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Morphological and sedimentary evolution of an alluvial floodplain in an urban area: geoarchaeological approaches and applications (Tours, France)

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ABSTRACT

Urban zones on alluvial plains offer considerable geoarchaeological potential for understanding river dynamics over large time spans and their relationship with land use, because of the extensive subsoil data that is available. In the alluvial plain of Tours, lying between the Loire and the Cher, multidisciplinary studies of the relationships between societies and environment have been conducted as part of an archaeological research programme launched in the 1960s. A sedimentary database containing data for 1309 surveys has been compiled and assembled in a geographic information system to produce geostatistical models of valley bottom geomorphology. The stratigraphy and chronology of alluvial filling have also been studied with information and C14 and OSL dating obtained during archaeological operations. Taken together, the results offer a new interpretation of the morphological evolution of the alluvial plain of Tours from the Weichselian to the present day, by providing new information that either validates or invalidates previous hypotheses: bedrock incision prior to the end of the Weichselian Upper Pleniglacial, coarse sedimentation during the Lateglacial, relative morphological stability up to the late Holocene. The morphological context of the first human settlements, which are not concentrated on the low alluvial reliefs, and the role of urbanization conditions on the present morphology of the valley floor are also presented. This applied study shows the relevance of combining different methodological approaches.

1. Introduction

In urban archaeology, recognizing the geometry of geological formations found under anthropogenic deposits can help understand the morphological framework of the earliest human occupation (e.g. Galinié et al., 2003a; Dominique et al., 2010; Schuldenrein and Aiuvalasit, 2011; Vermeulen et al., 2012). Urban zones situated in alluvial plains, such as Tours, supply many data from geological or geotechnical surveys and archaeological excavations. They thus offer considerable potential for understanding morphological and sedimentary dynamics over several millenia, the constraints they imposed on human occupation, and reciprocally, the consequences of urbanization on the alluvial plain during historical epochs (e.g. Butzer et al., 1983; Fabre and Monteil, 2001; Bravard, 2004; Uribelarreaa and Benito, 2008; Gaillot and Hofmann, 2009). As shown by Arnaud-Fassetta (2011), geoarchaeological studies in alluvial and urban settings reveal in particular the relationships between the hydrosedimentary variations of rivers and the development of the riverside towns (Bravard et al., 1997; Salvador et al., 2002), or the relationships between societies and river-related risks (Berger et al., 2004; Alline, 2007). There have been few studies combining traditional geomorphological approaches (site studies) and geostatistical modelling to produce a spatial reconstruction of the morphological structure of the first human settlements in urbanized alluvial plains (e.g. Dominique et al., 2010).

The ancient open agglomeration of Tours was created during the first half of the 1st c. AD. However, the discovery of an apparently

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vast settlement dating from the 2nd c. BC raises the question of whether there was a Gallic settlement prior to the Roman town (De Filippo, 2007). The former urban space, located within the 17th c. walls on the left bank of the Loire, has been the subject of an archaeological research programme for more than 40 years, providing abundant and robust archaeological documentation (Galinié, 2007). One of the first issues investigated by this programme was the relationship between societies and the environment.

This article presents different geostatistical models reconstructing the geomorphological characteristics of the alluvial plain of Tours (height of the top of the alluvium or of the limestone bedrock, thickness of fine and organic sediment or of anthropogenic deposits). These models are calculated from a sedimentary database using geostatistical analysis in a geographic information system. While the methods have been proven *a priori*, the validity of the proposed models is based on examination and detailed analysis of the data and interpretations using an interdisciplinary approach. The stratigraphy of deposits in the former urban space is also presented. The results were collated in order (a) to reconstruct the main features of the evolution of the alluvial plain of Tours since the Weichselian Pleniglacial, (b) to identify the factors underlying this evolution, and (c) to highlight certain characteristics of societies/environment interaction, defining in particular the physical context and how it was harnessed by the first human settlements.

2. Study area

2.1. Location and geological context

The study sector is situated in France, in the south-west of the Parisian Basin (Fig. 1a), in the urban district of Tours (town hall location: 47°23′26″ N; 0°41′21″ E). It is a stretch of alluvial plain, 6.7 km long and at most 4.5 km wide, the Loire flowing in the north part and its tributary the Cher in the south part (Fig. 1b). This 26.6 km^2 urbanized area is situated in a low-lying valley, bordered in the north and south by fairly steep slopes composed of Upper Cretaceous limestone and argilo-siliceous formations or of Eocene lacustrine limestone (Rasplus et al., 1974). At the bottom of the valley, current altitudes range between approximately 40 m NGF (general levelling of France) in the Loire bed in the west of the study area and 57 m NGF at the site of the buried Roman amphitheatre (Fig. 1b). The width of the valley decreases to 2.7 km at the confluence with the Choisille (Fig. 1b). This is due to the downward movement of Eocene limestone on the hillsides, which is harder than the Turonian limestone, due to faults that are well-known in this sector (Macaire and Mignot, 1979). The bedrock at the bottom of the valley is essentially composed of Turonian limestone, except at the western edge, where it is composed of Eocene limestone.

2.2. Current knowledge about the alluvial plain of Tours

According to Carcaud et al. (2002) and Burnouf et al. (2003), the last major phase of incision of the limestone bedrock by the Loire occurred during the Upper Weichselian Pleniglacial or the Last Glacial Maximum. This was followed until the Late Glacial by a phase of essentially sandy–gravelly sedimentation across the whole width of the valley, producing a multi-channel river pattern. During the Late Glacial–Holocene transition, the Loire and the Cher evolved towards a single-channel system, their paths becoming fixed to the north and south of the alluvial plain respectively. Finer organic sedimentation developed in the abandoned channels from the beginning of the Holocene (Vivent, 1998). The alluvium deposited during the Weichselian and Holocene is essentially sandy, gravelly and clayey silt, the latter granulometric fraction being generally relatively more abundant in the Cher deposits (Burnouf and Carcaud, 2000).

In the former urban space (Fig. 1b), extensive archaeological research has shown the existence of the residual remainder of a low fluvial terrace at the site of the Roman amphitheatre (Gay-Ovejero et al., 2007) and of palaeochannels filled with fine, organic sediment, initially deposited at the beginning of the Holocene (Dubant,

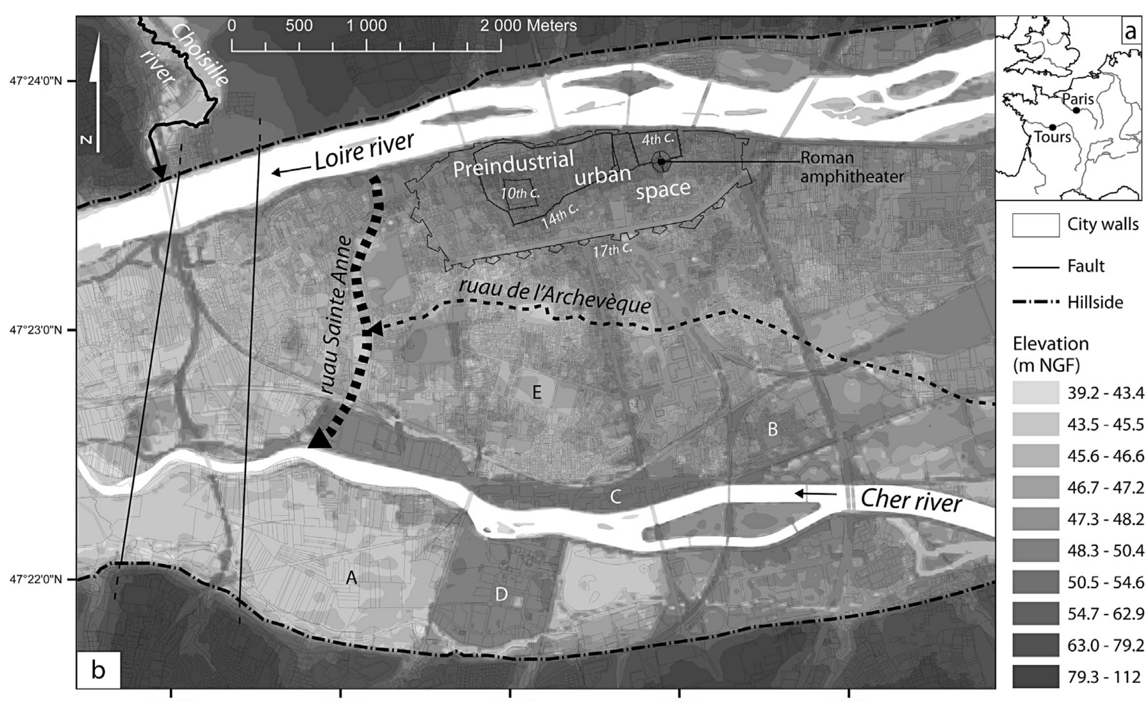

Fig. 1. Location maps. (a) location of the study area in north-western Europe. (b) current digital elevation model of the studied area.

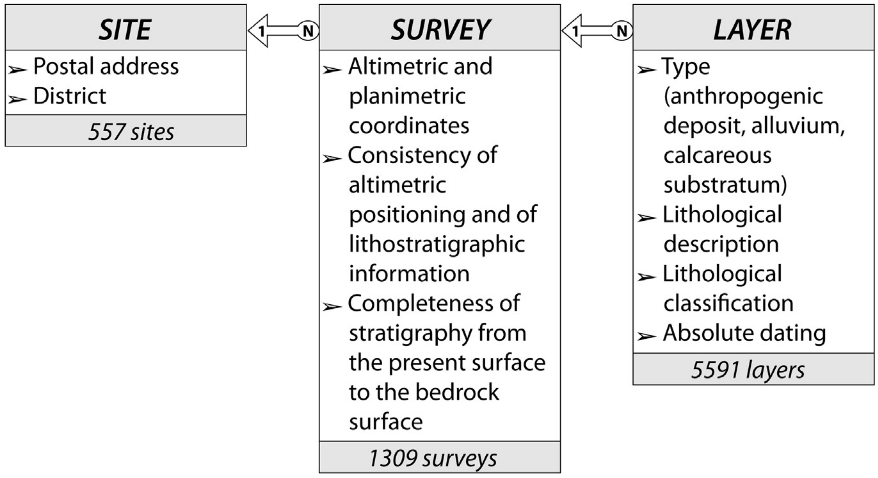

Fig. 2. Simplified structure of the sedimentary database for the alluvial plain of Tours.

1993; Jesset et al., 1996; Fouillet et al., 2002; David et al., 2013). The ancient and medieval town as a whole resembles a vast flat surface with anthropogenic micro-reliefs resulting from zones of dense population and high activity (Galinié, 1981).

The Loire and the Cher have been extensively developed and used since the Roman period (e.g. Neury et al., 2003; Garcin et al., 2006). Between the Roman period and today, the urban space spread into the low-flow channel of the Loire on the south bank, to a greater extent in the western part of the former urban space (approximately 200 m) than in the eastern part (approximately 50 m) (Galinié et al., 2003b). Channels are documented between the two rivers. The flow of the *ruau*[1] *de Sainte Anne*, an abrupt fluvial diffluence of the Loire towards the Cher (Fig. 1b), was regulated during the Middle Ages, and then definitively filled in at the end of the 18th c. The *ruau de l'Archevêque* (Fig. 1b) followed the general direction of the valley and flowed into the *ruau de Sainte Anne*. Its flow was regulated and it existed up to the middle of the 19th c., when it was filled in prior to urban development work towards the south.

3. Material and methods

3.1. Development and processing of a sedimentary database

A sedimentary database[2] was compiled in order to create geostatistical models of the geomorphological characteristics of the study sector. The database was compiled by checking data from archaeological, geological and geotechnical surveys. These data were heterogeneous and required manual checking and processing before they could be included in the database. This step is essential in order to establish control criteria and eliminate data showing inconsistencies. The following criteria were checked and classified for each survey: (1) consistency of planimetric and altimetric positioning, (2) quality of altimetric information, (3) completeness of stratigraphy from the present surface to the limestone bedrock, (4) quality of the lithostratigraphic information. Seven lithological facies representing different sedimentation environments were identified, notably in relation to sedimentary granularity and components, such as figurative organic matter, occasionally abundant:

- Clayey silt and clayey–peaty silt, corresponding to environments conducive to settling (e.g. low-energy floodplain or abandoned channel).
- Clayey–sandy silt and clayey–silty sand, corresponding to higher energy deposit systems (e.g. floodplain close to active channel, levees, islands).
- Sand, gravelly sand and gravel, corresponding to the high-energy environments of active channels (e.g. point bars or stream beds).

The database compiled in a database management system has a simple structure with three tables: "Site", "Survey" and "Layer" (Fig. 2). Altogether, 5591 layers from 1309 surveys were included in the database (Fig. 2).

3.2. Geostatistical analysis and creation of geomorphological models

Selected data, considered to be stationary, were processed using a standard geostatistical approach in three steps: (1) plotting and analysis of an experimental variogram to estimate the dispersion of the distribution of a variable in space (Matheron, 1963); (2) fitting a mathematical smoothing function, or theoretical variogram, on the experimental variogram; (3) interpolation by ordinary kriging (Krige, 1951; Matheron, 1963; Davis, 1973) in a GIS. Cross-validations and predicted standard error maps were systematically produced. The point bars and islands currently found in the channels of the Loire and the Cher were not modelled, because these structures were very mobile during the time-step studied. The model of the altitude of the top of the alluvium was enhanced by introducing additional points on the present course of the Loire and the Cher (60 and 57 points respectively) by manual extrapolation of the bathymetric data. The model of the cumulative thickness of clayey silt and clayey–peaty silt alluvium was produced by adding the thickness of all the layers composed by these two lithological facies for each survey, from the topographical surface to the bedrock, whether or not they were separated by layers belonging to other facies.

[1] A "*ruau*" is an old regional word for a secondary channel. It could be more or less connected to the active channels, but contained water throughout a hydrological year.

[2] The database and its user notice (in French) can be downloaded at: http://www.plan-loire.fr/index.php?id=1646&row=52&type=112.

Table 1
^{14}C dates obtained during archaeological excavations in the former urban space of Tours.

Date number	^{14}C age BP	Laboratory reference	2σ cal. age ranges BP	2σ cal. age ranges BC/AD	Elevation (m NGF)	Material	Sedimentary facies
1	3400 ± 150	UQ 1710	4083–3339	2134–1390 cal. BC	43.90–44.0	Peat/plant residues	Clayey–peaty silt
2	4150 ± 150	UQ 1803	5257–4164	3308–2215 cal. BC	42.50–42.55	Peat/plant residues	Clayey–peaty silt
3	9200 ± 150	UQ 1722	11,051–9912	9102–7963 cal. BC	42.30–42.35	Peat/plant residues	Clayey–peaty silt
4	8800 ± 150	Ly – 6370	10,207–9539	8258–7590 cal. BC	40.00–40.10	Peat/plant residues	Clayey–peaty silt
5	6075 ± 75	Ly – 6371	7161–6749	5212–4800 cal. BC	40.15–40.20	Peat/plant residues	Clayey–peaty silt
6	9630 ± 70	Ly – 6372	11,194–10,755	9245–8806 cal. BC	39.65–39.70	Peat/plant residues	Clayey–peaty silt
7	9970 ± 70	Ly – 6040	11,744–11,238	9795–9289 cal. BC	40.10–40.50	Peat/plant residues	Clayey–peaty silt
8	9795 ± 75	Ly – 6041	11,400–10,822	9451–8873 cal. BC	40.50–40.85	Peat/plant residues	Clayey–peaty silt
9	5120 ± 55	Ly – 6042	5989–5734	4040–3785 cal. BC	40.85–41.10	Peat/plant residues	Clayey–peaty silt
10	2215 ± 165	A 11975	2713–1868	764 cal. BC–82 cal. AD	44.96–45.01	Sediment bulk	Clayey silt
11	3630 ± 60	A 11635	4145–3730	2196– 1781 cal. BC	44.55–44.60	Sediment bulk	Clayey silt
12	4480 ± 55	A 11977	5309–4892	3360–2943 cal. BC	44.25–44.30	Sediment bulk	Clayey silt
13	4570 ± 90	A 11978	5577–4962	3628–3013 cal. BC	43.85–43.90	Sediment bulk	Clayey silt
14	4680 ± 120	A 11976	5648–4985	3699–3036 cal. BC	43.50–43.55	Sediment bulk	Clayey silt
15	4965 ± 100	A 11979	5920–5481	3971–3532 cal. BC	43.10–43.15	Sediment bulk	Clayey silt
16	5130 ± 200	A 11980	6310–5339	4361–3390 cal. BC	42.70–42.75	Sediment bulk	Clayey silt
17	8800 ± 165	A 11636	10,235–9526	8286–7577 cal. BC	42.00–42.05	Sediment bulk	Clayey silt
18	4460 ± 60	Poz – 38802	5298–4879	3349–2930 cal. BC	44.15–44.25	Sediment bulk	Clayey silt
19	3340 ± 35	Poz – 37273	3682–3475	1733–1526 cal. BC	44.05–44.10	Peat/plant residues	Clayey–peaty silt
20	4360 ± 30	Beta – 323747	5034–4853	3085–2904 cal. BC	45.10	Sediment bulk	Clayey silt
21	5030 ± 30	Beta – 323748	5891–5659	3942–3710 cal. BC	44.85–44.87	Sediment bulk	Clayey silt
22	4710 ± 40	Beta – 323749	5582–5321	3633–3372 cal. BC	45.18	Sediment bulk	Clayey silt
23	8520 ± 50	Beta – 323750	9550–9453	7601–7504 cal. BC	42.88	Sediment bulk	Clayey–sandy silt
24	4050 ± 30	Beta – 323751	4783–4426	2834–2477 cal. BC	43.57–43.60	Sediment bulk	Sand
25	5010 ± 30	Beta – 323752	5891–5655	3942–3706 cal. BC	41.99	Sediment bulk	Clayey–sandy silt
26	10,030 ± 40	Beta – 323753	11,750–11,328	9801–9379 cal. BC	41.36	Sediment bulk	Clayey–sandy silt
27	1910 ± 30	Beta – 317497	1929–1740	21–210 cal. AD	44.55–44.60	Peat/plant residues	Clayey–peaty silt

Table 2
OSL dates obtained during archaeological excavations in the former urban space of Tours.

Date number	OSL age (ka)	Age ranges OSL BP	Age ranges BC/AD	Elevation (m NGF)	Sedimentary facies
28	5.20 ± 0.57	5710–4570	3760–2620 OSL BC	46.00–46.46	Clayey–silty sand
29	7.47 ± 0.71	8120–6700	6170–4750 OSL BC	45.70–45.85	Clayey–silty sand
30	10.33 ± 0.49	10,760–9780	8810–7830 OSL BC	42.90–42.95	Sand
31	1.00 ± 0.05	990–890	960–1060 OSL AD	45.90–46.00	Clayey–sandy silt
32	0.83 ± 0.04	810–730	1140–1220 OSL AD	45.50–45.60	Sand
33	2.06 ± 0.10	2100–1900	150 OSL BC–50 OSL AD	45.82–45.92	Clayey–silty sand
34	19.13 ± 1.54	20,610–17,530	18,660–15,580 OSL BC	45.28–45.32	Clayey–silty sand

3.3. *Chronology of alluvial deposits in the former urban space*

The chronology of sedimentary deposits in the former urban was determined from 29 C14 datings (Table 1) and seven OSL datings (Table 2) obtained during archaeological operations (Fig. 3a). The C14 datings were calibrated with CALIB V6 software (Stuiver and Reimer, 1993) and the IntCal09 database (Reimer et al., 2009). The cal. ages (noted cal. BC/AD) are reported with the extremes values of the 2σ range (95.4%). The OSL datings were made between 2009 and 2012 on quartz grains with a good luminescence signal. The OSL ages were calculated using the central age model (Galbraith et al., 1999). They are reported as the extreme values of the uncertainty range on the measure minus 60 years (denoted OSL BC/AD) for comparison with the calibrated C14 ages.

One date is situated in the Upper Pleistocene (18,660–15,580 OSL BC) (Fig. 3b). The other dates are all situated in the Holocene, ranging from the beginning of the Interglacial (9801–9379 cal. BC) to the medieval period (1140–1220 OSL AD) (Fig. 3b).

3.4. *Stratigraphy of alluvial deposits in the former urban space*

A stratigraphic transect of 835 m long was constructed from 13 surveys in the median part of the former urban space (Fig. 3a). Given the spatio-temporal variability of the sedimentary records inherent to the river context (Macaire, 1990), the stratigraphy was determined from nine units composed of different lithological facies. The chronology and morphology of the alluvial deposits were determined by datings made on the transect samples and by all the datings carried out on the intersecting palaeochannel.

4. Results

4.1. *Geostatistical models*

4.1.1. *Limestone bedrock top surface model*

This model was made from 626 sample points (Fig. 4) and has an R^2[3] of 0.58. The least reliable sectors are located on the edge of the map (Fig. 5), where there are fewer data. The model shows the forms of erosion of the Loire and the Cher in the bedrock. The altitudes range between 47.8 (A, Fig. 4) and 36.5 m NGF (in the Loire channel), mean 42 m NGF.

A significant contrast appears in the interfluve (Fig. 4). Upstream of the *ruau de Sainte Anne*, the top surface of the bedrock appears roughly as parallel ridges running east–west and delimiting depressed corridors. Downstream of the *ruau de Sainte Anne*, although the model is less reliable (Fig. 5), the bedrock appears overdeepened with a less uneven relief.

[3] The coefficient of determination (R^2) indicates how well predicted values by the model fit measured values on the field. A perfect correlation gives $R^2 = 1$.

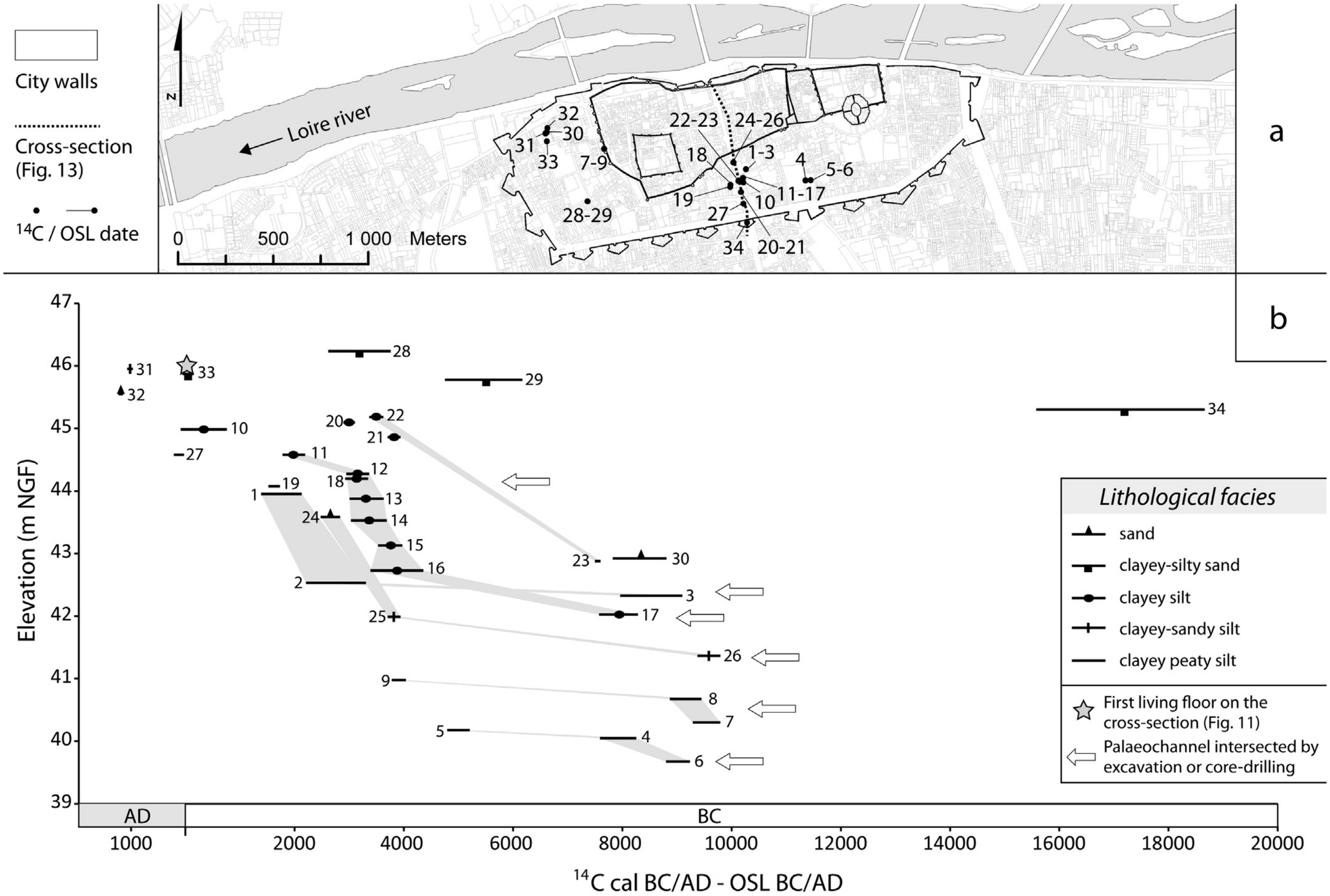

Fig. 3. ^{14}C and OSL dates obtained in the former urban space of Tours. (a) Location of dated samples. (b) Chronological, altimetric and lithological distribution of dated samples. Grey bars unite dates from one excavation or one core-drilling. See Tables 1 and 2 for the significance of dating numbers.

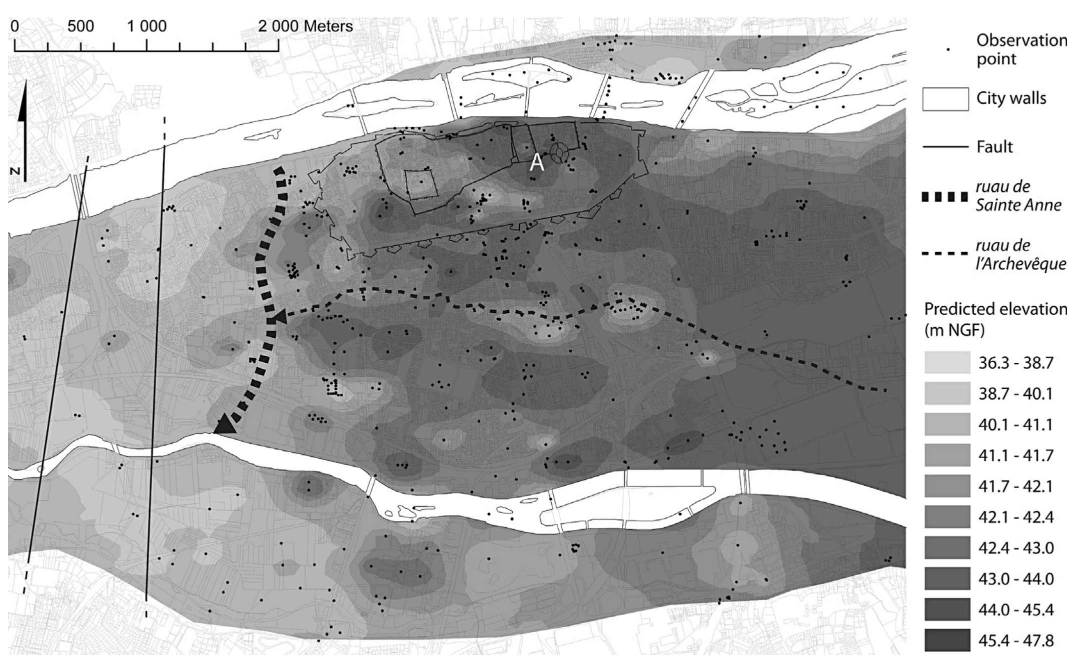

Fig. 4. Geostatistical model of the altitude of the top of the limestone bedrock of the alluvial plain of Tours (R^2: 0.58; mean standardized error: −0.001; average standard error: 1.28 m). A: highest point of the top of the calcareous bedrock.

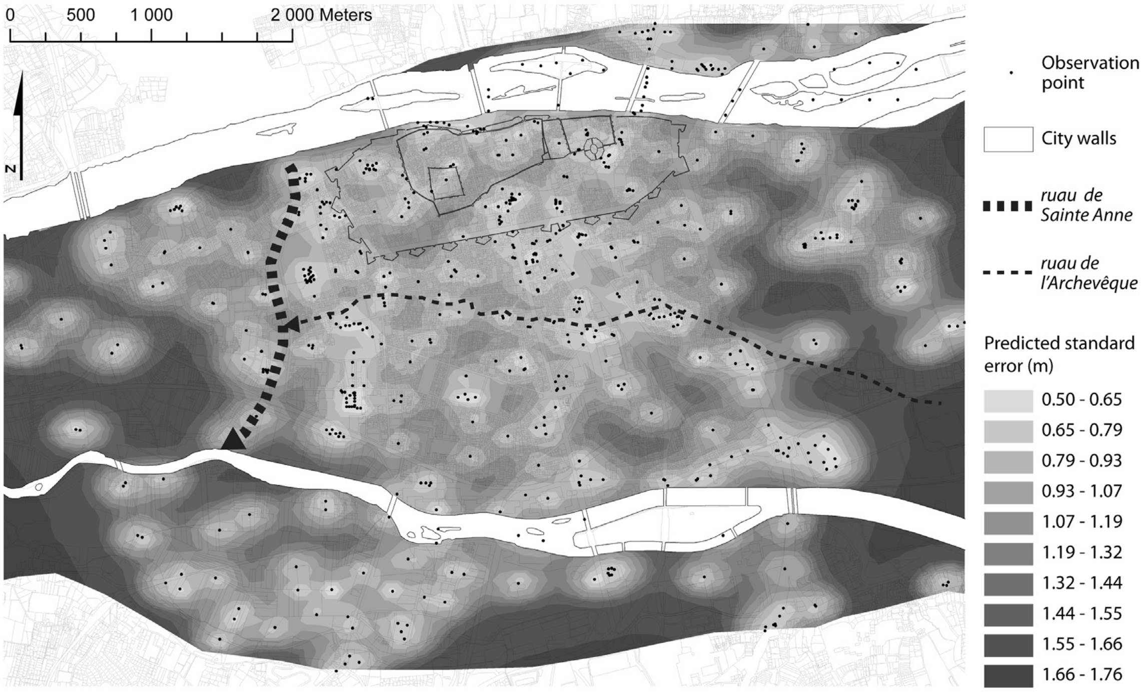

Fig. 5. Predicted standard error of the geostatistical model of the altitude of the top of the limestone bedrock of the alluvial plain of Tours.

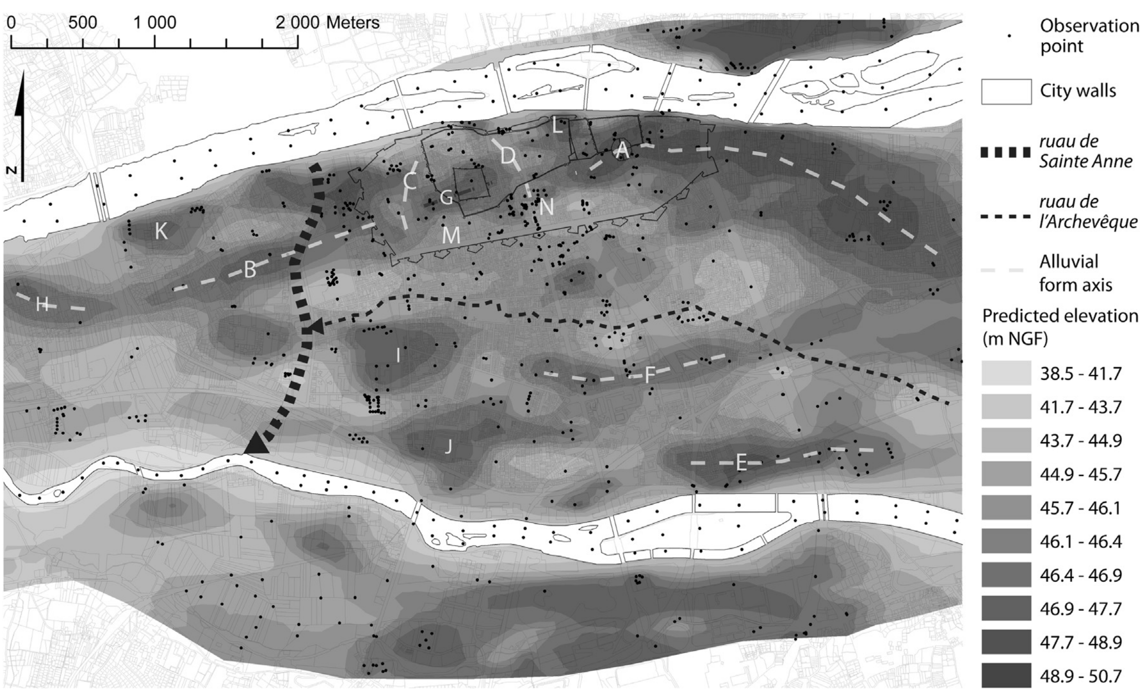

Fig. 6. Geostatistical model of the altitude of the top of the alluvium in the alluvial plain of Tours (R^2: 0.72; mean standardized error: 0.010; average standard error: 0.92 m). A: highest point of the top of the alluvium in the west part of the low fluvial terrace; B: natural levee; C, D: breach in levee; E, F: natural levee or point bar; G, H, I, J: natural levee or point bar intersected by thalwegs; K, L: Holocene island; M: protohistoric settlement; N: Roman baths.

4.1.2. Alluvium top surface model

This model was made by interpolating the data of 722 survey points with 177 additional points (Fig. 6). The model is fairly robust ($R^2 = 0.72$). The least reliable sectors are located at the edge of the map (Fig. 7).

The model does not represent a monogenetic, "snapshot" form of a particular period, because the fluvial palaeoreliefs continued to be covered by anthropogenic deposits between the 1st and 20th centuries AD. In general, the top surface is observed either as linear, following the line of the valley, or as elliptical. It is limited by

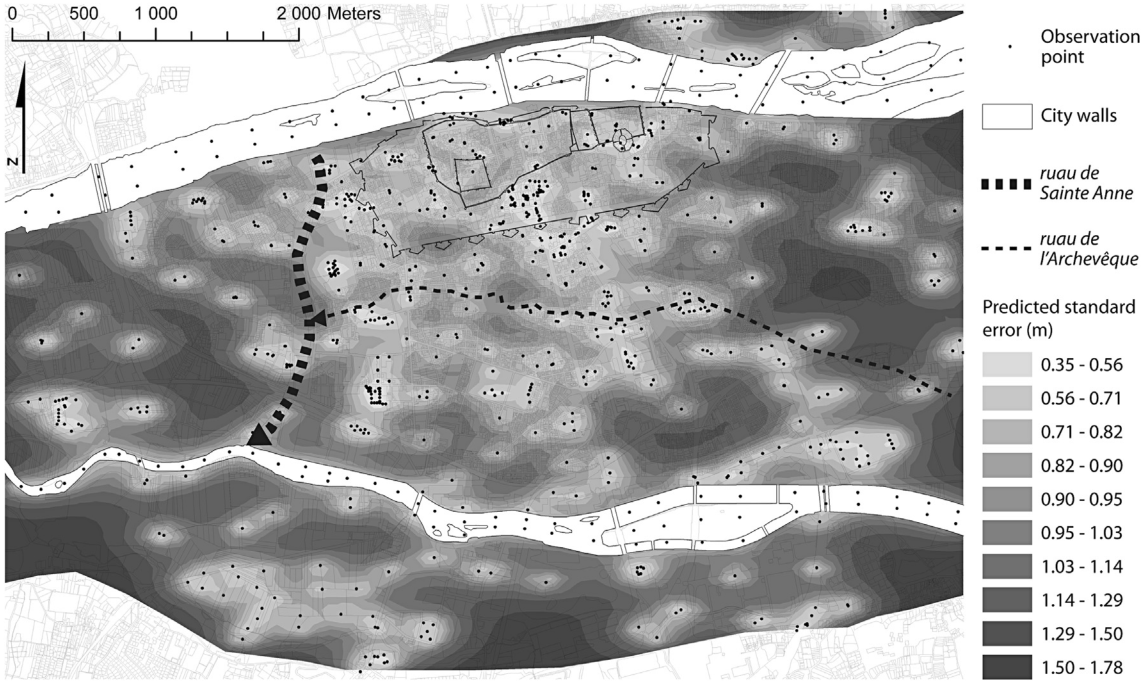

Fig. 7. Predicted standard error of the geostatistical model of the altitude of the top of the alluvium in the alluvial plain of Tours.

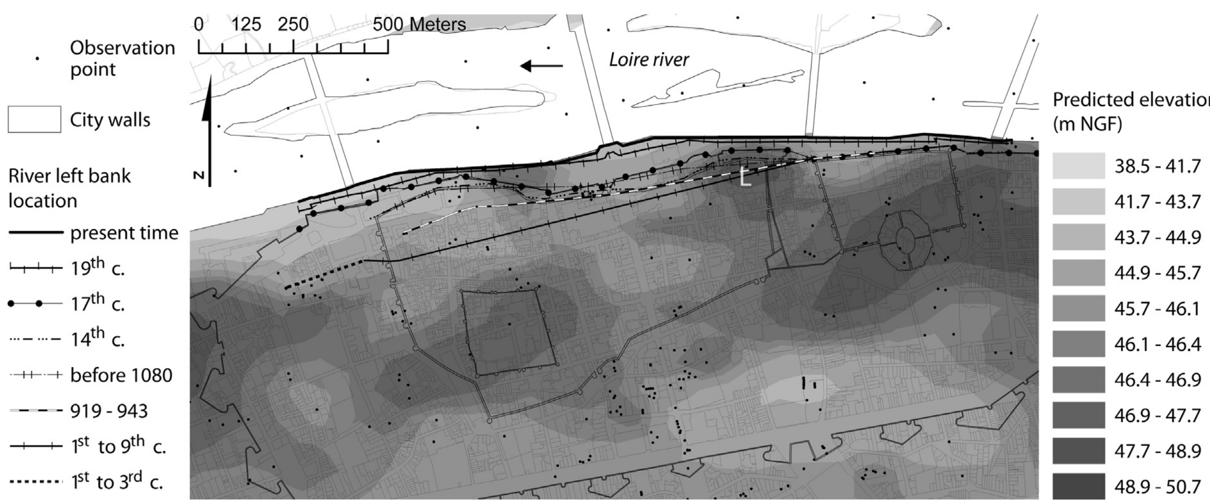

Fig. 8. Geostatistical model of the altitude of the top of the alluvium in the former urban space of Tours, and modifications of the location of the left bank of the Loire linked to advances in areas of human settlement. L: Holocene island.

depressed zones forming east–west corridors interconnected by more transversal thalwegs (Fig. 6). Altitudes range from 38.5 m NGF in the bed of the Loire to 50.7 m NGF (A, Fig. 6), with a mean of 45.6 m NGF.

In the north-east part of the study zone, a long (~2.5 km), wide (400–500 m) structure with a relatively high altitude (47.5 m–49 m NGF from east to west) forms a low fluvial terrace, reaching its highest point at the site of the Roman amphitheatre (A, Fig. 6). To the west of this terrace can be seen what could be considered to be a natural levee, lower and composed essentially of sandy deposits that are more or less rich in clayey silt matrix (B, Fig. 6). It appears to be dissected by a network of thalwegs (C and D, Fig. 6) that probably formed during breaching episodes. Other linear mounds, similar to natural levees or sedimentary bars, can be seen (E and F, Fig. 6).

Elliptical top surfaces can also be observed. They may derive from the dissection of the alluvial top surfaces already revealed by the thalwegs (G, H, I and J, Fig. 6). On the left bank of the present channel of the Loire, these structures could correspond to old Holocene islands (K and L, Fig. 6). This hypothesis is validated at the site of the island of Saint-Cosme, which takes its name from the priory that was established there in the 11th c. AD, and whose contours are clearly marked on the model (K, Fig. 6). This supports the hypothesis that the elliptical alluvial top surface modelled in the west part of the former urban space (L, Fig. 6; L, Fig. 8) could correspond to a former island, now connected to the bank.

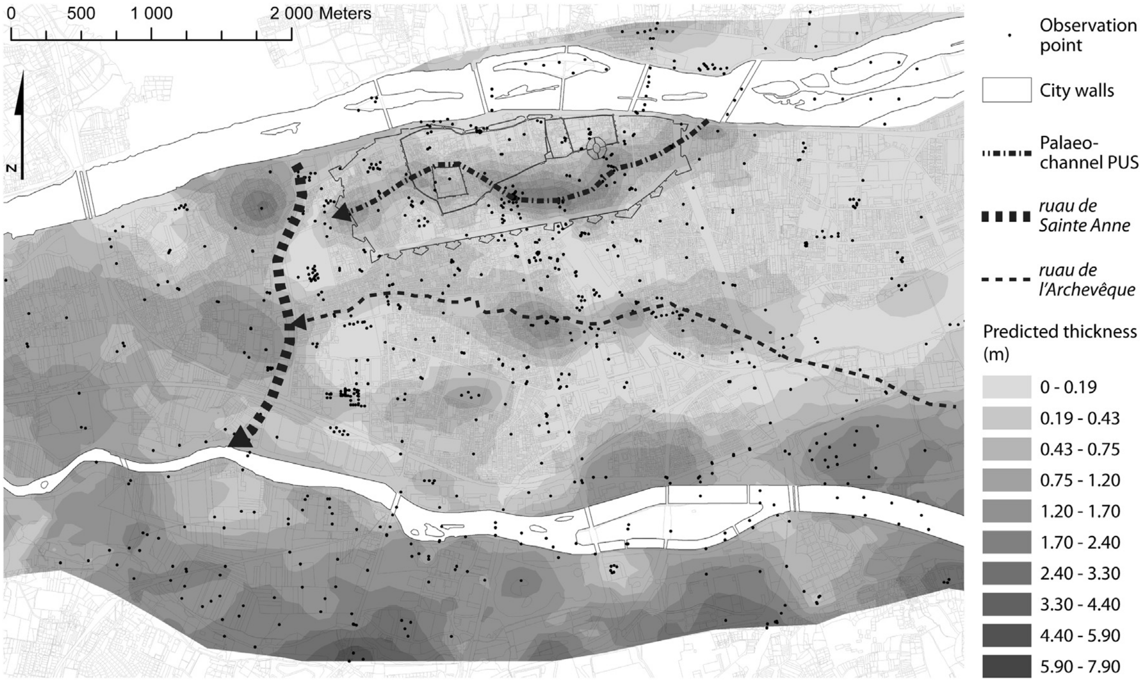

Fig. 9. Geostatistical model of the accumulated thickness of silty-clayey and peaty deposits in the alluvial plain of Tours (R^2: 0.61; mean standardized error: −0.002; average standard error: 0.91 m).

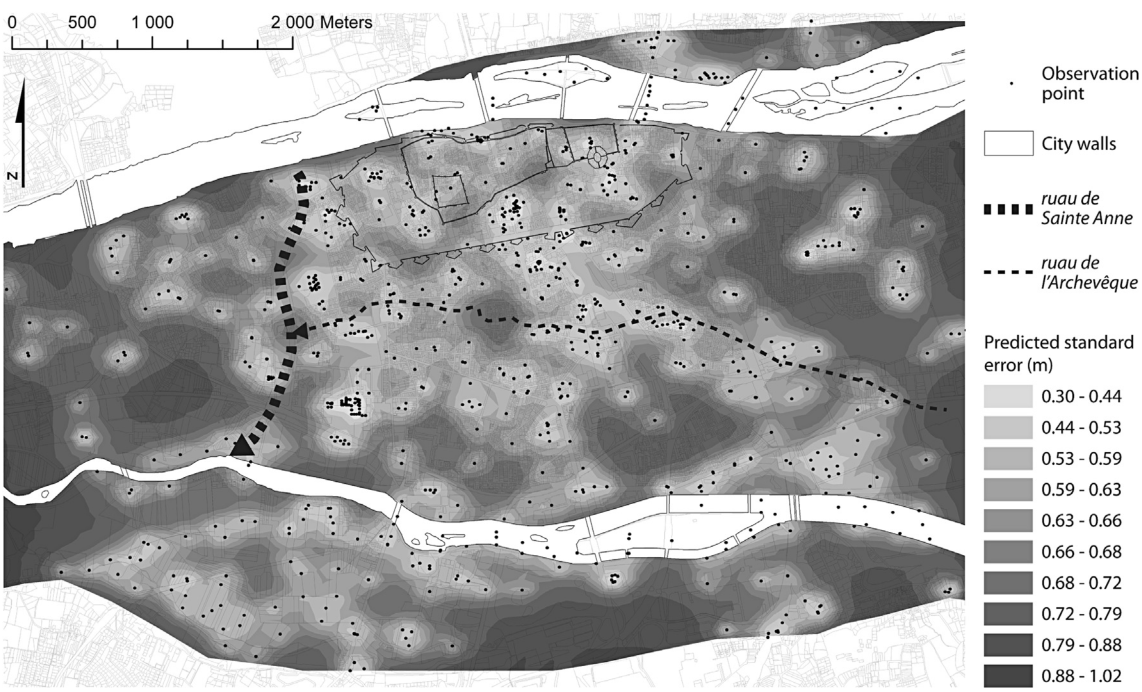

Fig. 10. Predicted standard error of the geostatistical model of the accumulated thickness of clayey–silty and clayey–peaty silt in the alluvial plain of Tours.

4.1.3. Model of thickness of clayey–silty and clayey–peaty silty deposits

This model was created by interpolating the data of 423 sedimentary layers from 211 sample points (Fig. 9) and has an R^2 of 0.61. The least reliable sectors are mainly located at the edge of the map (Fig. 10). It shows the sectors where the clayey–silty and clayey–peaty–silty deposits are thickest. In rivers, these sediments are deposited in calm environments conducive to settling and conservation of organic matter, such as disconnected channels, basins and floodplains (Bridge, 2003). Thickness varies from 0 to 7.9 m, locally at the foot of the southern slope of the valley, with a mean value of 0.6 m.

The clayey–silty and clayey–peaty–silty sediments are generally less thick in the interfluve upstream of the *ruau de Sainte Anne* (Fig. 9). However, in this sector, a belt corresponding to greater thicknesses can be observed on the known course of the *ruau de* *l'Archevêque* (Fig. 9), indicating that the model is relatively reliable. In the former urban space, a fairly similar belt has also been modelled (Fig. 9). It intersects archaeological sites where palaeochannels have been observed. These elements suggest the existence of a single palaeochannel winding across the whole of the former urban space (denoted "palaeochannel PUS") from the south-east to the north-west (Fig. 9).

4.1.4. Model of thickness of anthropogenic deposits

This model was created by interpolating the data of 739 survey points (Fig. 11) and has an R^2 of 0.64. The least reliable sectors are again mainly those on the edge of the map (Fig. 12). The thickness of the anthropogenic deposits is close to zero in all the sectors with low urbanization (A, Fig. 11) and is greatest (11.2 m) on the banks of the Loire. The average value for the whole model is 2.20 m.

The thickness of the anthropogenic deposits in the former urban space is significant, notably within the 14th c. wall, as already shown by previous geostatistical models (Laurent and Fondrillon, 2010), correlating significantly with the density of human occupation (Laurent, 2007). In the districts that have been developed since the last third of the 20th c. (B, C and D, Fig. 11), deposits can be up to 7 m thick. Conversely, in some sectors that were urbanized in the 19th c. (E, Fig. 11) or that are closer to the outskirts (on the east and west edges of the area under study), they are less than 1 m thick.

4.2. Alluvium stratigraphy and geometry in the former urban space

The lithological facies and their distribution in the cross-section are shown in Fig. 13.

Unit 1: Gravelly sand and coarse sand deposits lying on the limestone bedrock and deposited before 18,660–15,580 OSL BC (34, Fig. 3 and Table 2). They indicate a high-energy sedimentation environment associated with an active channel.

Unit 2: Sand, clayey–silty sand and clayey silt deposits covering Unit 1 and deposited about 18,660–15,580 OSL BC. These sediments could correspond to those of a floodplain close to active channels. The deposits of units 1 and 2 and the limestone bedrock were incised by a palaeochannel after 18,660–15,580 OSL BC and before the first Holocene deposits.

Unit 3: Gravelly sand deposits covering the limestone bedrock. They indicate a high-energy sedimentation environment associated with an active channel. The deposits of Unit 3 and the bedrock were incised by a palaeochannel before 9801–9379 cal. BC (26, Fig. 3 and Table 1).

Unit 4: Clayey–sandy silt deposits, rich in organic matter, with clayey silty and peaty layers covering the limestone bedrock and Unit 3. These sediments were deposited from 9801 to 9379 cal. BC and at least up to 7601–7504 cal. BC (23, Fig. 3 and Table 1). They indicate a calm hydrodynamic context, with episodes of relatively higher energy producing sandy inputs, which could correspond to an abandoned secondary channel that was occasionally reconnected to the main channel. The deposits of Unit 4 were incised after 7601–7504 cal. BC and before 5212–4800 cal. BC (5, Fig. 3 and Table 1).

Unit 5: Clayey–peaty silt deposits with clayey–sandy silt layers covering Unit 4. They were deposited from 5212 to 4800 cal. BC and at least up to 2134–1390 cal. BC (1, Fig. 3 and Table 1). The deposits and their geometry are characteristic of an abandoned channel. These deposits were incised by a small channel after 2134–1390 cal. BC and before 764 cal. BC/82 cal. AD (10, Fig. 3 and Table 1).

Unit 6: Sand and gravelly sand deposits filling the incised channel in Unit 5. They were deposited after 2134–1390 cal. BC and before 764 cal. BC/82 cal. AD and indicate a high-energy hydrodynamic context associated with an active channel.

Unit 7: Sand and occasionally clayey silt deposits covering Units 1, 5 and 6 and deposited after 2134–1390 cal. BC, up to 764 cal. BC/82 cal. AD, and potentially up to the creation of the ancient

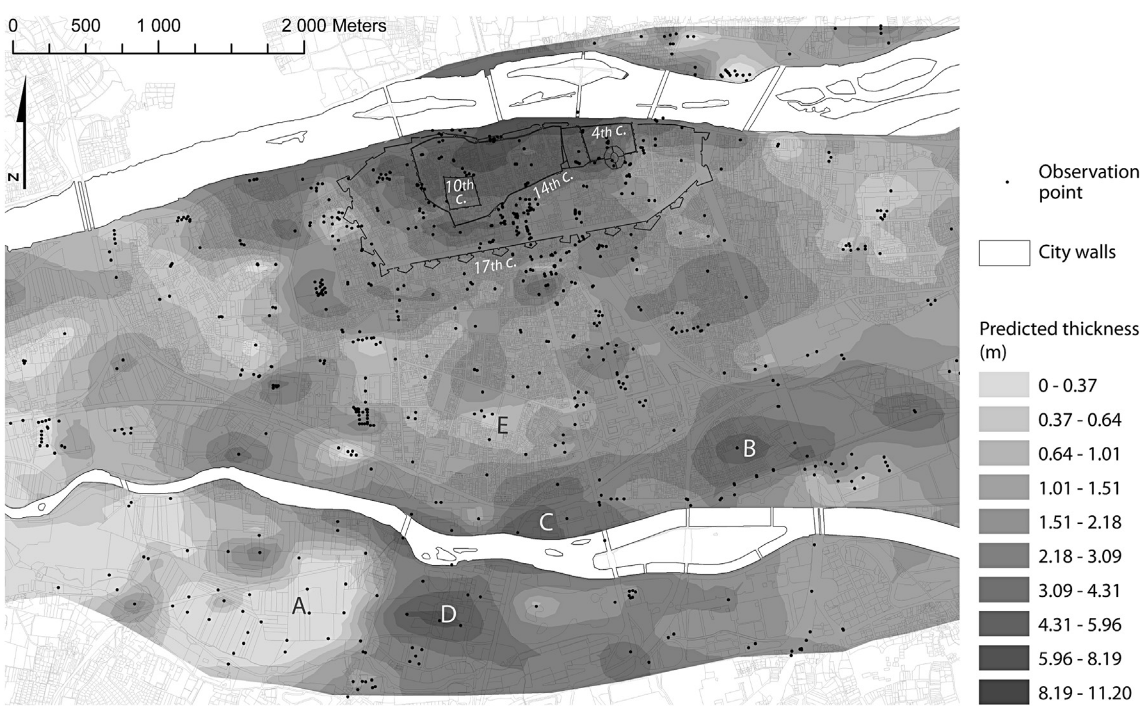

Fig. 11. Geostatistical model of the thickness of anthropogenic deposits in the alluvial plain of Tours (R^2: 0.64; mean standardized error: −0.003; average standard error: 1.13 m). A: plain of La Gloriette; B: Beaujardin district; C: the Rives du Cher district; D: the Deux Lions district; E: Thiers district; F: Rabelais district.

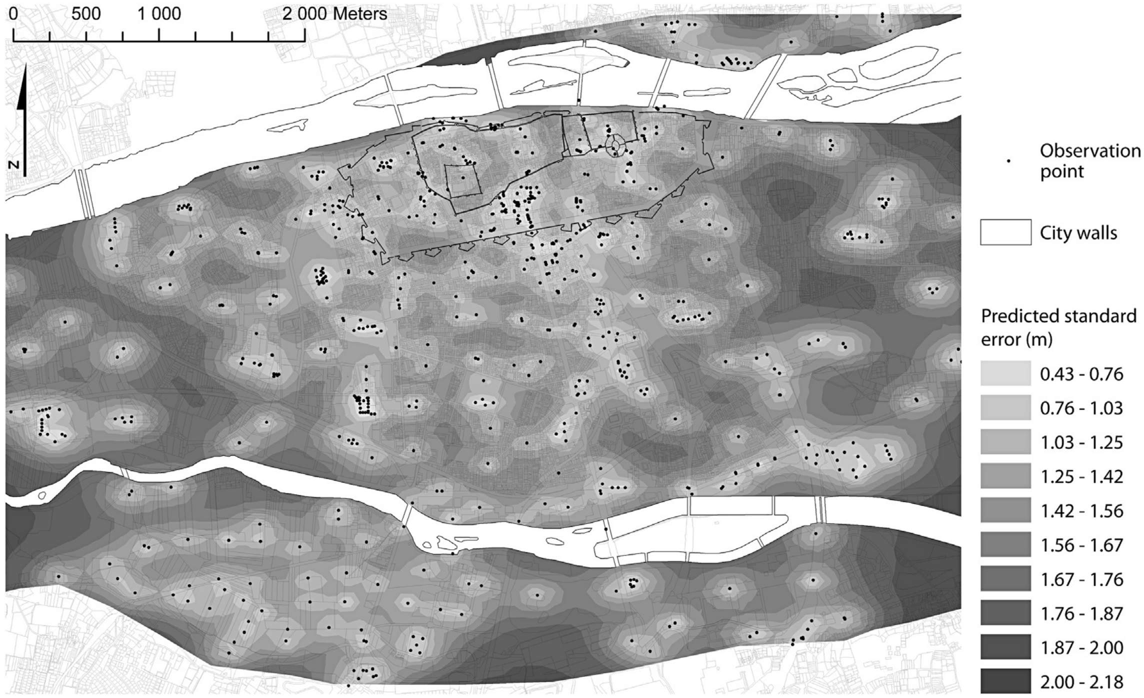

Fig. 12. Predicted standard error of the geostatistical model of the thickness of anthropogenic deposits in the alluvial plain of Tours.

town. The nature and geometry of these sediments suggests that they correspond to floodplain deposits close to the active channel.

Unit 8: Anthropized or anthropogenic clayey–peaty silt deposits (gallo-roman ceramics, fauna, cobblestones, etc.) laid down at least as early as 21–210 cal. AD (27, Fig. 3 and Table 1) in a depression in the deposits of Units 1 and 2. This structure is fairly wide, which rules out the possibility that it was man-made, suggesting rather that it was initially a natural depression that was probably restructured at the edges.

Unit 9: Anthropogenic deposits, comprising the whole archaeological stratigraphy since the 1st c. AD and resulting from 2000 years of varied human occupation. This unit is particularly thick at the edge of the channel of the Loire, becoming steadily thinner towards the SSE.

5. Discussion

The major features of the morphological and sedimentary evolution of the alluvial plain of Tours since the Weichselian have been reconstructed by cross-referencing models and lithostratigraphic data, and linked to climate, anthropogenic and internal forcing.

5.1. Weichselian period

The pattern of evolution of the alluvial plain of Tours proposed below for the Weichselian period differs in part from previous hypotheses (Carcaud et al., 2002; Burnouf et al., 2003). The shape of the top of the bedrock is probably polygenic. However, it could in part have been shaped during a major incision phase of the valley before 18,660–15,580 OSL BC, which locally spared the deposits forming the low terrace (A, Fig. 6). In the downstream part of the Choisille valley, which flows into the Loire valley just downstream of Tours (Fig. 1), the last major incision of the bedrock developed before the Weichselian Middle Pleniglacial (Morin et al., 2011). This implies an incision at least as great as that of the Loire in Tours at the same period. A similar incision phase, prior to the emergence of true periglacial climatic conditions, in other words before the Weichselian Middle Pleniglacial, was observed further upstream on the Middle Loire (Castanet, 2008) and in North-West Europe (van Huissteden et al., 2001; Antoine et al., 2007).

The origin of the considerable overdeepening of the bedrock in the west of the study sector (Fig. 4) could be neotectonic, related to known faults. This slight subsidence probably occurred prior to the deposit of Weichselian and Holocene alluvium, as indicated by the absence of a significant depressed zone on the model of the altitude of the top surface of the alluvium (Fig. 6). The thickening of the clayey–silty and peaty deposits in this sector (Fig. 9), testifying to the local decrease in the hydraulic gradient and in the related sedimentary transport capacity, and evidence of neotectonic activity in other sectors close to the Middle Loire valley (Champion et al., 1971), seem to support this hypothesis.

After the last major phase of Weichselian incision, sedimentation started to occur in the alluvial plain before 18,660–15,580 OSL BC with the deposition of generally sandy-gravelly or sandy alluvium (unit 1, Fig. 13). These facies and their distribution indicate sedimentation in high-energy, multi-channel river systems, characteristic of periglacial environments. They could have been anastomosing braided-stream systems (Bridge, 2003), which is supported by the models of the altitude of the top of the bedrock and of alluvium, clearly showing corridors that are inter-connected by small thalwegs (Figs. 4 and 6). This type of deposit is uniformly distributed at the base of the sedimentary fill of floodplains in north-west Europe and has been attributed to different periods of the Weichselian Pleniglacial, or to the Pleniglacial without further specifications (Haesaerts, 1984; van Huissteden et al., 1986; Brown and Keough, 1992; Antoine, 1997; Houben et al., 2001; Pastre et al., 2003). Above the deposits of Unit 1, the sediments of Unit 2 were deposited from 18,660–15,580 OSL BC (Fig. 13). The clear difference in granularity between these two units could suggest a modification of the river system, linked to the cold, dry climatic conditions at that period (Huijzer and Vandenberghe, 1998). However, this is a

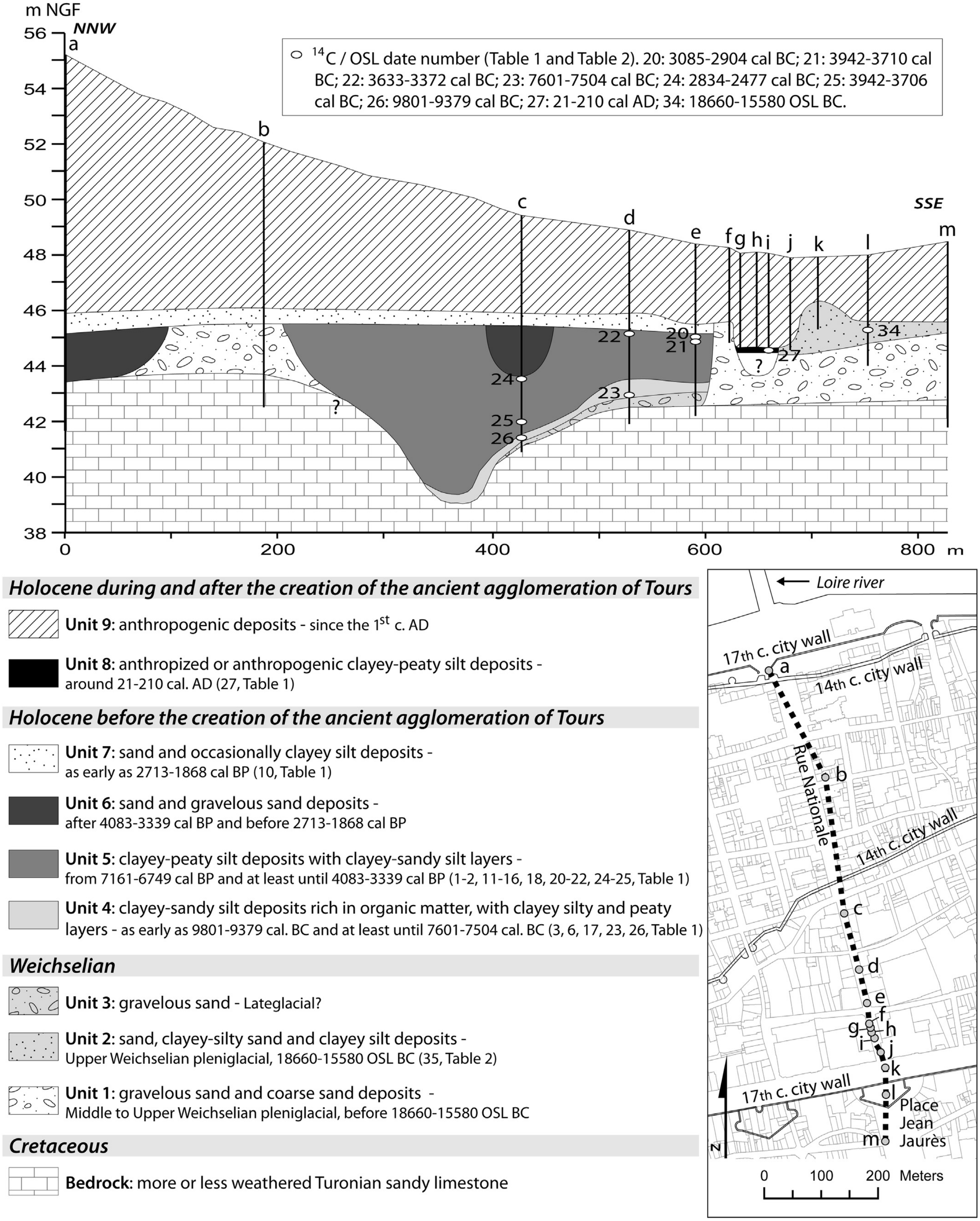

Fig. 13. Stratigraphic cross-section in the former urban space of Tours.

one-off observation, and the Weichselian Upper Pleniglacial is generally characterized in the Middle and Upper Loire by the deposit of coarse sediments indicating a high-energy environment (Colls et al., 2001; Straffin and Blum, 2002; Castanet, 2008). The difference in facies between Units 1 and 2 could thus be merely the result of a local migration of channels in the alluvial plain.

In the PUS palaeochannel, the deposits of Units 1 and 2 and the limestone bedrock were incised after 18,660–15,580 OSL BC and before the establishment of Unit 3 (Fig. 13). This episode could be seen in relation to Bölling warming (Taylor et al., 1993), which led to a fluvial metamorphosis often associated with a phase of channel incision, largely observed in the Middle Loire and its basin (Castanet, 2008; Piana et al., 2009; Morin et al., 2011), in the Paris basin (Antoine, 1997; Pastre et al., 1997) and in north-west Europe (Haesaerts, 1984; Tebbens et al., 1999; Mol et al., 2000). The sandy–gravelly Unit 3 (Fig. 13) could be contemporary with the younger Dryas, when there was considerable hill-slope erosion in the upstream basin of the Loire (Gay et al., 1998; Négrel et al., 2004; Macaire et al., 2010), with episodic reactivation of channels and coarse sediment deposit further upstream of the Middle Loire (Castanet, 2008).

The incision of Unit 3 and the bedrock before 9801–9379 cal. BC (Fig. 13) probably occurred in the channels that were active during the Lateglacial–Holocene transition, linked to warming during that period, as already widely observed in the Middle Loire (Carcaud et al., 2002; Burnouf et al., 2003; Castanet, 2008), in the Paris basin (Antoine, 1997; Pastre et al., 1997) and in north-west Europe (Vandenberghe et al., 1994; Tebbens et al., 1999; Mol et al., 2000). In Tours, this incision period marks the shift of the main channels of the Loire and the Cher to the north and south of the alluvial plain respectively, while the secondary channels, like the PUS palaeochannel (Fig. 9) or the *ruau de l'Archevêque*, became gradually disconnected.

5.2. Holocene period before the first human settlement

In the abandoned channels, deposition of organic clayey–sandy silt with clayey silty and peaty layers occurred from 9801 to 9379 cal. BC (unit 4, Fig. 13). However, the channels were abandoned gradually, the presence of a fairly abundant sandy fraction in certain levels of Unit 4 indicating clearly that they were occasionally reconnected to the main channel. The abundance of organic matter in the abandoned channels or floodplains at the beginning of the Holocene has been observed elsewhere in the Middle Loire and its tributaries (Garcin et al., 1999; Piana et al., 2009; Morin et al., 2011), in the Paris basin (Antoine, 1997; Pastre et al., 1997) and in north-west Europe (Lefèvre et al., 1993; Tebbens et al., 1999). The main channel of the Loire remained active but confined to the old low-flow channel, as indicated by sandy deposits laid down towards 8810–7830 OSL BC (30, Fig. 3 and Table 2) 200 m south of the present course of the left bank of the Loire.

Between 7601–7504 and 5212–4800 cal. BC an incision phase, which partly eroded the earlier Holocene deposits, developed in the PUS palaeochannel, indicating that the latter was reconnected to the main channel of the Loire. This occurred at the same time as a phase of an upsurge of river activity characterized by increased frequency and magnitude of floods in the Middle Loire and its tributaries (Castanet, 2008; Piana et al., 2009) and more generally in Europe (Starkel, 1999). The pollen sequences of the Loire and its tributaries in the Tours area are often truncated, showing clearly that this renewed river activity led to a gap in sedimentation (Visset, 2011). It is likely that breaks in the natural levee of the left bank occurred at this time. This seems to be indicated by the deposition of clayey–sandy–silty sediments about 6170–4750 OSL BC (28 and 29, Fig. 3 and Table 2) in the extension of a thalweg cutting through the natural levee (C, Fig. 6) and probably corresponding to crevasse splay deposits (Bridge, 2003).

From 5212 to 4800 cal. BC, the fine and organic deposits laid down in Unit 5 (Fig. 13) again indicate the disconnection of the PUS palaeochannel from the main channel. Under this calm hydrodynamic condition, sedimentation continued at least up to 2134–1390 cal. BC, with no discernible break, and the PUS palaeochannel was completely filled. This indicates a relative morphological stability of the alluvial plain over several millennia. The average level of the river was probably relatively low at this period, limiting lateral sedimentary input and furthering the disconnection of the palaeochannel. This general downward trend of river activity has already been suggested in the Middle Loire during the Middle and Upper Holocene (Arnaud-Fassetta et al., 2010).

Between 2134–1390 cal. BC and 764 cal. BC/82 cal. AD, a small channel, subsequently filled in by sandy and sandy–gravelly alluvium of Unit 6, was carved out in Unit 5 (Fig. 13). This represents an increase in river flow with morphological consequences in the floodplain. A similar increase has been observed from 2250 cal. BC in other sectors of the Middle Loire (Carcaud et al., 2002; Garcin et al., 2006; Arnaud-Fassetta et al., 2010). This has been related to a change in climate, which was more humid at that time (Guiot, 1987), possibly accentuated by the impact of human activities on the hillsides of the Upper Loire (Arnaud-Fassetta et al., 2010); anthropisation brought about a significant increase in hillside erosion in the upstream basin after 3350 cal. BC (Macaire et al., 2010), contributing to the input of sediment downstream.

After 764 cal. BC/82 cal. AD and up to the creation of the ancient town, the Weichselian and Holocene alluvium was covered by mainly sandy deposits in Unit 7 (Fig. 13), leading to a general rise of the average level of the river during this period. The *ruau de l'Archevêque* was not covered and was able to retain its hydrological functioning, albeit restricted, until it was filled in the 19th c. The covering of Unit 7 is thus not uniform across the whole alluvial plain, and probably remained close to the active channels.

5.3. Holocene period after the first human settlement

The alluvial reliefs inherited from quaternary evolution of the valley floor are modest, but worthy of note in an environment subject to hydrological hazards. Nevertheless, in the former urban space, the earliest occupied areas were in the higher zones, such as the Roman amphitheatre which took advantage of the low fluvial terrace (A, Fig. 6), and lower zones, such as the protohistoric settlement (M, Fig. 6) or the Roman baths (N, Fig. 6). This confirms that there are no pre-existing riverside sites that are specifically suitable for human settlement (e.g. Burnouf et al., 2001).

In the southern part of the former urban space, anthropogenic sediments of Unit 8 were deposited in a small channel about 21–210 cal. AD (Fig. 13). This channel functioned during the Holocene, but could also be a morphological legacy of the Weichselian that filled with water following a rise in the mean level of the piezometric surface during the Upper Holocene.

The wooden constructions in use during the first few decades of the open Roman town were replaced during the second half of the 1st c. AD by stone buildings or buildings associating stone foundations and wooden superstructure (Jouquand, 2007). This reconstruction phase was systematically preceded by the raising of the ground, sometimes over one metre thick (*ibid*.; Lorans et al., 2013). This was undoubtedly related to the need for flood protection, or more likely for protection against a gradual rise of the top of the alluvial water table, which was very shallow at that time (Driard, 2007). This rise was probably not related to climate forcing, because the Gallo-Roman period was not specifically humid (Büntgen et al., 2011). It could have been caused by strong sedimentary accretion in the active channels, leading to a general rise in the piezometric surface.

The rise in the piezometric surface, related to sedimentary accretion in the active channels, could also have been increased by human impact, as the alder forest in the alluvial plain of Tours started to decline during the Iron Age (Visset, 2011) and almost completely disappeared during the early Roman Empire (Vivent, 1998). By reducing evotranspiration and increasing runoff, this disappearance could have contributed to a rise in the level of water bodies in the valley (Smith and Charman, 1988; Chapman and Rose, 1991; Macaire et al., 2006; Morin et al., 2011). This phenomenon could also have been accentuated by civil and monumental constructions, because they required the exploitation of local resources (wood, quarries).

In the former urban space, as well as in many sectors of the alluvial plain, the thickness of anthropogenic deposits is generally greater than that of underlying alluvial deposits, although the latter were deposited over much longer periods. Currently, there are considerable differences in altitude between the highest sectors, in which urbanization was either very early (former urban space) or very recent (B, C and D, Fig. 1b), and lower sectors where urbanization either occurred in recent times (E, Fig. 1b) or is almost absent (A, Fig. 1b). These reliefs were not caused by the original morphology of the alluvial plain but by the thickness of anthropogenic deposits (Fig. 11), linked locally to the modalities of occupation and urbanization.

During the first millennium AD, some periods were probably more favourable for the spreading of the urban space into the low-flow channel of the Loire, on the south bank (Galinié et al., 2003b). Particularly, the channel of the Loire moved laterally: it has made progress to the south, probably by the 4th c., then to the north before the 9th–11th c.

At the scale of the Middle Loire River, the construction of bank stabilization works in the early Middle Ages contributed to the morphological stability of the alluvial plain. Since then, changes in river morphology have been limited to the constrained low-flow channel (sediment bars, islands), while the frequency and magnitude of major floods has increased (Garcin et al., 2006).

6. Conclusion

This study made use of a large number of sub-soil data, combining different methods. It identified the morphological and sedimentary evolution of the urbanized alluvial plain of Tours since the Weichselian, the morphological context of the first human settlements, and also the role of urbanization conditions on the present morphology of the valley floor. The study also contributes to our knowledge and understanding of the evolution of the flow of the Middle Loire in the recent Quaternary.

Since the last incision of the limestone bedrock, prior to the end of the Weichselian Upper Pleniglacial, coarse sediment was deposited in multi-channel systems, probably starting in the Weichselian Middle Pleniglacial. An incision phase followed by the deposition of coarse alluvium in the Late Glacial can be observed. The incision of channels during the transition between the Late Glacial and the Holocene brought about a migration of the Loire and the Cher to approximately the level of their present low-flow channels and a gradual abandoning of secondary channels. Organic sedimentation developed in these partially abandoned channels from the start of the Holocene and up to about 2134–1390 cal. BC, indicating a relative morphological stability of the alluvial plain and a relatively low average level of the river. However, reconnection of the secondary channels, together with a phase of moderate incision of earlier Holocene deposits between 7601–7504 cal. BC and 5212–4800 cal. BC, was observed. An upsurge of river flow occurred after 2134–1390 cal. BC and possibly up to human settlement in the 1st c. AD, with a morphological impact in the sectors close to the active channels.

The earliest human occupation was not concentrated on the low alluvial reliefs. Systematic fill during the second half of the 1st c. AD is likely to reflect a need for protection against a rise of the piezometric surface, probably caused by sedimentary accretion in the active channels and accentuated by human activity in the alluvial plain (exploitation of resources). Most of the present reliefs of the alluvial plain, notably in the former urban space, are due to the thickness of anthropogenic deposits.

The geomorphological models of the alluvial plain of Tours could be used as decision-making tools for local archaeology purposes. They could help schedule archaeological research, notably in the former urban space, by providing an estimation of the thickness of the archaeological deposit and highlighting gaps in documentation. These models could also prove useful for programming geotechnical operations and the technical management of the urban subsoil. The approach used in Tours can be reproduced in other towns located on alluvial plains which possess robust sedimentary and archaeological documentation.

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