2013) to west (Pastre et al. 2003): the Oldest Dryas open and steppe environment is respectively consistent with the OV-I ("Open Vegetation I") and PAZ 1/2 as well as the Bølling shrub formation with the Hippophae-phase and PAZ 3. From 14 to 13.5 cal. BP, the transitional layer which is characterized by low values of *Betula* and *Pinus* and a rise of *Poaceae* may correspond to the first part of the Allerød, described as the OV-II and Allerød a-b (Turner et al., 2013) and PAZ 4/5 (Pastre et al., 2003). Finally, the *Pinus* rise occurred simultaneously around 13.5 – 13.3 cal. BP in these different areas, which confirmed the relevance of our biostratigraphical divisions and the correlation with the ice-core chronology already noticed in these previous studies.

The onset of the Younger Dryas is marked by the incision of the Allerød unit and then by the accumulation of a mixture of chalky and silty sediments in channels (Fig. **8**8). These deposits are supposedly produced by the weathering of chalky bedrock on the slopes during freeze-thaw cycles and then transported from the hillslopes by intensive runoff (Antoine et al., 2003). These interpretations imply both a climatic deterioration and a decrease of vegetation cover that lead to an increase of the fluvial activity. These hypotheses are consistent with other studies performed in the Paris Basin and in NW European rivers (Vandenberghe et al., 1994; Pastre et al., 2003). The rise in NAP percentages of steppe taxa and heliophilous shrubs and the decrease of *Pinus* pollen are representative of the beginning of the Younger Dryas biozone of NW Europe around 10950 BP (Isarin, 1997). Therefore, the sedimentological and palynological features of the Boitet sequence are archetypal of the onset of Younger Dryas (Limondin-Lozouet and Antoine 2001; Pastre et al., 2003). Our data reveal a twofold division for this period in the pollen record that we interpret as reflecting the shift from a cold and wet phase toward a warmer and drier climate (Fig. **8**8). A similar subdivision of malacological and palynological sequences has been identified in the Oise and the Somme valleys (Paris Basin), (Limondin-Lozouet and Antoine, 2001; Ponel et al., 2005), but also has been broadly recognised throughout Western Europe (Bohncke et al., 1993; Walker, 1995) as far as the Mediterranean area (Burjachs et al., 2016), and eastward up to the Jeetzel valley in Germany (Turner et al., 2013). This subdivision is attributed to changes in the North Atlantic thermohaline circulation (Isarin et al., 1998).

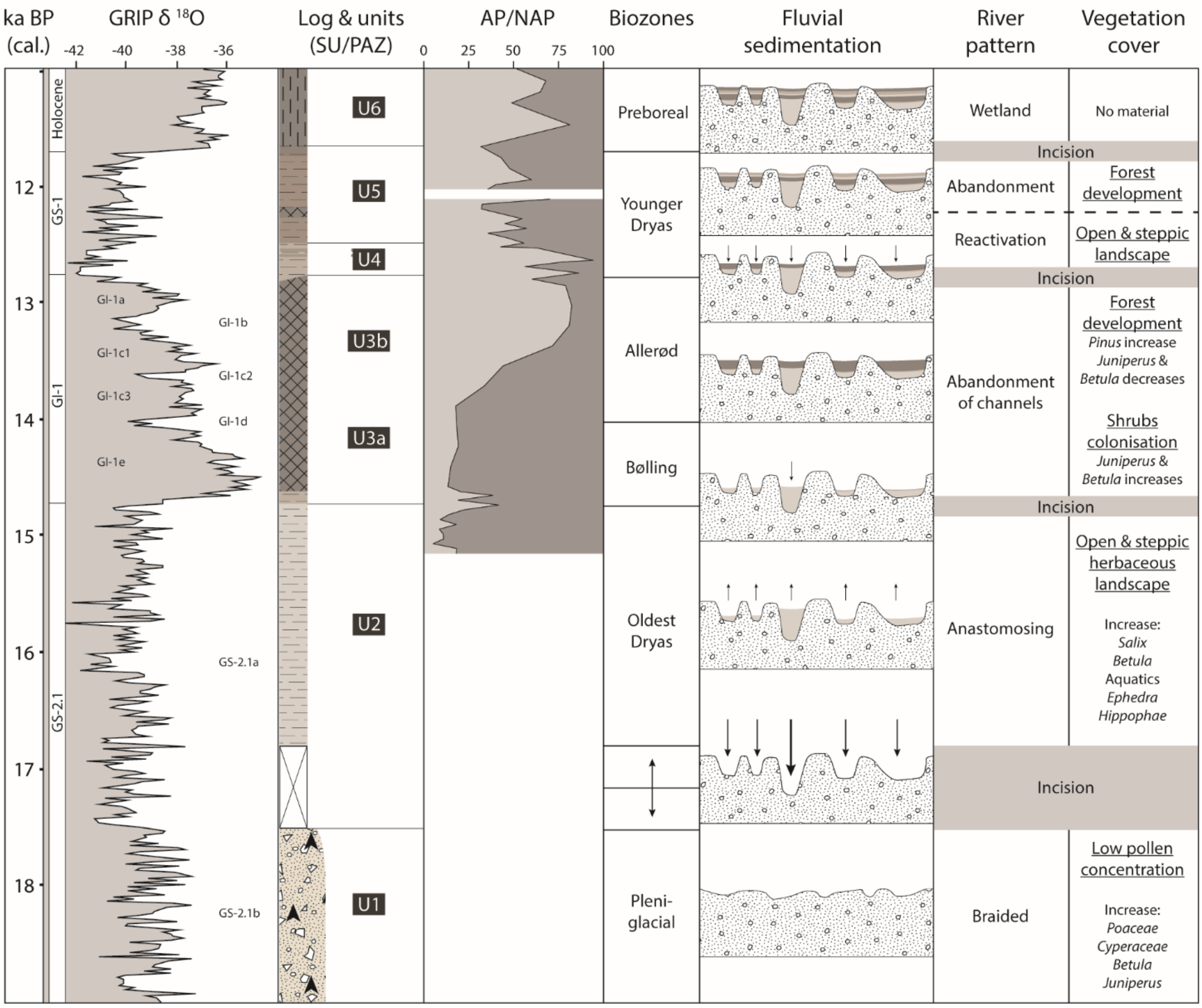

Fig. 8. Comparison of the main climatic, fluvial and vegetation changes in the Boitet valley during Lateglacial.

5.2 Preservation potential and geomorphological features as key factors for recording Lateglacial alluvial deposits

Sedimentary sequences in the Marais de Saint Gond catchment reveal global similarities with NW European rivers that are interpreted as fluvial system evolution to climate changes. However, some local differences have also been highlighted. Among them, two distinctive features of the Boitet sequence are the preservation of Oldest Dryas deposits, and the development of low-energy multichannel systems during the Oldest Dryas and Younger Dryas. It is likely that these features can be partly explained by some local geomorphological context (Mol et al., 2000), illustrated by the investigation of a headwater drainage area of a tributary river, with a small-sized catchment.

Our study reveals a low-energy anastomosed system of numerous narrow channels of 10-20 m width prior to Bølling organic rich sedimentation. Some narrow multichannel systems occurring after the Pleniglacial and displaying a low sinuosity have been described in NW European rivers, such as those highlighted in the Selle valley (Antoine et al., 2003; Ponel et al., 2005) or in the Maas and Warta rivers in Poland (Vandenberghe et al., 1994). These multichannel systems have been interpreted as 'transitional systems' to explain the fluvial changes from Pleniglacial braided to Bølling meandering rivers (Vandenberghe, 1995; Huisink, 1997; Kasse et al., 2005; Kasse et al., 2010; Erkens et al., 2011; Turner et al., 2013). Several have demonstrated that this transitional phase could take place before 14.7 cal. BP (Huisink, 1997).

Transitional patterns in alluvial system was initially perceived as an intrinsic change of the river morphodynamics in response to climate change. For instance, such patterns have been commonly described in cold-to-warm transition, such as Pleniglacial to Lateglacial (Huisink, 1997). In the case of anastomosed rivers, they are characterised by aggradational processes and developed under different conditions; favoured by a low-gradient plain where the amount of available sediment is higher than the capacity of transport or by an upstream area with high sediment supply. Aggradation arises in downstream accumulation zones where channels are not able to transport all sediment coming from upstream, as it is the case in alluvial fans (Smith and Smith, 1980; Smith, 1986; Mather et al., 2017) or deltas (Makaske, 2001; Makaske et al., 2017). Alternatively, such patterns are found in tributaries or headwater drainage areas due to a high-discharge/excess of sediment supply, e.g. the Morava River (Bábek et al., 2018), the Jeetzel valley (Turner et al., 2013) or the Moervaart palaeolake (Crombé et al., 2013). The latter reveals an evolution of the drainage system, from an anastomosed network to a single meandering channel, caused by lacustrine level decrease. In the Dordogne valley, Bertran et al. (2013) demonstrate the development of an anabranching river around 18000 – 17000 cal. BP which lasted throughout the Lateglacial. Therefore, the identification of an anastomosed river system in the Boitet catchment is consistent with these observations. Moreover, this anastomosed system is a tributary of a large and marshy accumulation area (Saint-Gond marshes) resulted from the two hydrographic captures. The capture of the Somme-Soude River at the end of Pleniglacial, which has taken place upstream of the Saint-Gond marshes and the Boitet catchment, probably induced a major disruption in the drainage system (Tricart, 1949). As demonstrated by Maher et al. (2007), such capture lead to a decrease in water and sediment discharges and to a valley infilling with fines in the beheaded river system. This suggests that it was partly responsible for an alluvial aggradation of the Saint-Gond marshes area and of its tributaries. In addition to this geomorphological context, the headwater position of the Boitet catchment characterised by a connectivity of the hillslope to the valley floor, and the chalky bedrock weathered by freeze-thaw cycles, may explain the development of this anastomosed pattern characterised by fine alluvial aggradation during the Oldest Dryas cold period. Such a fluvial evolution as a response to both climatic change and particular catchment features have been already demonstrated in Belgium (Crombé et al., 2013) and may correspond to allocyclic-autocyclic coupling factors which could have triggered the moment when a threshold was exceeded (Schumm, 1977). Indeed, the latter developed the idea that fluvial records may not only reflect external forcing factors like climatic changes but also intrinsic factors. Intrinsic features, e.g. topography, geology, vegetation cover, may be responsible for delayed responses or autonomous changes, and these factors and processes could differ from one basin to another (Prosser et al., 1994).

Analyses of depositional sequences in river systems show that alluvial records are formed by successive cut-and-fill cycles. As a consequence, the preservation potential of sedimentary sequences and river morphodynamic evolution is ultimately dependent of the intensity of the incision/sedimentation phases. For instance, most studies performed in NW Europe are focused on large catchments (>2500 km²) in downstream areas of main rivers and have stressed a broad incision at the onset of Bølling warming, hence the Oldest Dryas aggradation may have been eroded. Conversely, we suspect that the preservation potential of sedimentary sequences in those small-scale catchments is higher than for larger rivers, favoured by an upstream position, as suggested by Houben (2003). Indeed, in a headstream area, the river dynamics are more dependent on internal factors such as topography or subsoil lithology than that of a wider lowland river which gathers many tributaries (Vandenberghe, 1995; Vandenberghe, 2003). The relative importance of local factors in the alluvial preservation may explain why some headwater catchments present some peculiarities, e.g. the Rochy-Condé in the Thérain valley (Paris Basin). Conversely, sedimentary deposits in downstream areas reflect the global evolution of the entire catchment as the sum of the tributary responses. These will erase their specific local features leading to a climate-driven record, such as it has been shown in the Somme and Seine rivers. In the Paris Basin, Pastre et al. (2003) had already noticed that the geomorphological context contributes to the river evolution in spite of the major influence of climatic shifts. They demonstrate the contrast between main rivers active channels and small catchments. During Bølling, channel infilling deposits of the main valleys (e.g. Oise valley at Houdancourt and Lacroix-Saint-Ouen sites or Seine valley at Bazoches site) are characterised by a sandy-silty load. On the contrary, like the Boitet valley, organic deposits and peat formation are much more common for this period in small valleys and abandoned channels e.g. the Selle and Thérain valleys described above. The Thérain River is also a good point of comparison with our study; a pre-Bølling organic-rich deposit, subsequent to an undated clayey-silty deposition, has been dated to around 13,250 ± 84 BP (16126-15475 cal. BP; Pastre et al., 2003). Despite the lack of sedimentological details, the presence of a few organic silty layers prior to Bølling warming, which is rarely observed, may be related to the first organic sedimentation of the channel II (Fig. 6). These features further highlight the importance of the local geomorphological conditions, such as the catchment size or the channel activity, and the resulting preservation potential, on the river evolution.

Besides temporal dynamics, spatial dynamics also have significant implications for river evolution. In addition to the narrow multichannel system, one larger paleomeander of 40 m width characterized by coarser sedimentation is observed in the easternmost part of the valley (Fig. 3) which hypothetically may have remained partly active during Bølling-Allerød stadial. Such variability of the fluvial dynamics in the alluvial plain is frequently observed: numerous NW European studies have noticed a complex Lateglacial multichannel transition from braided to meandering patterns during which these dynamics differed depending on channel activity, e.g. the abandonment of some of the channels whereas some of them remained active at the same time (Vandenberghe et al., 1994; Crombé et al., 2013; Turner et al. 2013).

6 Conclusion

We demonstrate that the fluvial evolution is triggered by climate changes and by geomorphological controls that can be strongly coupled, particularly in headwater areas where preservation potential reveals contrasting responses with different timings. Therefore, the choice of the geomorphological area (headwater area; wetland or lakes; alluvial plain of a wide drainage basin) seems decisive and determines the preservation potential of alluvial river systems. Upstream sections are important areas to investigate hydro-sedimentary delivery from slopes to valley floors. As such, they record more directly hydrosystem responses to forcing factors. It appears that focus on the headwater streams provides new data about hydrosystem adjustment to the last Glacial-Interglacial transition. The coupled 'spatial-multiproxy analyses and comparisons with more regional environmental data and climate reconstructions demonstrate the importance of climatic mechanisms on the whole hydrosystem and particularly the strong potential of preservation of alluvial archives in headwater drainage basins.

7 Acknowledgments

This work has benefited from the support of the research program "Programme sur le Néolithique des Marais de Saint-Gond et de la vallée du Petit Morin (Marne, France)" (R. Martineau dir.) and the PRES Bourgogne Franche-Comté for funding of the fieldwork, the laboratory analyses and the radiocarbon dating. The laboratory measurements were undertaken at the PES and CPEP platforms of the UMR 6249 Chrono-environnement - UBFC University. We thank Julien Didier, Maxime Mermet, Léa Bidaud and Vincent Favreau for their help with the coring and the geophysical investigations and Thomas Keep for assistance in translation. We are also grateful to Mr. and Mrs. Mathieu for their logistical support on the fieldwork. Suggestions from Jean-François Pastre, Jef Vandenberghe, Laurent Deschodt and Martin Stokes improved this manuscript.

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