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Fluvial system evolution and environmental changes during the Holocene in the Mue valley (Western France)

Laurent Lespez [a,*], Martine Clet-Pellerin [b], Nicole Limondin-Lozouet [c], Jean-François Pastre [c], Michel Fontugne [d], Cyril Marcigny [e]

[a] *Université de Caen-Basse-Normandie, GEOPHEN-LETG UMR CNRS 6554, Esplanade de la Paix, BP 5186, 14032 Caen cedex, France*
[b] *M2C-UMR CNRS 6143, Esplanade de la Paix, BP 5186, 14032 Caen cedex, France*
[c] *LGP UMR CNRS 8591, 1 place A. Briand, 92195 Meudon cedex, France*
[d] *LSCE-UMR CEA-CNRS 1572, avenue de la Terrasse, 91198 Gif/Yvette cedex, France*
[e] *INRAP Basse-Normandie, Le Chaos, 14400 Longues-sur-Mer, France*

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Abstract

Geomorphological and palaeoenvironmental research on Holocene sedimentation in the Mue valley provides evidence for fluvial system changes related to climate and human activities in Normandy, a poorly studied area of the Paris basin. The 24-km long valley bottom has been investigated through a systematic survey. It shows an original longitudinal sedimentary pattern in relation with valley morphology and local geological controls. Minerogenic, tufaceous and peaty deposits provide opportunities for multi-proxy analyses and radiocarbon dating control. Sedimentation began around 9500 ^{14}C BP with silt deposition in a meandering system. The Boreal and the Lower Atlantic periods (8500–6000 ^{14}C BP) were mainly characterized by unlithified calcareous tufa. Locally, these deposits are very thick (7 to 13 m). The tufa formed barrages across the valley bottom, providing an autogenic control on upstream sedimentation. During the Upper Atlantic period (6000–4700 ^{14}C BP), the valley experienced a decrease in calcareous sedimentation and the development of organic deposits. At the beginning of the Subboreal (4700–3500 ^{14}C BP), peat deposits expanded, especially behind the tufa barrages. The valley bottom was characterized by large marshy areas whereas the regional vegetation was progressively modified by human activities. At the end of the Subboreal (3300–3000 ^{14}C BP) the infilling of the valley by calcareous silt was caused by an increase of river activity related to climatic and land use changes. From the Iron Age and Gallo-Roman periods (2800–1700 ^{14}C BP), the valley bottom was filled by silty overbank deposits related to an increase of soil erosion. The slopes and river system were once again coupled and the fluvial system functioned as a continuum from upstream to downstream. The alluvial record of the Mue valley reflects a broad regional pattern of environmental changes but presents particular features, which highlight the need of longitudinal studies to take into account spatial and temporal discontinuities of Holocene hydro-sedimentary systems, even in small order valleys.

Keywords: Fluvial System; Alluvial records; Longitudinal arrangement; Tufa; Holocene; Normandy

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* Corresponding author. Tel.: +33 231566427; fax: +33 231566386.
E-mail addresses: laurent.lespez@unicaen.fr (L. Lespez), martine.clet-pellerin@unicaen.fr (M. Clet-Pellerin), Nicole.Limondin@cnrs-bellevue.fr (N. Limondin-Lozouet), Jean-François-Pastre@cnrs-bellevue.fr (J.-F. Pastre), Michel.Fontugne@lsce.cnrs-gif.fr (M. Fontugne), cyril.marcigny@inrap.fr (C. Marcigny).

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1. Introduction

Research on the fluvial responses to climatic and anthropogenic changes during the Holocene have been numerous in Europe and give evidence of the role of the different controls (e.g. Starkel, 1983; Gregory et al., 1995; Brown, 1997; Benito et al., 1998; Maddy et al., 2001). Nevertheless, they also underline the complexity of Holocene fluvial archives and particularly their fragmentary pattern, which renders precise chronostratigraphic studies difficult, and the distinction between autogenic controls and external environmental influences (Brown, 1997; Lewin et al., 2005). To take into account the lateral variability of the valley-bottom alluvial filling, most investigations are based on extended cross-sections using backhoe trenches or closely spaced augers while, in lowland areas, the longitudinal complexity is more often neglected even if it appears important to understand the fluvial system as a whole (Brown, 1990; Macklin, 1999). Indeed, the discontinuity of sediment routes through a catchment and along a river is the norm (Brown, 1990; Harvey, 2002; Hooke, 2003; Kasai et al., 2006). In addition, in sedimentary basins, specific alluvial features like transverse tufa barrages can interrupt the continuity of sediment transfer (Pedley et al., 2000; Pentecost, 2005). These observations underline the necessity of systematic

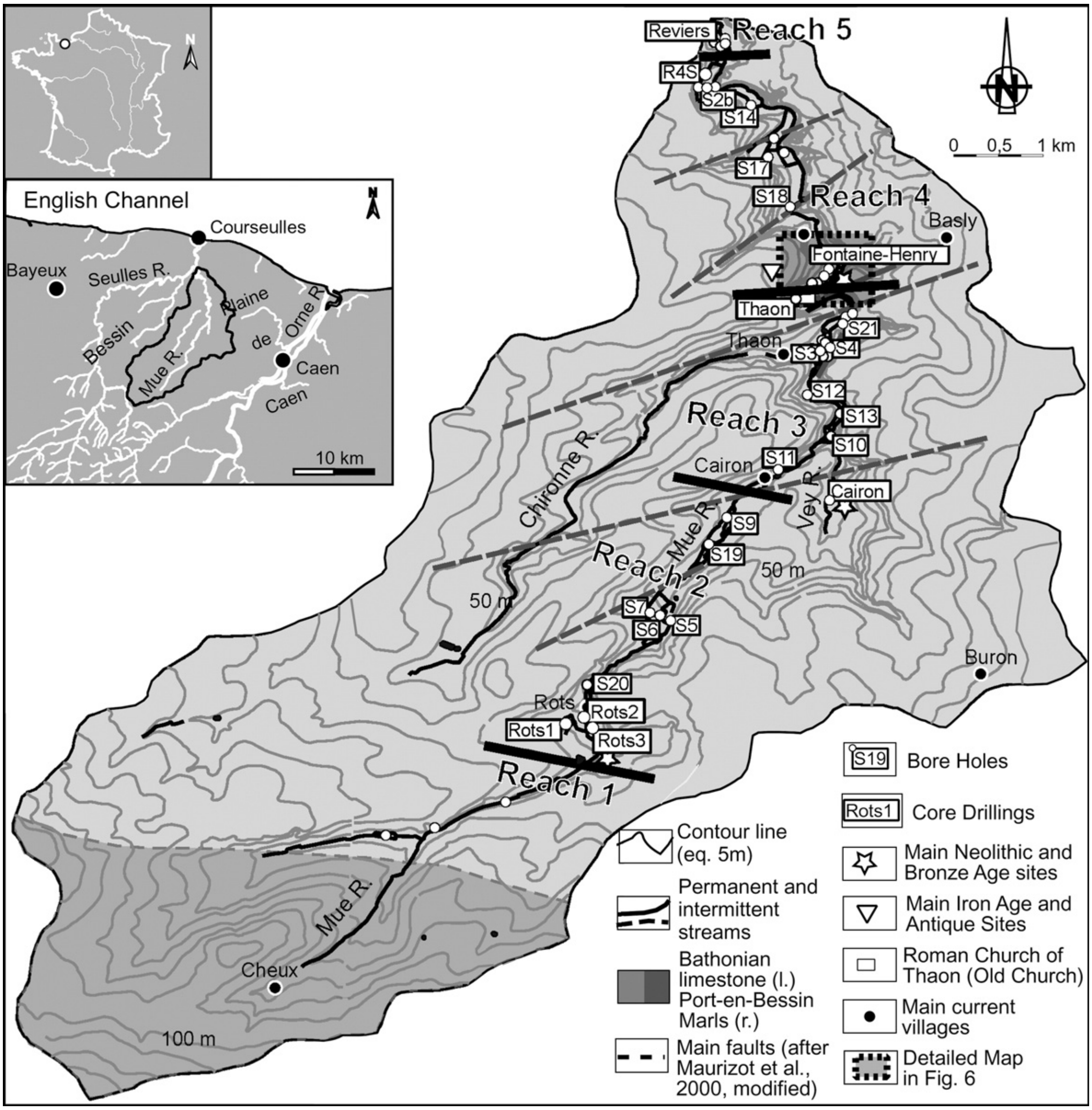

Fig. 1. Location of bore holes and core drillings in the Mue river basin.

studies from upstream to downstream to understand the heterogeneity of valley bottom deposits, particularly in small-scale river basins in which it appears most feasible to conduct such analyses (Brown, 1990).

The Mue valley, located in the Plain of Caen (Normandy), provides an opportunity to analyse the complexity of a small fluvial system in a poorly studied area of northern France (Fig. 1). Various studies have documented the alluvial sedimentary sequences of the Paris Basin during the Lateglacial and the Holocene, determining the main changes experienced by the fluvial system in the northern (Antoine et al., 2003) and central parts (Pastre et al., 2001, 2003, 2006) of the basin. Therefore, although the Seine valley has recently been studied (Sebag, 2002; Lesueur et al., 2003), the western part of the basin is poorly known, making comparison with changes of western European rivers difficult. Based on a systematic hand and power auger survey, the aim of this geomorphological and palaeoecological research is to determine the longitudinal pattern of the alluvial filling in the Mue valley and define the role of climate, human activities and autogenic controls on Holocene fluvial dynamics.

2. Study area

The Mue river is the last right-side tributary of the Seulles, a coastal river of Normandy. The river basin is small (97 km^2) and the valley is entrenched from 15 m to 40 m in Mesozoic limestone (Bathonian) which overlays the marls of Port-en-Bessin (Fig. 1). Being 24 km long, the longitudinal profile of the valley bottom is complex. It is characterized by five reaches with different morphologies (Fig. 2). The steepest reaches (3.5–7.4‰) are more often narrow (50–75 m) while the wider reaches (120–500 m) have a weaker slope (1–2‰). This longitudinal pattern is explained by the intraplate tectonic activity on the southern side of the English Channel (Lagarde et al., 2000). Locally, uplifted blocks are the results of dislocation of the late Cenozoic erosional surface by differential tectonic activity (Font, 2002). In addition to this pattern, we observe the role of the N50° faults which define the orientation of the valley (Fig. 1).

Today, the land use of the river basin is characterized by intensive agriculture on loamy productive soils of the Plain of Caen, with meadows or wet fallow land in the valley bottom and fallow land to forested area on slopes. The river has an average discharge of 0.35 m^3/s and has experienced a monthly maximum of 1.5 m^3/s and a monthly minimum of 0.1 m^3/s during the period 1970–1998. Groundwater of the Bathonian aquifer is the main water supply and contributes to sustaining flow in summer even if pumping for the urban area of Caen has contributed to low water levels in summer (Cador et al., 2001). Since the Middle-Ages, the flow has been almost totally controlled. Indeed, 60% of the last 14 km of the stream correspond to mill or tail races which supplied more than 20 water-mills in the 18th century (Lespez et al., 2005a).

In the Plain of Caen and more generally in Normandy, geomorphological research on Holocene fluvial systems remains scarce (Elhaï, 1963; Lespez et al., 2004, 2005a,b; Germain-Vallée and Lespez, 2006). Previous research on the Mue valley has provided evidence of the importance of Holocene alluvial filling and the local role of a tufa barrage downstream (Clet-Pellerin et al., 1990). Nonetheless, the Holocene chronostratigraphy was never established and the question of climatic and human impacts on the fluvial system during the Holocene remained open in an area where archaeological data are numerous and indicate dense settlement since the Middle Neolithic (*c.* 5500 BP) (Desloges, 1997; San Juan et al., 1999; Ghesquière and Marcigny, in press).

3. Methods

A systematic geomorphological survey was carried out in the valley bottom to reconstruct the Holocene alluvial chronostratigraphy (Fig. 1). Partial or complete cross-sections through the valley, and auger holes and cores regularly placed from upstream to downstream, were investigated as the main objective was to understand the longitudinal pattern of the filling. First, we obtained thirty-six hand augers and cores (3–7 m deep) along the valley and twenty-six bore holes (1–4 m deep) in the Thaon–Fontaine–Henry area. Then five cores were drilled (3–12 m deep) in key areas. Each core was described in the field according to texture, grain size, colour, vegetal remains and macrofossil content. In the laboratory, sedimentological analyses were focused on the cores but also concerned the rest of the Holocene sedimentation to characterize the general pattern of the alluvial dynamics along the valley bottom. Seven samples come from the current sediments and sixty-seven from sampling in the former deposits. Grain size analyses were made using a Laser Granulometer (Beckman-Coulter, LS 200). The sand and gravel fraction was sieved and examined under a binocular microscope.

Suitable cores were used for palaeoecological analyses. The organic sediments of the Cairon, Fontaine–Henry, Reviers and Rots cores were selected for pollen analyses (120 samples each 3 to 10 cm). Indeed, despite the problem of preservation and the waterborne

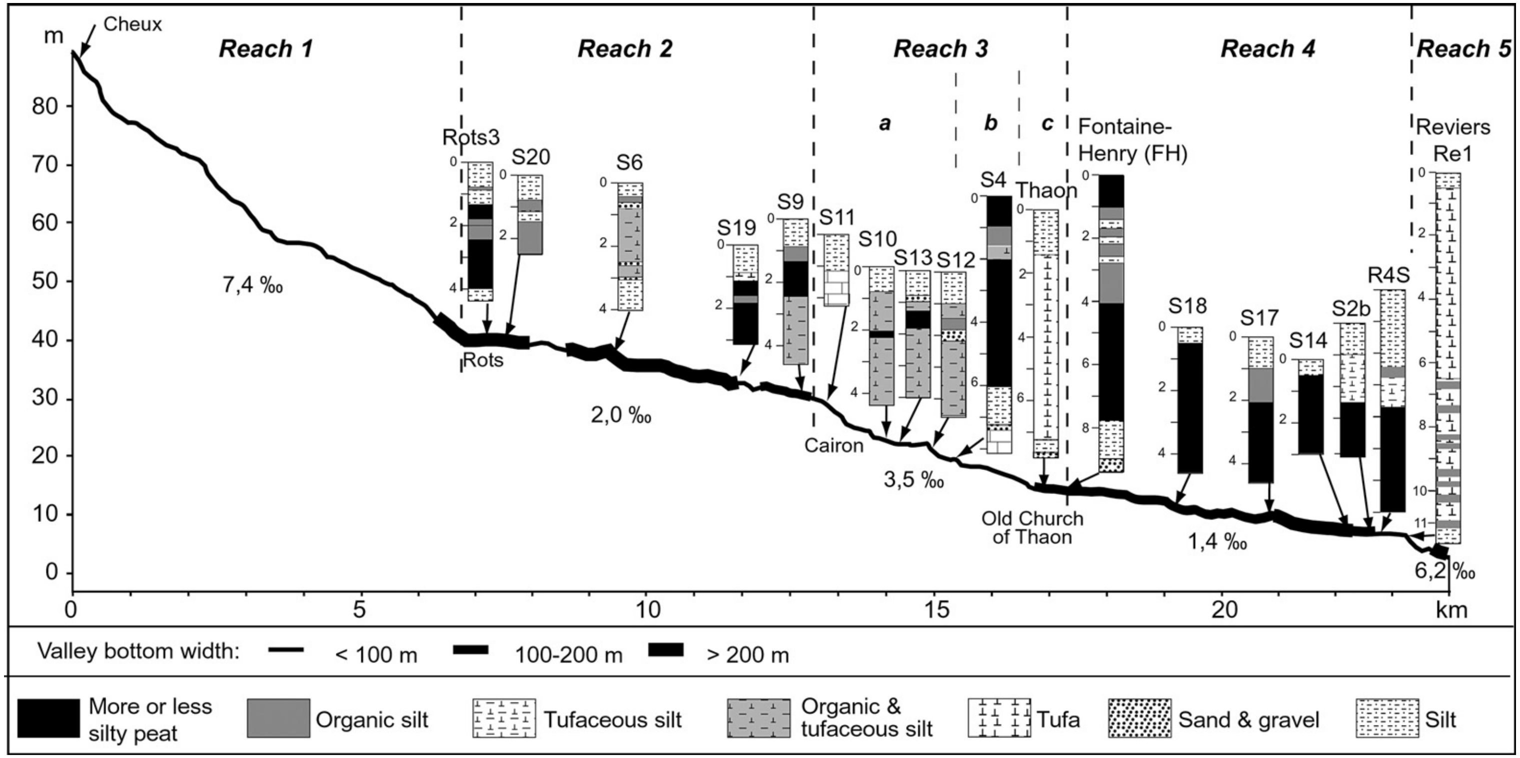

Fig. 2. Holocene sedimentation in the Mue valley bottom indicating the longitudinal arrangement of deposition.

Table 1
Information on the Mue Valley samples submitted for radiocarbon dating

Location	Lab. code	Core drilling	Depth (m)	Materials	Methods	Dates ^{14}C BP (1 σ)	Δ ^{13}C %O	Calibrated dates BP (2 σ)
Thaon-Colonie de vacances	Gif-11716	S3	3.17–3.28	Peaty silt	Conventional	4535±60	−28.26	3496–3026 BC
Thaon-Colonie de vacances	Gif-11714	S3	1.90–1.98	Peaty silt	Conventional	3300±40	−28.05	1686–1462 BC
Thaon-Old Church	Erl-6604	Thaon	7.20–7.30	Shell *Cepea*	AMS	9214±68	−12.4	8607–8287 BC
Thaon-Old Church	Erl-6605	Thaon	1.79–1.89	Shell *Cepea*	AMS	5220±69	−12.5	4243–3806 BC
Fontaine–Henry	Gif-11175	FH11	2.47–2.65	Organic silt	Conventional	7740±80	−23.1	6976–6423 BC
Fontaine–Henry	Gif-11711	FH14	2.40–2.50	Organic silt	Conventional	3245±40	−27.78	1675–1429 BC
Fontaine–Henry	Gif-11713	FH25	2.90–3.00	Organic silt	Conventional	5030±65	−25.91	3962–3669 BC
Fontaine–Henry	Gif-11864	FH	7.71–7.75	Peat	Conventional	4475±40	−28.68	3351–2942 BC
Fontaine–Henry	Gif-11868	FH	5.05–5.10	Peat	Conventional	3150±45	−29.65	1518–1316 BC
Fontaine–Henry	Gif-11867	FH	3.96–4.01	Peat	Conventional	2420±40	−28.6	762–398 BC
Fontaine–Henry	Gif-11865	FH	1.45–1.52	Peat	Conventional	1500±45	−28.3	436–643 AD
Reviers	Erl-6608	Reviers	11.24–11.30	Organic silt	AMS	7715±66	−28.1	6651–6438 BC
Reviers	Erl-6607	Reviers	8.45–8.53	Organic silt	AMS	5989±50	−28.9	4996–4726 BC
Reviers	Erl-6606	Reviers	6.75–6.80	Charcoal	AMS	5315±45	−29.7	4317–3999 BC
Cairon	Erl-6790	Cairon	1.98–2.02	Organic silt	AMS	8102±58	−28.3	7321–6829 BC
Cairon	Erl-6789	Cairon	1.78–1.81	Peat	AMS	6695±49	−29.2	5713–5487 BC
Cairon	Erl-6788	Cairon	1.56–1.59	Peat	AMS	6242±49	−29.0	5316–5059 BC
Cairon	Erl-6787	Cairon	0.78–0.82	Peat	AMS	5108±47	−29.4	4033–3791 BC

Calibrated age according to CALIB rev. 4.3. (Stuiver and Reimer, 1993).

contamination, recent studies highlight the potential value of pollen data obtained in floodplain fens to reconstruct the environment of the valley bottom and surrounding areas (Leroyer, 1997; Brown, 1999). Continuous sampling at 4–15 cm intervals was adopted for malacological study of the Thaon core (30 samples) following methods developed at Saint–Germain–Le-Vasson, which is located some 40 km southward (Limondin-Lozouet and Preece, 2004).

The chronology is based on archaeological remains and radiocarbon dating. Twenty-one organic samples were analysed for radiocarbon dating (shells, plant remains, charcoal, total organic mater). Twelve have been obtained by conventional methods at LSCE (Gif/Yvette, France) and nine by the Accelerated Mass Spectrometry (AMS) method at the Physikalisches Institut of Erlangen (Germany). Use of organic sediment from fluvial deposits and shell carbonate for dating may introduce complications because of the potential of reworking, contamination and the hard water effect. To improve the chronological framework, we used *Cepaea* shells which incorporate minimal quantities of ancient carbon from bedrock sources and which are generally considered ideal for dating purposes (Limondin-Lozouet and Preece, 2004). Sediment dating was validated by correlation with local and regional pollen records (Clet-Pellerin and Verron, 2004; Lespez et al., 2005b). Data are quoted in ^{14}C BP in the text, and calibrated age ranges according to Calib. Rev. 4.3. (Stuiver and Reimer, 1993) are given in Table 1.

4. Results

The Holocene sediments are 4 to 12 m thick from Rots (upstream) to Reviers (downstream). They are characterized by low lateral variability, which is observed in most of the cross-sections whereas heterogeneity of the longitudinal arrangement and the sedimentary facies is high. A classification based on mean grain size and the sorting index of Folk and Ward (1957) provide evidence of seven facies (Fig. 3 and Table 2). The mineral deposits are not well developed in the valley bottom and the sediment is mainly characterized by carbonate or organic deposits. The carbonate deposits are related to the high content of dissolved load of the river water caused by spring activity and the Ca-rich ground water supply, while the organic deposits are explained by the extension of floodplain fens related to a high water level in the valley bottom.

4.1. Longitudinal pattern of the alluvial filling at the valley scale

Along the Mue valley and its tributaries, we observed seven distinct morpho-sedimentary reaches (Figs. 2 and 4). The chronozones used in the presentation of the results correspond to those defined by Mangerud et al. (1974), widely used in the Paris basin (Leroyer, 1997; Pastre et al., 2001; Clet-Pellerin and Verron, 2004).

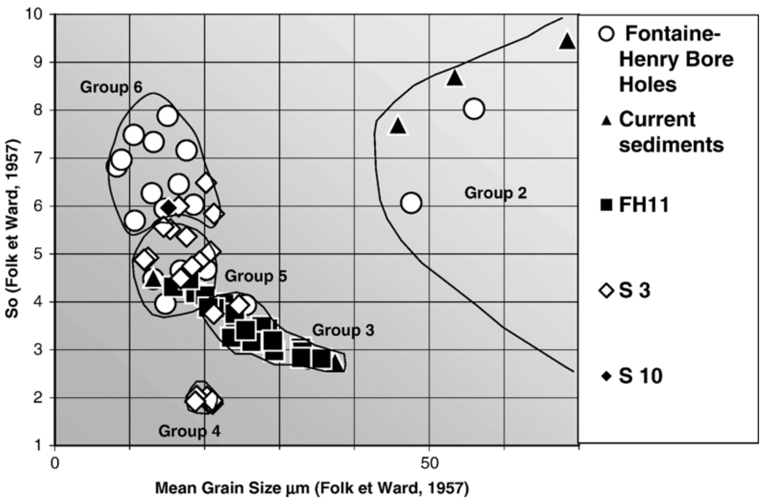

Fig. 3. Sedimentary facies in relation with grain size analyses.

4.1.1. Reach 1

Along the upper Mue and the Chironne, the Holocene deposits are less than 2 m thick and correspond mainly to colluvial silts. Along the Vey, the deposits are also 2 to 2.5 m thick but they are more organic sediments. In the core drillings at Cairon, we have identified four stratigraphic units with radiocarbon dating control. The bottom unit corresponds to grey-green sandy silts which indicate a fluvial dynamic. Between the end of the Boreal (8102±58 ^{14}C BP) and the beginning of the Atlantic periods (*post* 6695±49 ^{14}C BP), it is covered by peat layers, organic silts and organic silts with oncoids. During the end of the Atlantic (6242±49 ^{14}C BP) and the beginning of the Subboreal (5108±47 ^{14}C BP), the valley bottom is characterized by peat deposits in a floodplain fen. After, colluvial silts have totally covered the valley bottom.

4.1.2. Reach 2

Along this reach, sedimentation is mainly developed in the valley axis where it reaches 4 m. In the absence of radiocarbon dating, the dating control is not accurate but a general chronological pattern is provided by the palynostratigraphy of two core drillings and particularly the appearance of walnut and the recent development of pine (Rots 1&3, Lespez et al., 2005b). At the bottom, a coarse alluvial deposit (sand and gravel, U1) has been covered by grey silts (U2). Then, the reach is alternately characterized by organic and tufaceous sediment. Peat and organic silts have been deposited during the Atlantic (U3a) and the Subatlantic periods (U5). They are often interrupted by a calcareous silt layer (U4). Tufaceous sedimentation is mainly comprised of poorly sorted, multimodel silts, rich in oncoids (U3b). Finally, the valley bottom was covered by colluvial and overbank silts (U6).

4.1.3. Reach 3a

Upstream, this reach begins with a section where Holocene sedimentation is very low (S11) but, downstream, it becomes more complex and deeper up to 5 m. From Cairon to Thaon, we observe a succession of six sedimentary units in the filling. At the base, on S24 a sandy silt layer (U1) is covered by grey silts (U2). But the bulk of the sediment corresponds to whitish calcareous silts with numerous oncoids and fine layers of organic silt or peat (U3). A date obtained (4535±60 BP ^{14}C BP) in the middle of this unit (S3) indicates the Suboreal period for its deposition. It is often bounded by an organic layer (U4) dated at the end of the Subboreal on S3 (3300±40 ^{14}C BP). Overlaying this we often observed a whitish calcareous silt layer (U5) before sedimentation returned to more organic deposits (U6). The Holocene stratigraphy is closed by a silty sediment which fills the valley bottom (U7).

4.1.4. Reach 3b

From the confluence with the Chironne to the Old Church of Thaon, the sedimentation is mainly organic.

Table 2
The different sedimentary facies and alluvial environments in the Mue Valley

	Facies	Alluvial environment
Group 1	Tufaceous sands (oncoids)	Unattached travertine Spring, channel margin
Group 2	Alluvial sands	Channel
Group 3	Overbank silts	Floodplain
Group 4	Fine silts	Marsh, waterholes
Group 5	Fine and organic silts	Marsh
Group 6	Heterometric tufaceous sediment	Channel margin, backswamps
Group 7	Peat	Marsh

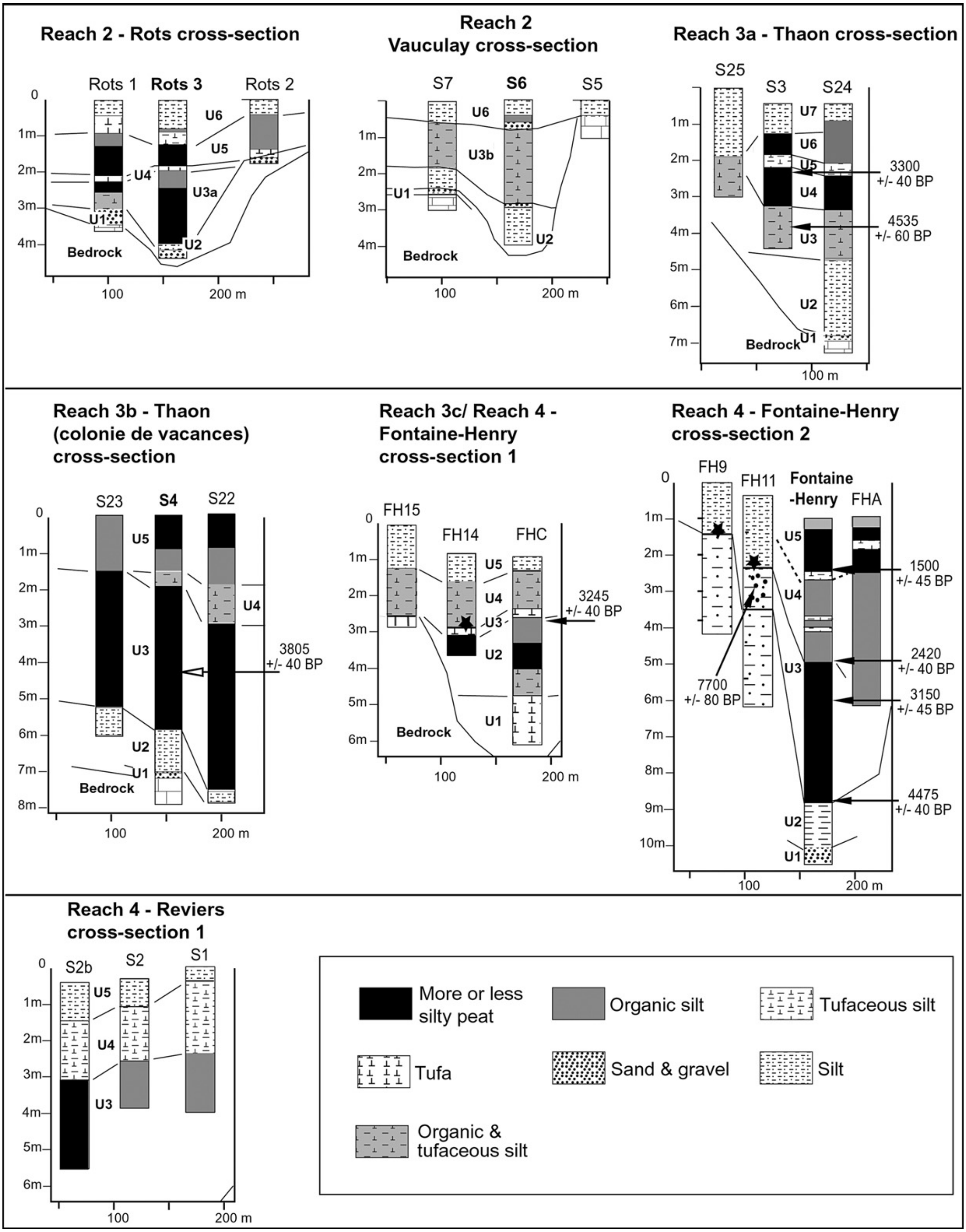

Fig. 4. Simplified cross-sections in the Mue valley bottom from upstream (reach 2) to downstream (reach 4).

In detail, we observe 5 sedimentary units. The limestone is covered, locally (S4), by a sandy silt layer (U1) and by grey silts (U2). However, the main Holocene sedimentation corresponds to peat and organic silts of 3.5 to 5 m thickness (U3). Such sediment has been deposited during the Subboreal and the Subatlantic periods in accordance with a radiocarbon age (3805±40 ^{14}C BP) obtained from the middle of this sequence. The sedimentation becomes progressively siltier (U5) and we observed silt layers with fragments of oncoids intercalated in the organic sedimentation (U4) as in reach 3a. Finally, a silt sedimentation has filled in the valley bottom except in some places where the sedimentation remains organic (U6).

4.1.5. Reach 3c

Downstream, at the bottom of the Old Church of Thaon, the sedimentation corresponds mainly to tufa deposits (Figs. 5 and 6). The core drilling of Thaon presents five sedimentary units. Calcareous gravel and cobbles in a greyish sandy matrix (U1) are bounded by grey silts (U2). A date (9214±68 ^{14}C BP) gives a Preboreal age for this unit. These are overlain by tufaceous sediments, which have built a large unattached travertine deposit which occupies the entire valley bottom. At first, the sedimentation corresponds to oncolitic facies, mainly constituted by fragments of oncoids, interbedded with thin silty layers (U3). Then, we noted a coarser deposit, with spherical and cylindrical oncoids predominant (U4). This sequence is dated to the Boreal and the Atlantic periods by a radiocarbon dating (5220±69 ^{14}C BP) obtained at the top. The tufaceous sediment is covered by grey silts, more or less organic or carbonated (U5).

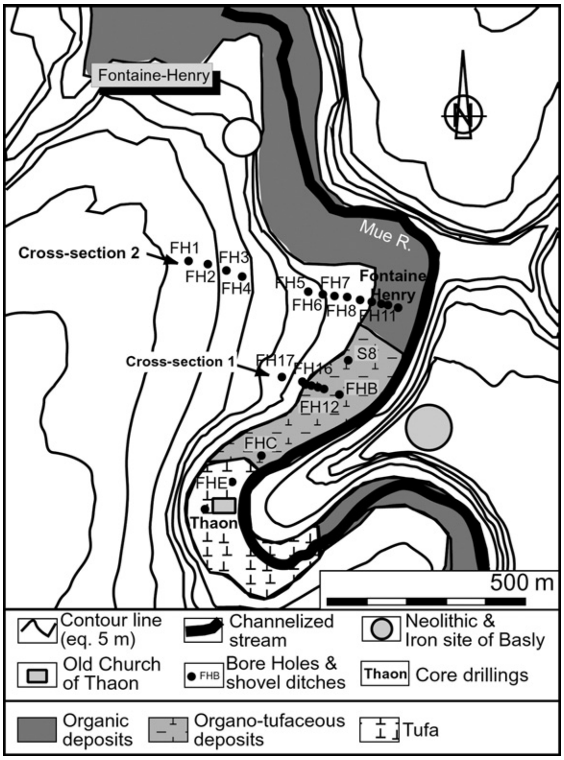

Fig. 5. Bore holes and core drilling locations and main Holocene sedimentation in the valley bottom from the end of the third to the fourth reaches.

4.1.6. Reach 4

Along 6 km, the sediment is mainly organic. The core drilling at Fontaine–Henry enables us to observe five sedimentary units. At the base, calcareous gravel and cobbles in a greyish sandy matrix (U1) are bounded by grey silt (U2). These are overlain by organic sediment which fills in the entire valley bottom and can reach 7 m (U3). The lower sediments in this unit are a fibrous peat radiocarbon dated to the second part of the Subboreal (4475±40 and 2420±40 ^{14}C BP, Fontaine–Henry) in accordance with the pollen assemblage identified at R4S. This was then followed by the deposition of organic silts, often alternating with minerogenic or tufaceous silts (U4). Finally, a silty sediment has filled in the valley bottom except in some places where the sedimentation remains organic and in some places peaty (U5).

4.1.7. Reach 5

This reach corresponds to the tufa deposit of Reviers. Core Re1 has five sedimentary units and improved results obtained by previous studies (Clet-Pellerin et al., 1990). At the base, we observed sandy grey silt covered by more fine dark grey silt. Tufa sediment then built a huge unattached travertine deposit which takes up the entire valley bottom as in reach 3c. The sediment is of fine tufaceous oncolitic layers (30–50 cm) alternating with organic silt or peat (5–10 cm). This sequence is Atlantic, as testified by 3 radiocarbon dates (with ages ranging from 7715±60 to 5315±60 ^{14}C BP). Overlaying this is a coarser deposit where the spherical oncoids are predominant with several thin organic layers. This unit belongs to the Subboreal and Subatlantic periods, as suggested by the palynostratigraphy. Finally, the tufaceous sediment is covered by silt.

4.2. Longitudinal pattern at the local scale, from tufaceous to organic infilling

Several core drillings with palynological data and radiocarbon dating control allow an understanding of the succession of tufaceous to organic deposits from the third to the fourth reaches (Fig. 5). The onset of the tufaceous sediment at Reviers is dated from the Boreal period. The vertical accretionary trend is maintained to the Atlantic, while organic sediment developed upstream is mainly dated to the Subboreal. Consequently, the organic sedimentation is probably in relation to a higher water level in the valley bottom partly caused by the tufaceous barrage, which progressively made drainage more difficult. Downstream, the transition from tufaceous to organic sedimentation is progressive (Figs. 5 and 7). Along 0.5 km, the Subboreal sedimentation is composed by silts and oncoids which come from the erosion of oncolithic sediments, and by organic silts which indicate their deposition in a fen floodplain. Further downstream, sedimentation is mainly organic.

4.3. Valley bottom environmental changes: contribution of multi-proxy data

4.3.1. The pollen data

The pollen analyses have been undertaken on seven core-drillings in the Mue valley and the detailed results are published in Clet-Pellerin et al. (1990) and Lespez et al. (2005b). The main data are summarized in Fig. 8 and highlight water level changes and human impacts on the vegetation cover of the valley bottom and slopes. During the first part of the Holocene, alder-hazel woodland was probably surrounded by mixed oak woodland. But, in the valley bottom, the environment was never totally forested because the wetlands experienced specific vegetation. Three periods are characterized by spreading of wetland vegetation cover in relation with a high water level: 5200–4800 ^{14}C BP at Rots and Reviers, 2900–2200 ^{14}C BP and 1500–1000 ^{14}C BP at Fontaine–Henry and Rots.

Human impact on the vegetation cover was deduced from the occurrence of ruderal, meadow, pasture and cultivated plants in the pollen diagrams. During the Boreal and the Lower Atlantic periods the ecological impact of Mesolithic peoples was very limited. At the end of the Atlantic, the impact of the Early and Middle

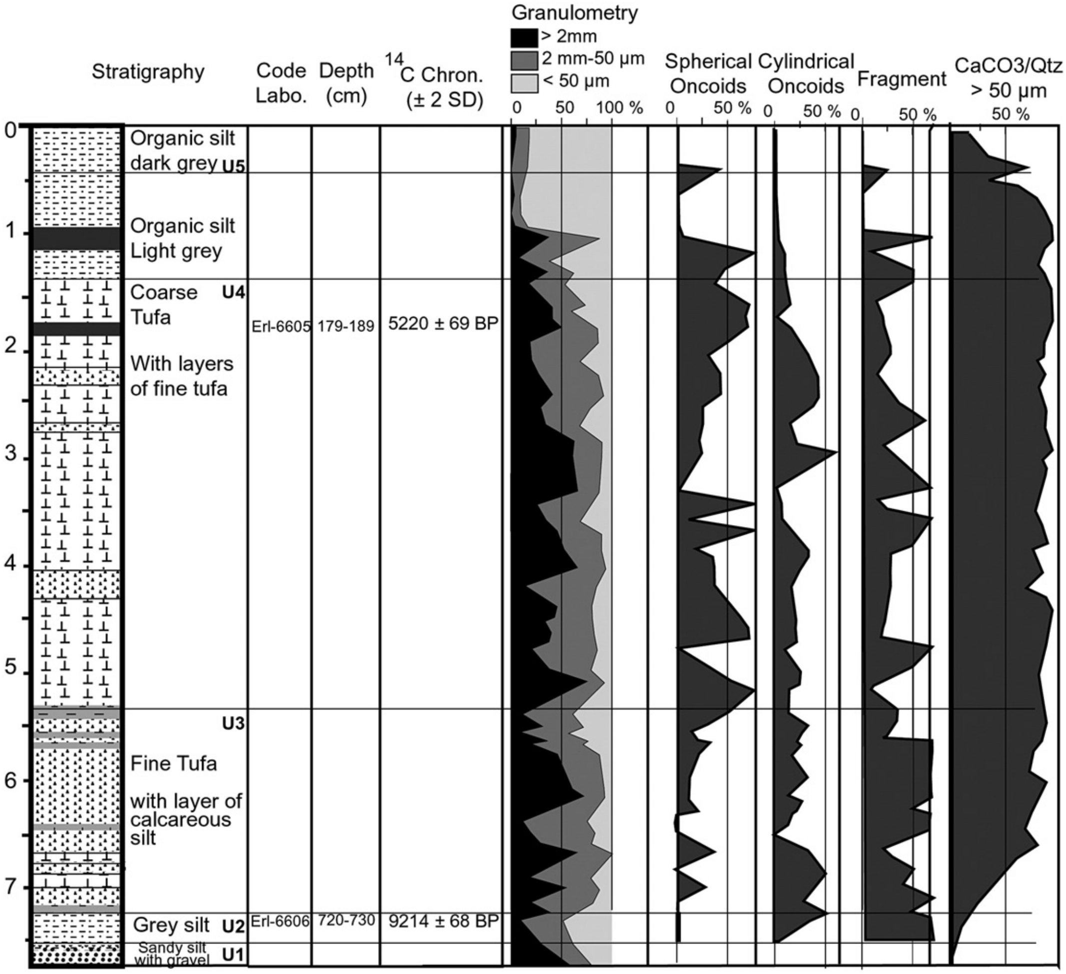

Fig. 6. Chronostratigraphy and sedimentological analyses of the Thaon core.

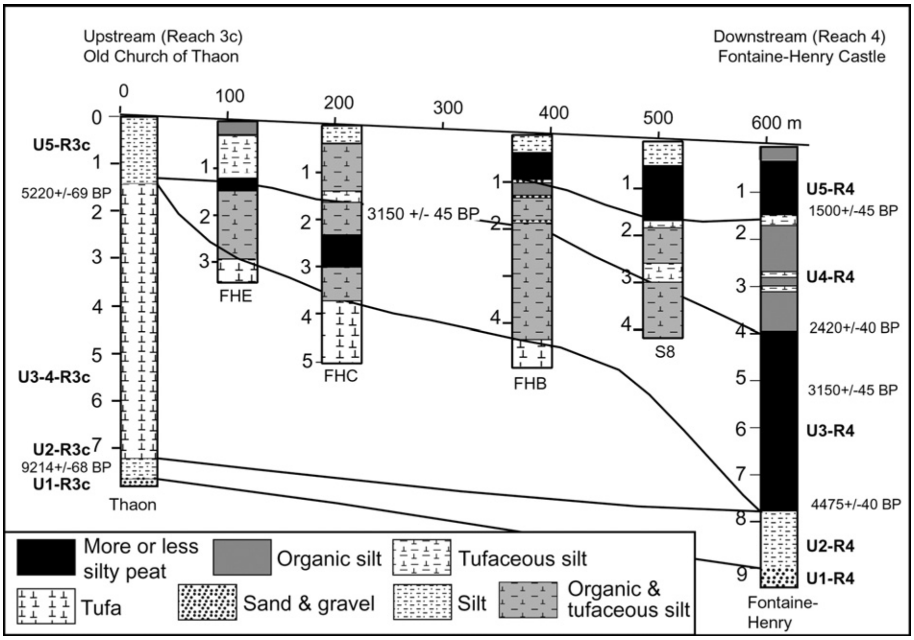

Fig. 7. Longitudinal morphostratigraphic cross-section from the third to the fourth reaches.

Neolithic (5700–5200 ^{14}C BP) has been detected locally near the archaeological sites of Rots and Cairon by increases of ruderal plants and the first occurrence of cereals (Lespez et al., 2005b; Ghesquière and Marcigny, in press). However, during the Late Neolithic, the clearance episodes were probably localised in time and in space: the pollen data suggest small-scale temporary clearances with regeneration. From the Middle Bronze Age, ruderal and meadow plants appear frequently and the presence of cereal is regularly testified. The Bronze Age is a period of widespread but localised vegetation change. The main period of forest clearance and lasting land use change in the valley bottom is the Iron Age, as observed in many valleys of Normandy characterized by systematic clearance (Clet-Pellerin and Verron, 2004; Lespez et al., 2004). After this period the entire river basin was cultivated, and fallow land and wooded areas were scarce.

4.3.2. The malacological data

The biostratigraphy of the tufa deposits of Thaon follows the Holocene molluscan succession established at Saint–Germain–Le-Vasson (Limondin-Lozouet and Preece, 2004). Molluscan assemblages allow us to define five biozones illustrating evidence of local changes in the valley bottom environment. The detailed results of the malacological analyses are published in Lespez et al. (2005b). During the Boreal, snail assemblages indicate a patchy environment with woody areas and grassland. During the main part of the Lower Atlantic, low numbers of shells and predominance of aquatic species may indicate an increase in flood frequency. During the Upper Atlantic molluscan populations allow us to recognize a composite landscape, mixing grassy areas and wooded patches. No clear indications of human impact on the local environment are registered by malacofaunas despite the proximity of several archaeological sites of the Late Neolithic. The Late Atlantic has faunas characterized by aquatic and marshy species. They might be related to a palaeohydrological oscillation around 5000 year ^{14}C BP identified in the palynological data. Following this period molluscan assemblages are dominated by open-ground snails. This allows us to recognize a more open environment and the decline of forested areas, suggesting a stronger impact of human activity, although onset of this episode remains unclear due to the lack of accurate dating controls.

5. Discussion: Fluvial system adjustments to climatic, human and autogenic controls and comparison with northwest European river systems

5.1. Preboreal and Boreal (10,000–8000 ^{14}C BP)

Along the valley, Late Pleistocene fluvial sands and gravels are covered by grey silts (Fig. 9). Most of these sediments come from the erosion of the loess widely deposited on the plateau and valley bottom. They

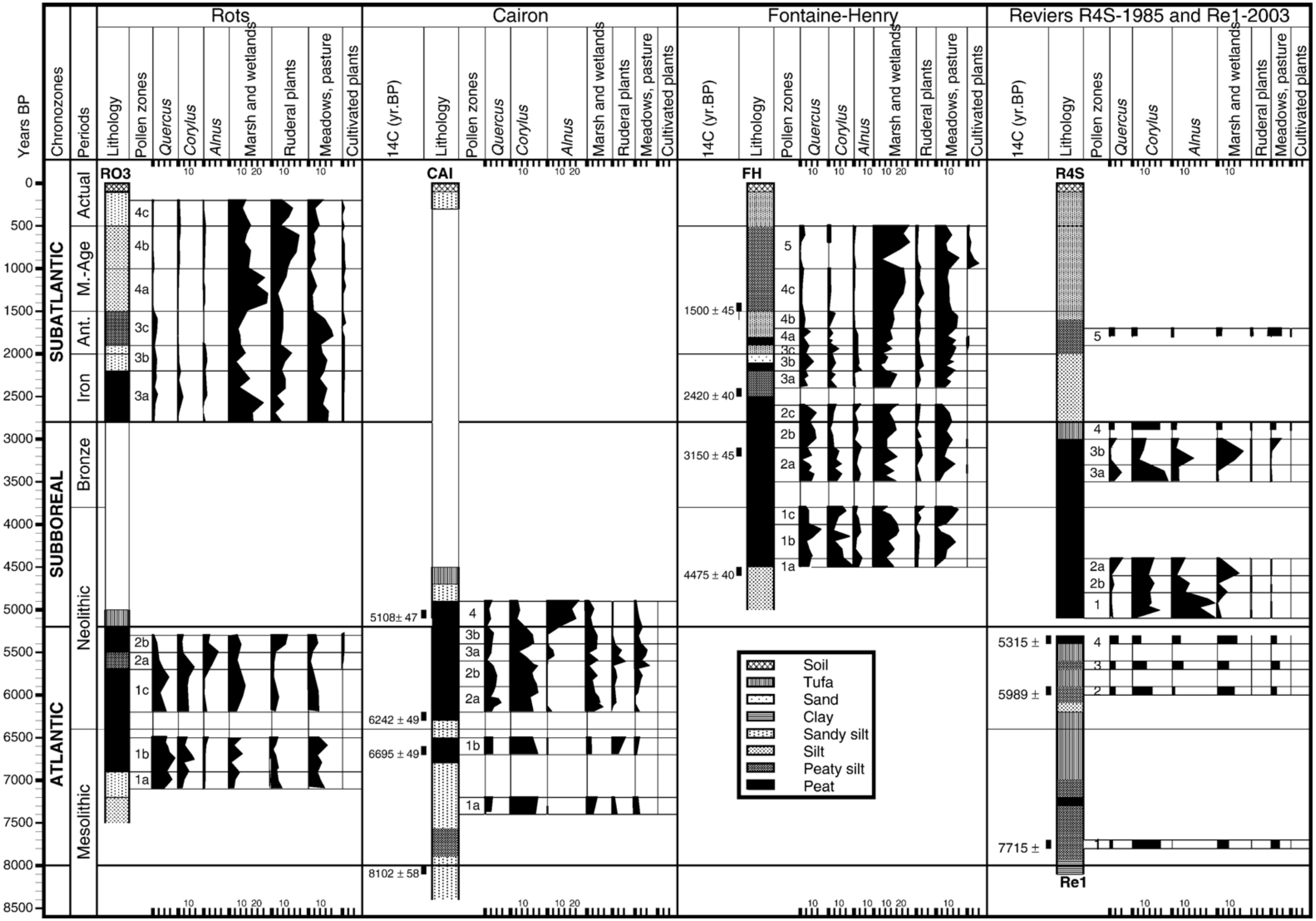

Fig. 8. Core drillings in the Mue valley and simplified pollen diagrams (% calculated from total number of pollen grains, fern and aquatic plants excluded).

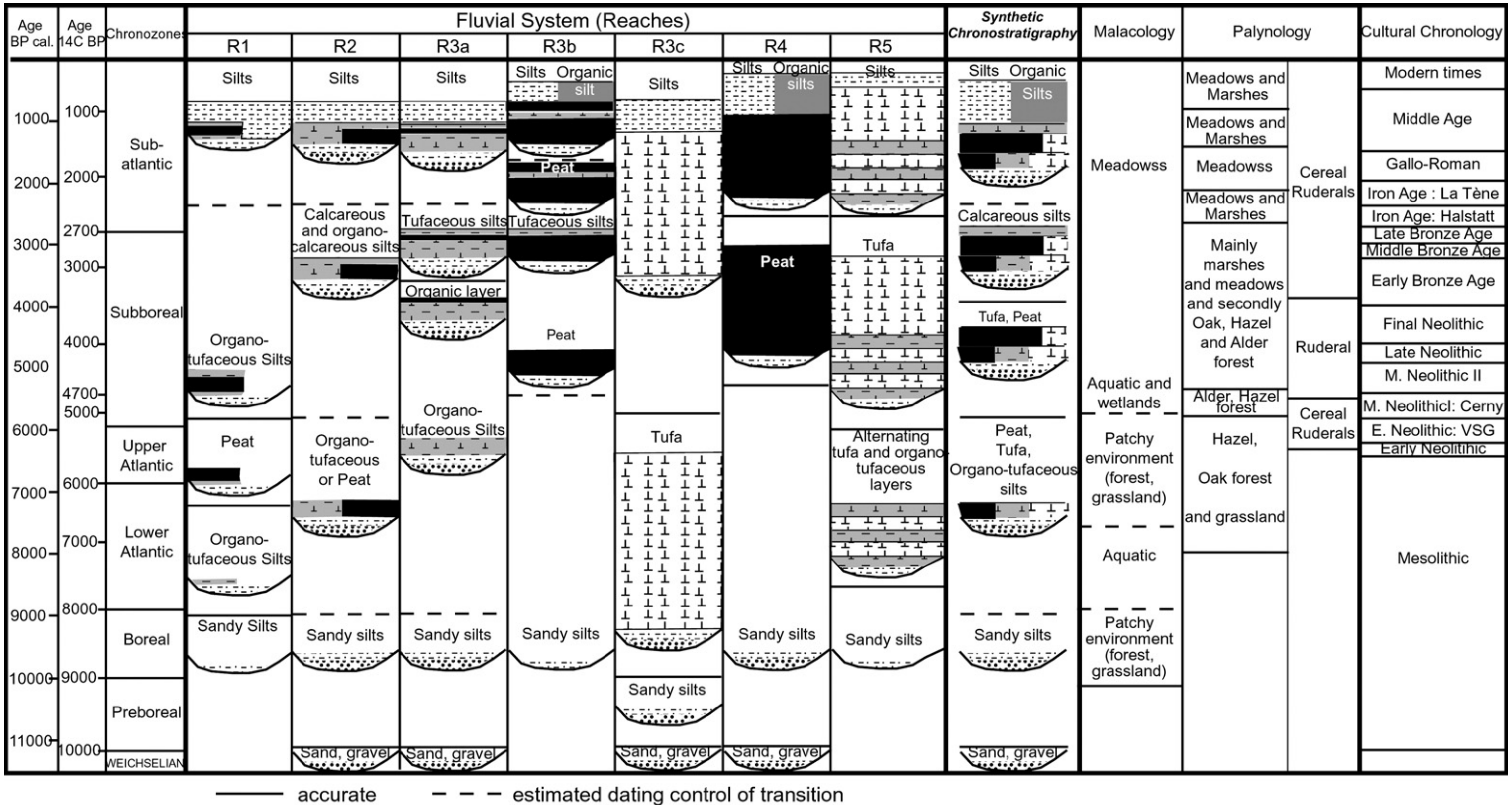

Fig. 9. Synthetic diagram of palaeoenvironmental changes in the Mue valley during the Holocene.

correspond mainly to overbank deposits related to a well defined stream, probably a meandering system, while the environment of the valley bottom was composed of wood and grassland patches, as indicated by the malacological assemblages. The fluvial system functions as a continuum from upstream to downstream and the valley bottom still experienced good drainage. The development of floodplain backswamp areas, which has characterized many valley bottoms of southern England and northwest Europe (Brown, 1995; Pastre et al., 2001; Antoine et al., 2003; Collins et al., 2006), was experienced later in the Mue valley. Locally, we observe the onset of tufa deposits which is more widely registered in valleys of the Paris basin (Antoine et al., 2003), lowland Britain and western Europe (Brown, 1997; Collins et al., 2006).

5.2. Lower Atlantic (8000–6500 ^{14}C BP)

The travertine deposit of Thaon is the first element of the calcareous sediment that occurs in several areas of the valley bottom. Tufa formation indicates suspended load decreasing, whereas dissolved load becomes the predominant discharge in the fluvial system. This is explained by the stabilization of the slopes in a well-forested environment which minimizes runoff and the supply of fine-grained material into the valley (Pastre et al., 2001). In the Beuvronne valley, Orth et al. (2004) show that the quartz content of the valley bottom filling is less than 1% during this period. The increase of dissolution is related to soil formation, spring activities and higher water tables. The calcareous sediment is often interbedded with organic layers which are related to the increase of marshy areas. This period appears as the local sedimentary signature of the Holocene Climatic Optimum. Impacts of the Neolithic populations on the river system remain low. The building of the main unattached travertine of Thaon and Reviers is responsible for the major discontinuity of the fluvial system. This valley bottom architecture underlines the role of geological setting as observed in many small river systems of lowland sedimentary areas in northwest Europe (Pedley et al., 2000). However, organic sedimentation appears predominant in the Paris basin (Pastre et al., 2001, 2003; Antoine et al., 2003; Orth et al., 2004), lowland Britain and more generally in western European valleys (Brown, 1997; Gibbard and Lewin, 2002).

5.3. Upper Atlantic and Lower Subboreal (6500–4500 ^{14}C BP)

During the Upper Atlantic, the peak of tufa sedimentation was reached, as in most northwest European regions (Goudie et al., 1993; Pedley et al., 2000; Pentecost, 2005). Nevertheless, organic sedimentation increased in the valley bottom. This is explained by a higher water table. This sedimentation pattern indicates an inactive meandering or anastomosing river system. The river would not have had the power to migrate freely in the dense alder floodplain woodland of the Lower Subboreal as in British valleys (Brown, 1995). Despite the importance of Middle Neolithic settlement in the river basin, pollen indicates that woodland clearance seems to have been scarce and temporary on the valley bottom and on surrounding slopes. Consequences of human activities appear only locally, in the immediate vicinity of archaeological sites. Very low sedimentological changes in relation with human activities are observed in the Mue valley during the Atlantic and the Lower Subboreal periods, like in most of British valleys (Macklin, 1999; Collins et al., 2006). In contrast, they are more clearly recorded in other areas of the Paris basin where lateral erosion processes, silt and sand deposits are observed, even if they have still little impact on channel dimensions and geometry (Pastre et al., 2001).

5.4. Middle part of the Subboreal (4500–3500 ^{14}C BP)

During the middle part of the Subboreal, we observe the generalization of sedimentation along all the reaches. If the unattached travertine barrage of Reviers was still active, tufaceous sedimentation had ended at Thaon. More generally, organic sedimentation (organic silts and peat) became predominant. In the valley bottom, the abrupt decrease of the alder swamp forest could be related to the development of open grassland and pasture (Brown, 1997). In the surrounding areas, forest cover changes are more difficult to identify while the available archaeological data indicate numerous settlements on the plateau during the Late Neolithic (Clet-Pellerin and Verron, 2004). Therefore, fluvial activity remained low, probably in relation to low flood discharges and low level of soil erosion and colluvial transfer. During this period, autogenic control was the dominant-controlling factor related to the travertine deposits which created discontinuities in the valley bottom. The increase of brown silts, related to impacts of Neolithic and early Bronze Age populations, and recorded in the other parts of the Paris basin (Pastre et al., 2001), is not experienced in the Mue fluvial system.

5.5. Late Subboreal (3500–2800 ^{14}C BP)

This period is characterized by important changes in the fluvial system. Within reaches 2, 3b and 4, organic sediments are often covered by a poorly sorted and multimodal tufaceous silt sediment. It suggests erosion of tufaceous sediments of the valley bottom and of loamy soils developed on the plateau. It implies also well-defined streams and powerful flows, probably in a meandering system. The radiocarbon dates obtained at the bottom of these deposits within the third and fourth reaches indicate an age *post* 3300±40 ^{14}C BP and 3245±45 ^{14}C BP. This short fluvial change can be explained by the convergence of climatic and anthropogenic factors. Indeed, it is contemporaneous with a wet oscillation around 3500–3000 ^{14}C BP experienced in northwest Europe (Magny, 1992; Barber et al., 2003) and well documented by the fluvial systems of the Paris basin (Pastre et al., 2001, 2006) and Great Britain (Lewin and Macklin, 2003; Lewin et al., 2005). Furthermore, the higher suspended load supply can be related to an increase of land use changes, testified by the onset of cereals and the development of ruderal and meadow plants in pollen diagrams (Fig. 8). Moreover, the archaeological data indicate a more dense settlement pattern during the Middle Bronze Age and the beginning of the Late Bronze Age (Marcigny et al., in press). Such a hypothesis is in accordance with research conducted in the central part of the Paris basin (Pastre et al., 2001, 2006) and more generally in northwest European valleys, where accelerated fine alluviation took place and is often associated with land use controls coupled with erosive storms or climatic oscillation (Brown, 1997; Pastre et al., 2006; Collins et al., 2006).

5.6. Subatlantic (post 2800 ^{14}C BP)

The number and the size of floodplain swamps greatly decreased. The valley bottom experienced silt sedimentation mainly constituted by overbank and colluvial deposits. Floodplain vertical accretion was enhanced by accelerated soil erosion and production of fine sediments resulting from anthropogenic influences. This change has also been observed in the Seulles floodplain, where 3 to 4 m of overbank sediment were deposited after 2241 ±41 BP (Lespez et al., 2006). The farming of the river basin was probably complete as testified by the pollen diagrams of the valley and more generally in Normandy (Clet-Pellerin and Verron, 2004; Lespez et al., 2004). Furthermore, numerous small settlements are testified from the Late Bronze age and the beginning of the Iron Age (Hallstatt) on the plateau. In addition, during the La Tène period, archaeological data and carpological remains (cereal, leguminous plants) indicate complete settlement of the river basin with groups of big farms which controlled several hundred hectares of cultivated land (San Juan et al., 1999). Nevertheless, the onset of this change can also be related to a conjunction with a wet oscillation, locally witnessed by the available pollen data and more generally registered in northwest Europe (Magny, 1992; Van Geel et al., 1996; Barber et al., 2003) and experienced by numerous fluvial systems (Pastre et al., 2001; Lewin and Macklin, 2003; Pastre et al., 2006), including those of the western Paris basin (Larue, 2002; Sebag, 2002; Germain-Vallée and Lespez, 2006). The land use change exceeded a threshold which rendered the fluvial system more sensitive to large scale climatic changes or individual hydrological events. The fluvial system once again became a continuum without significant changes from upstream to downstream. This was reinforced during the last millennia by the control of the flow to supply the numerous water-mills built along the river (Lespez et al., 2005a).

During the first part of the Subatlantic period (Iron Age and Roman period) increasing alluviation, related to soil erosion, was widespread throughout the Paris basin (Kuzucuoglu et al., 1992; Pastre et al., 2001, 2006) and northwest Europe (e. g. Brown, 1997). Therefore, important variability in alluvial records reflects catchment conditions and human intervention within the river channel. For example, in other parts of the Paris basin, the development of peat deposition is still registered in many small tributaries during the first part of the Subatlantic period (Pastre et al., 2001, 2006). At least, during the Middle Ages, floodplain management explains why a small lowland river in northwest Europe has experienced restricted channel change (Brown, 1997). In contrast, major and upland river systems are still sensitive to climate-related variations such as the Little Ice Age (Macklin, 1999; Pastre et al., 2001; Gregory et al., 2006).

6. Conclusion

Research undertaken in the Mue valley gives for the first time a precise chronostratigraphical pattern of Holocene alluvial filling in the Plain of Caen and more generally in Normandy. It allows comparisons with both sides of the English Channel. The Mue valley record is broadly similar to other fluvial systems of the Paris basin and lowland Britain (Pastre et al., 2001; Brown, 1997; Gibbard and Lewin, 2002) but presents particular features, especially in relation to its limestone catchment, important groundwater supply and high solute load.

The longitudinal pattern appears particularly complex. During the Boreal and Subatlantic, the system was a continuum with a well-marked stream. In contrast, the variability of the longitudinal arrangement was high from around 8500 until 3500 ^{14}C BP. Thus, the impact of climatic oscillations on the river system is difficult to demonstrate because of the low stream power and the limited slope-channel coupling. The role of the travertine barrage in the triggering of organic sedimentation was identified, indicating an autogenic control. From 3500 ^{14}C BP, the fluvial system changed completely, with human control appearing dominant. Land use effects explain the increase of suspended load. Flow turbidity is one of the main factors which explain the "Late Holocene Tufa decline" registered in the Mue valley, as in other European areas (Goudie et al., 1993). Nonetheless, as tufaceous sedimentation reached its peak around 5000 ^{14}C BP, palaeohydrological influences can also be invoked due to the lowering of the water table during the second part of the Holocene. After 2800 ^{14}C BP, the fine mineral sediment supply has prevented organic and tufaceous sedimentation in most of the valley bottom. Furthermore, this land use change increases the potential sensitivity of the catchment to climatic oscillations and individual hydrological events, as the river system became once again a continuum due to the efficiency of slope-channel coupling and the transport capacity of stream flows. However, since the medieval period, the coupling between slopes and stream was progressively broken, especially due to river management associated with the water mills system.

Small order river systems located in a limestone catchment, characterized by low fluvial dynamics and fluvial pattern changes during the last millennium, appear homogenous and relatively simple to understand. However, research on the Mue valley has demonstrated spatial and temporal complexities for such fluvial systems. This implies the necessity, when undertaking floodplain palaeohydrological research, to take into account (1) the balance between surface runoff and groundwater supply and (2) longitudinal discontinuities resulting from tectonic pattern, geomorphological heritage and/or autogenic controls.

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