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Morphodynamics of the Upper Pleistocene Garonne River (SW France): conditions of braiding/meandering transition

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Abstract :

The Garonne River developed through the Quaternary a huge network of asymmetric strath terraces. The last terrace is contemporary to the last glaciation. The mapping of the paleochannels preserved below the last Terrace of the Garonne River (southwest of France), by mean of remote sensing based on aerial photographs and field data, allows us to investigate the factors controlling factors of the transition braiding meandering related to the end of the last glaciation in the Pyrenees. Three channels patterns preserved in the infill of the lowest terrace of the Garonne River, could be evidenced. In chronological order, these patterns are: 1- braided channels before 30 ka, 2- low sinuosity gravel meandering channels until 15 ka and 3- high sinuosity gravel meandering channels before the end of the Younger Dryas. The available datings and palynologic data allow us to link this changes in fluvial morphology to the end of the last glaciation in the Pyrenees. The braided/meandering transition occurred 30 ka ago and the sinuosity sharply increased after 14 ka. This transition, in the context of the glacial retreat in the upstream Garonne valley is the result of interplay between vegetation and hydrologic regime of the river, which evolved from a glacial regime with high water stage in spring/summer to a pluvio-nival regime with high water stage in winter/spring leaving uncovered gravel bars by the time of vegetation germination.

Keywords:

Fluvial dynamics, meandering, braiding, fluvial terrace, Garonne, France, würmian glaciation

1 – Introduction

The study of fluvial planforms is a classic tool used in fluvial geomorphology for tracing changes in rivers dynamics. In ancient fluvial systems, fluvial styles are inferred from facies associations by mean of facies models (Miall, 1996). Only a few examples of observed ancient fluvial planform are available in the literature (Cuevas Martinez et al., 2009) and none of them deal with braided or meandering streams. Nevertheless, examples of ancient fluvial systems in which fluvial style can be observed both in planforms and outcrops (Rhine valley, southeastern coast of New Zealand) are available in quaternary systems but have not been studied up to now. Studies of the evolution of ancient fluvial forms could be of great interest in order to constrain the morphological changes associated with stages of lateral and vertical incision involved the formation and abandonment of quaternary fluvial terraces.

Since Penck and Brückner (1909) and their study of the terrace network of the alpine rivers, the link between the timing of quaternary glacial cycles and alluvial terrace abandonment has been widely studied and precised (Vandenberghe and Maddy,

2000; 2001; Bridgland and Westaway 2008a; 2008b). In the case of the Pyrenean rivers, recent studies emphasized the link between climatic fluctuations and alluvial terraces formation (Delmas et al., 2011; Stange et al., 2013). Though the terrace network was widely studied (Hubschman, 1975a; 1975b; Revel and Bourgeat, 1981; Bourgeat et al., 1984) in terms of geometry and pedology, almost nothing is known about the morphological characteristics of the rivers that gave birth to these alluvial terraces.

The Garonne River is the longest tributary issued from the northern side of the Pyrenees. On its middle course, on the north pyrenean piedmont, this river has carved an impressively wide (up to 25 km) and deep (175m) network of asymmetric stepped alluvial terraces all along Quaternary times. We focused our study on the lowest terrace of the Garonne. Due to its extensive preserved surface and its young age this terrace provides an exceptional

This article is aimed at showing the first extensive survey of a river planform evolution contemporary to the formation of a strath terrace as a response to the end of the last glacial cycle over a 40 km long reach, representing the 120 km² swept

by the river between the beginning of aggradation on the last terrace and its abandonment. This study is based on outcrop description, well log interpretations and remote sensing based on aerial photography. The transition between the different styles identified and the timing of changes in fluvial processes in response to climate change at the end of the last glaciation will be the base of our discussion.

2 – Geological and geomorphological settings

The Garonne river (southwest of France) is 647 km long. It rises on the slopes of Aneto Peak (highest summit of the Pyrenees). Its catchment covers 55 000 km², it is the major drain of the southwest of France. This terrace network developed through Quaternary times (Icole, 1974, Hushman, 1975 a, b).

Southward from Boussens, the substratum of the terrace network is made of alternating synclines and anticlines of the sub-pyrenean zone made of series from Upper cretaceous to Paleocene to Eocene limestone bearing series (Fig. 1).

To the north, this substratum is made of the syn-orogenic to post-orogenic molasses of the north Pyrenean foreland basin (Aquitaine basin). These molasses consist in fluvial deposits made of clays, marls, lacustrine/palustrine limestones and channelized sandstones and conglomerates. The age of these molasses ranges, in the studied area, from Oligocene to Miocene (Crouzel, 1957; Cahuzac et al., 1995; Dubreuilh et al., 1995; Antoine et al., 1997; Biteau et al., 2006). The molasses are sometimes overlain by alluvial deposits of the Lannemezan Formation, probably Pliocene to Lower Quaternary in age (Icole, 1974). The cumulated vertical incision of the Garonne river within the Lannemezan Fm. and molasses is up to 200 m.

Six main stepped terraces levels were identified (Hubschmann, 1975a; 1975b), labelled thereafter T1, the youngest to T6, the oldest (Fig. 1). The five oldest terraces are only known on the left bank of the Garonne. The youngest (T1 on Fig. 1) is mainly developed on the left bank, and poorly developed on the right bank due to the migration of the Garonne River toward the east (Fig. 1).

The chronology of these terraces is poorly constrained. The oldest and highest one (T6 on Fig.1) re-incised Pliocene to Lower Quaternary deposits of the Lannemezan Fm. (Icole, 1974). No precise datings are available, lower quaternary (Günz) age was attributed to this terrace (Icole, 1974) due to its position at the top of the terrace network and by analogy with Penck and Brückner (1909) stratigraphy of quaternary times. Terraces T5 to T2 are neither dated, ages were attributed to Mindel and Riss due to their elevation and infill weathering (Hushman, 1975a,b ; Stange et al., (2013).

The youngest terrace is the only one whose age is satisfactorily constrained. Charcoal sampled a few meter above the base of the infill gave 10,651+/-457 yrs Cal BP and 11,242+/-593 yrs Cal BP (Bourgeat et al., 1984; calibration CalPal). ¹⁰Be exposure dating in pits by Stange et al. (2013) indicates an abandonment age of T1 at 14.6 +9.6/-4.3 ¹⁰Be ka in Plaine de Rivière (upstream from Boussens, Fig. 1) and 13.1 +6.7/-3.9 ¹⁰Be ka in Cazères (Fig.1). Downstream from Toulouse (Fig. 1) several recent studies (Bruxelles et al. 2010, Bruxelles and Jarry, 2011, Carozza et al., 2013) based on radiocarbon dating constrained the age of silts covering the channel deposits of T1. After the abandonment of T1, the Garonne River started incising its molassic substratum carving several local terraces between T1 and the modern channel (Stange et al., 2013). Nowadays, in the studied area, upstream from Toulouse, the Garonne River flows on the molassic substratum. The post-T1 incision varies from south to north from 5 to 10m (Fig. 1). Though differences, datings indicate terrace T1 was abandoned during tardiglacial times.

We focused our study on a 40 km long segment of the up-to-5km-wide lower terrace between the topographic front of the Pyrenees (located to the north of the “Petites Pyrénées”, Fig. 1) to the south and the confluence with the Ariège River (10 km south of Toulouse) to the north.

3 – Data and methods

3.1– Remote sensing

Remote sensing based on the huge database of aerial photographs of the IGN (French Geographical Survey) allowed us to map the paleo-channels of the Garonne when it flew on the last terrace. We used panchromatic aerial photographs and orthorectified colour aerial photographs. The database includes all the aerial campaigns led between 1942 and 2008. Ground resolution, depending of the campaign flight altitude and camera type varies from 25 to 60 cm-wide pixels. Depending of the period of the year of the flight, the ground may exhibit a singular pattern (Figures 3 and 4). This pattern can correspond to: 1) differences in soil moisture on non-vegetated fields (fall and winter campaigns), 2) differences in vegetation growth (spring and summer campaigns) in response to soil moisture variations. Contrast intensity varies from a campaign to another but the pattern drawn on the same parcel remains the same through years.

Due to spectral response differences, each parcel was treated separately on the selected photographs. The treatment consists in a threshold filtering (leading to binarization on low contrast parcels) in order to enhance the original contrast (see examples later, Figs. 3 and 4).

3.2- Well log database

We interpolated an isopach map of the

quaternary sediments preserved below the terrace (Fig. 7) using the well log database of the BRGM (French geological survey) available through its online GIS Infoterre (<http://infoterre.brgm.fr>). This database takes into account all the pits, piezometers, pit quarries and wells cored in the sediments preserved below the terrace for quarry exploitation and water supply purposes. More than 950 logging reports were checked and re-interpreted. 300 wells crossed the base of the terrace deposits and went into the underlying substratum made of the oligocene "Molasses". Wells that did not cross the base of the gravel deposits were also used as minimum value of thickness. Thickness data were then interpolated. Considering the heterogeneity of the wells spatial distribution, we used a minimum curvature algorithm in order to avoid bull eyes effects.

4 – Paleochannel mapping

The channel patterns reconstructed by mean of remote sensing provide a vision of successive channels of the Garonne. Toward the North, the long-term urbanization and land use of the city of Muret and the southern suburbs of Toulouse (prior to the 40's), together with the poor quality of the 1940's and 1950's aerial photographs, do not allow for mapping the paleochannels clearly enough. The map of the Garonne paleochannels preserved below terrace T1 is shown on Figure 2.

4.1 – Fluvial styles

Two fluvial styles can be interpreted from the processed aerial photographs: braided pattern (Fig. 3) and meander belts (Fig. 4). Several braided areas could be recognised as well as three meander belts.

4.1.1- Braided streams

Braided streams were identified on 4 braided areas (BA: BA 1 to 4 from south to north on Fig. 2). Braided patterns are shown on Figure 3. Figure 3B exhibits the typical channel pattern encountered on the four braided areas. The pattern is made of low angle bifurcations (B, Fig. 3B) and downstream junctions (J, Fig. 3B, Ferguson, 1993) separating diamond shaped bars. Head channels disappearing upstream at the top of braid bars can also be identified (H, Fig. 3B). Channels width varies from 25 to 100m and shows the classical hierarchy of braided channels (Bridge, 1993) with wide central channels (1, Fig 3B) and narrow cross bar channels (2, Fig. 3B) isolating diamond shaped braid bars.

In BA 1, braided channels width varies from 25 to 45m. Mean channels direction indicates paleocurrents striking N38E. Northwards, BA 2 is the largest braided area identified on terrace T1 (Fig. 2). BA 2 is bounded to the left by terrace T2 scarp and to the right by meander belts (see § 4.1.2 below). BA 2 is 19 km long and its mean width is 1.6 km. On BA 2, braided channel width reaches 75 to 125 m. Mean channel direction varies from N60E-70E to the south, then it describes a gentle northward curve in the Laffite

Vigordane area, reaching values N10E-20E to the north. To the north paleocurrents reveal another curve to the northwest with values of N30E and local bends till N70E.

BA 3 (Fig. 2, Fig. 3B) is located in the central part of the study area to the northwest of Carbonne. BA 3 is bounded on its left and right bank by meander belts. Braided channel geometry is similar than in BA 2 and paleocurrent trends are parallel to those of BA 2 in the same reach (N30E with bends reaching N70E). It suggests that BA 2 and 3 belong to the same ancient braided reach of the Garonne.

The northernmost braided area (BA 4 on Fig. 2) is located southward from Muret, it is bounded to the northwest and to the southwest by meander belts. In this area, braiding pattern is radically different than in the three other braiding areas. Channels are more sinuous and exhibit a better downstream continuity. Nevertheless it exhibits numerous bifurcations and junctions and the same hierarchy in channel width (Fig. 3C). Due to curvier channels, the diamond shape of braid bars is difficult to identify (Fig. 3C). Despite these similarities, this pattern also exhibits lateral accretion surfaces characteristic of meandering channels (M, Fig. 3C). We interpret this planform as a wandering channel pattern (Brierley and Hickin., 1991, Fig. 3C). Though different in shape than the other braiding areas this area cannot be considered as contemporaneous to the meanders. It would better represent a downstream evolution of the braided pattern as it is observed in several modern rivers (Brierley and Hickin, 1991).

Similarities and continuity in paleocurrents and a similar morphology seem to indicate that the four braided areas identified belong to a single stage of evolution of the river morphology. Younger channels separated then these braided areas.

4.1.2 – Meander belts

Three meander belts can be identified based on their channel pattern, sinuosity and their geometric relationships. Figure 4 exhibits the fluvial patterns corresponding to these meander belts. On Figure, we can see the pattern is made of a single band, with weak downstream variations. This band is sinuous and corresponds to the former channel. Inside the bends, arcuate lines, locally crosscutting the others can be identified (PB on Fig. 4B). These arcuate lines correspond to lateral accretion surfaces and depict a point bar. In the inner part of the first pointbar, another channel can be seen (CCh on Fig. 4B), due to its location, this channel can be interpreted as a chute channel.

The first Meander belt is MB1 (Fig. 2, Fig. 4), it is the major feature of terrace T1 (Fig. 2). In the southern part of T1, between Boussens and Cazères, MB1 occupies most of the terrace surface. In this southern part, channels exhibit poor downstream continuity due to numerous meander cut-off. Channels exhibit width

60-90m and sinuosity up to 1.4 (Fig. 4C). MB1 is bounded to the right by MB2 (Fig. 2). North of Cazères, MB1 divides into two branches isolating BA1. Northeastward, MB1 bounds BA2 and disappears as it is cut by MB2 over a 3km reach. MB1 re-appears northward to the south of Laffite Vigordane, bounding to the left BA2 and still bounded to the right by MB2. Northward, between Laffite Vigordane and Carbonne MB1 divides newly into two branches. The left one crosscuts the braided deposits, separating BA2 and BA3. This branch is the results of the limited wandering of an only meandering channel. This branch is 750m to 1 km wide what corresponds to the amplitude of the meanders observed in the area (Fig. 4B). Channel width increases to 125 m. The right branch bypasses BA3 to the right. MB1 is preserved here due to the disappearance of MB2. To the northeast of Carbonne, this branch disappears, crosscut by the reappearing MB2. To the north MB1 extends the left branch mentioned above. Between Carbonne and Muret MB1 completely replaces BA2 and reaches terrace T2 scarp, isolating BA4. To the north of BA4, MB1 is replaced by MB2. In terms of topography, the surface on top of MB1 remains at the same elevation than Braided Areas (BA 1 to 4, Fig. 2) such that no scarp allows discriminating them on the field.

The second meander belt, MB2 (Fig.2) only occurs on the right part of terrace T1, close to the scarp separating T1 from the modern channel of the river. MB2 is made of more sinuous channels than MB1. This higher sinuosity can be seen looking at the shape of the left MB2 boundary exhibiting numerous well-preserved meander loops. Meanders of MB2 mainly show lateral accretion and less downstream migration than meanders of MB1 (Fig.2). Channels are XXX m-wide. MB2 appears downstream from Boussens (south of Fig. 2). Here, MB2 channels crosscut MB1 meanders. MB2 develops then downstream, with fluctuating width. To the northeast of Cazères MB2 completely cuts MB1, making it disappear and also crosscuts BA2. MB2 abruptly disappears a few kilometers south from Carbonne, close to the confluence with the Arize River. It reappears a few kilometres downstream from Carbonne, crosscutting BA3 and then, northward newly cutting MB1 channels. Northward, it bounds BA 4 to the right. Finally, to the southwest of Muret, to the north of BA4, MB2 crosscuts MB1 meanders, reaching the scarp of terrace T2. Toward Muret MB2 occupies the whole width of terrace T1.

In terms of topography, to the south (between Boussens and Cazères) a 5 m high scarp separates MB2 from MB1. Downstream, this scarp elevation diminishes, occurring punctually along the boundary (relics of the former cutbanks?). It finally disappears between Cazères and Carbone. Downstream, MB2, MB1, BA2 and BA3 remain at the same elevation.

A third meander belt was identified (MB3). MB3 is poorly preserved. It only locates in the inner part of modern meanders of the Garonne River (Fig. 2). They result from the modern meander scroll. On a

topographic point of view these accretion surfaces testifying of the recent motion of the Channel are located below the terrace T1 level and above the modern channel. Hence, we can think these accretion surface are contemporary to the incision which provoked the final abandonment of T1.

4.2 - Relative chronology

In Terms of chronology, braided channels seem to be the oldest because they have been superimposed by meander belts. Meander of MB1 eroded and/or reworked sediments of Braided Channels. To the northwest of Cazères (Fig. 2) the terrace scarp between T2 and T1 exhibits a “re-entrant” showing channels of MB1 eroded the former braided deposits as well as T2 scarp. To the south (north of Cazères, Fig.1), MB1 meanders crosscut BA1. To the north (Carbonne), MB1 separates BA2 and BA3.

MB2, due to its location on the right part (southeast) of the terrace, close to the modern river and the meander loops cutting BA2, BA3 and MB1 meanders indicate these meanders are younger; this seems confirmed by its position at lower elevation. The radiocarbon ages by Bourgeat et al. (1984), significantly younger than the other ages presented in introduction were performed on samples issued from the base of the sediments of MB2 (Fig.1). They seem to confirm that MB2 postdates BA2, BA3 and MB1. MB3, located close to the modern course of the Garonne River is younger than MB2 and represents the last stage of the river course before or during the final abandonment of terrace T1.

5- Sedimentology

Thanks to the numerous quarries excavating the deposits of the lower terrace of the Garonne, the first meters below the terrace and above the water table can be easily studied in terms of facies analysis (Figure 1.5).

The deposits consist in non-cemented round pebbles to cobbles with sandy matrix interbedded with sandy lenses. Outcrops exhibit decametre to hectometre-wide and metre-deep channels made of stacked gravel bars partly interbedded with sand dunes organized in lateral accretion bedforms. Channels exhibit low depth compare to the thickness of sediments preserved on the terrace.

5.1. Braided Channels

In the area of Laffite Vigordane (Fig.1, Fig. 5), a quarry front illustrates the typical facies associations encountered. Before the exploitation of the quarry a well was cored (Fig. 5A). Figure 5C shows the lithologic log of the sediments encountered in the well, from base to top: 1) from 14 m to 13,30 m: sandy marls and limestones of the Oligocene molasses. 2) from 13,30 to 3,00 m: gravels with sandy matrix, 3) from 3,00 to 2,60 m: grey-blue medium sands, 4) from 2,60m to 1,40m: gravels with grey sandy matrix, 5) From 1,40 to 0,60m : gravels with sandy matrix

cemented by iron and manganese oxides resulting from the pedogenesis below the terrace surface after its abandonment, 6) brown clayish and silty sands and 7) humus and clays horizon. The working face of the quarry pit helped us to understand better the geometry of the gravel and sand bodies in the first meters below the terrace. This working face illustrates the five first meters below the surface. Figure 5 represents the face of the pit quarry as seen on June 2012. From top to base on Figure 5B, the face exhibits light brown clays and silts, unconsolidated sands interfingering within the underlying gravels. Below these deposits, most of the face is made of unconsolidated sandy matrix gravels interbedded with medium to coarse sands lenses. The gravels are organized into decametre-wide and metre-deep concave up and flat-topped swales. These swales exhibit a single-storey fill made of apparently lateral migrating bars exhibiting low angle centimetre thick heterolithic stratifications. No significant erosional surfaces were identified within the swale fill. Imbricated clasts reveal currents striking N32E, mostly oblique toward the working face and in accordance with the channel strike observed on aerial photographs (Fig. 5A). The sandy lenses identified are metre-wide and centimetre-thick. Their shape is flat-based and convex up topped. These sands exhibit planar and trough cross bedding (Fig. 5D).

The overall geometry (symmetric, weak depth), size (decametre wide and decimetre deep) of the channels identified together with the grain size of the infill supports the interpretation of braided channels. The good preservation of sand bars within the channel fills as well as the lack of erosional surfaces within and between channels infill indicate high conditions of aggradation during deposition.

5.2. Gravel bed meandering channels

In the area of Cazères (Fig.1) another quarry pit allowed us to investigate the sedimentology of the meandering channels. Like in Laffite Vigordane, a well cored in the deposits of the terrace reached the molassic substratum. The sedimentary log on Figure 6A shows, compared to braided channel deposits (Fig. 5C) more variations in grain size. The column is made of metre-thick alternating sands, pebbly sands and pebble beds organized in seven fining upward sequences. The base of the terrace infill was reached at 13.5 m

Figure 6B exhibits the pit quarry face. At first sight, this outcrop presents great similarities with the outcrop of braided channels presented in §5.1. Sediments have the same grain size. Nevertheless we can observe on Figure. 6B there is more heterogeneity in grain size distribution as observed in well (Fig. 6A). In terms of architectural elements, the outcrop, from left to right, is made of alternating pebbles and sandy pebbles. Geometry of these beds is planar and inclined. To the left of the outcrop, apparent dip changes following the change in direction of the working face. Inclined planar beds occupy the left half of the outcrop. To the right,

apparent dip slightly diminishes. Beds are then cut by more inclined beds. To the right, these beds exhibit a regular decrease of dip until they remain flat, describing a half swale. At the base of this swale, gravels are organized in planar inclined beds corresponding to the lee-side of a gravel bar. Paleocurrents measured on the planar beds reveals a N47E-striking mean current showing the flow was mostly perpendicular to the working face in the axis of the channel. Apparent flat stratification corresponds in fact to planar inclined surfaces dipping perpendicularly to the outcrop. The overall architecture of the outcrop consists in a lateral accretion macroform passing to a channel axis filled by downstream accreting gravel bars. The outcrop depicts a meander pointbar and its neighbouring channel. Considering paleocurrents, the point bar is the left bank of the channel. The cutbank to the right of the channel could not be recognized.

The channel identified on the right part of the outcrop is 120 m-wide and 4 m-deep. The width of this channel has the same order of magnitude than those observed on the map (Fig. 2) in the same area. Compared to braided channel previously described, the gravel bed meandering channel of the Cazères pit quarry is wider and deeper. It also exhibits outcrop-scaled sigmoidal stratifications associated to heterogeneity in grain size, with alternating sandy pebbles and pebbly sands. Together with their inclined geometry can be interpreted as an equivalent of the IHS (Inclined Heterolithic Sandstones) for gravel meandering channels. IHS are widely described in sandy meandering rivers (Thomas et al., 1987) as corresponding to lateral accretion macroforms (Miall, 1996) and are characteristic of meandering channels.

6 – Sediment thickness

The thickness of sediments of the terrace infill observed in wells and pits ranges 3 to 19 m (Fig. 7A). Sediment thickness roughly diminishes from south to north. To the south, a few kilometres northeast of Boussens, local strong variations in thickness occur. In this area, terrace T1 substratum corresponds to the north-dipping Upper Cretaceous to Eocene sedimentary series of the subpyrenean folds. These sediments are made of alternating limestones and marls. The sharp changes in thickness observed correspond to local pools and riffles carved in the strath by differential erosion due to lithologic contrasts. These pools and riffles can be observed on the topographic maps of the strath, to the south (Fig. 7B).

A depoaxis with thicknesses around 12-16 m occurs between Boussens and Carbonne along the boundary with terrace T2 (northwestern boundary of the terrace). Southeastward from this depoaxis, the thickness diminishes rapidly to 6 m and less. This area of low thickness locates along the boundary between T1 and the Garonne River. Comparing thickness map with the paleochannel

map (Fig. 2), we can quote the abatement in thickness is associated with the transition between braiding patterns and meandering belts. It suggests that more aggradation occurred during braidplain deposition than meanders.

A sharp decrease of thickness can be observed downstream, to the northwest of Carbone. There, thickness varies from 17 m to 5 m over 5 km. Northward Muret thickness remains low (1 to 6 m) with weak variations. As observed southward, areas of low thickness are also located along the boundary between T1 and the Garonne River.

The comparison of the isopach map with the paleochannels map on Figure 2 shows the depoaxis described above is associated with the deposits of the Braided Area 2 (BA2) though low thicknesses areas are associated with meanders. To the north, between Carbone and Muret, sediment thickness remains low. In this area, the lowest thicknesses (6 to 4m and less) are associated to Braided Area 4 (BA4) while slightly higher thicknesses (5 to 7m) corresponds to Meander Belt 1 (MB1 on Fig. 2). It would indicate that, in this part of the terrace, less fluvial aggradation occurred by the time of deposition of braided streams than in the south of the terrace, though aggradation of meanders of MB1 was as equivalent or slightly higher than braided streams aggradation. As observed southward, deposits located close to the eastern boundary of terrace T1 exhibit the lowest thicknesses and are associated with MB 2 deposits.

7 – Discussion

7.1 – Chronology and end of the würmian glaciation

Our results allow us to refine the conditions of the abandonment of the T1 terrace at the end of the Würmian glaciation. Recently, Stange et al., (2013) showed evidence for the role of the quaternary climatic fluctuations on the abandonment of the terraces of the Garonne. In their study, Stange et al., (2013) provide datings of the sediment of the Barbazan Lake, (see figure 8). The curve represents the age vs. depth in the core. The gradient of the curve represents the sedimentation rate.

Andrieu-Ponel et al. (1988) also studied the sediments of the Barbazan Lake in terms of sedimentology, palynology and radiometric datings. In terms of sedimentology, Andrieu-Ponel et al. (1988) showed the base of the column is made of glacial deposits (rythmites and lacustrine turbidites). In contrast, above 10m (i.e. following ~30 ka), sediments lack glacial influence and are only resulting from decantation processes. It shows that the Barbazan Lake was no more under the influence of the retreating glacier and that sedimentary input was directly controlled by the precipitation in the source catchment (Fig. 8).

Evolution of palynomorphs through time shows

a drastic change in the vegetation surrounding the lake around 30 000 yrs Cal BP. Before, vegetation was mainly made of *Abies*, *Picea* and *Fagus* whereas following 30 ka, vegetation was dominated by *Artemisia*, showing vegetation becomes bushy as a response to a dryer climate until 16 900 yrs Cal BP (Van Campo, 1985; Jalut and Turu I Michels, 2006). This dryer climate is corroborated by the occurrence of loess deposits in the Garonne valley and its tributaries in the Toulouse area since 26366 +/- 1773yrs Cal BP (Revel and Bourgeat, 1981). During the Bölling/Allerød (16 900 – 14 075 yrs Cal BP), rapid changes in the vegetation are observed with the appearance of *Juniperus*, *Betula*, *Abies* (Jalut and Turu I Michels, 2006). This dynamic of colonization by warmer climate species stops during the older Dryas (12 895 -11 700 yrs Cal BP, Jalut and Turu I Michels, 2006). After the end of the younger Dryas (8320-8070 yrs Cal BP, for Carozza et al., 2014), vegetation changes to deciduous trees such as *Quercus*, *Ulmus*, *Salix* and *Corylus* (Jalut and Turu I Michels, 2006; work in progress cited in Carozza et al., 2014).

Correlation between channel belt datings, climatic and vegetation data show a strong relation between climate evolution and river morphodynamics. Indeed, though they are not dated, braided stream of BA1-4 can be contemporary to the pleniglacial stage and the beginning of the glacial retreat in the Pyrenees. The change in sedimentation in the Barbazan Lake (around 30 000 yrs Cal BP) associated with a drier climate and different vegetation seems to indicate a change in the hydrologic regime of the Garonne which can originate a change in fluvial patterns from braided to meandering (Fig. 8).

Dates on terrace T1 exhibited on Figure 9 reveals the abandonment of MB1 occurred around 14 000 yrs Cal BP. It corresponds to the period of the Bölling/Allerød. Hence we propose the abandonment of MB1 is related to hydraulic events related to the warm period of the Bölling, mainly an increase in precipitation as shown by the increase in sedimentation rate in the Barbazan Lake (Fig. 8). Available dates from the literature are younger for MB2 channels than for other channels (Fig. 9; Bourgeat et al., 1984). Moreover, these ages are maximum values as they do not come from silts above the channel deposits. These observations made us correlate the increase in sinuosity of the Garonne with the Younger Dryas event and more precisely with the warming and increase in precipitations in the Garonne catchment at the end of this period, as shown by the increase in sedimentation rates in the Barbazan Lake (Fig. 8, Stange et al., 2013). Consequently, surface exposure ages by Stange et al. (2013) would not show the final abandonment of T1 but only the abandonment of MB1, the final abandonment of T1 occurring later, following the abandonment of MB2 at the end of the Younger Dryas (Fig. 9). This chronology is

summarized on figure 10.

This analysis of the morphodynamic evolution of the Garonne river by the times of formation of T1 confirms the climatic control of the terraces abandonment previously proposed by Stange et al. (2013). Considering datings, it seems the Older to Younger Dryas terrace identified by Stange et al. (2013) upstream from our study area disappears downstream and makes an only terrace level together with the Würmian (MIS 2) terrace (T1 terrace in this study).

7.2 – Braiding /meandering transition

As shown in the previous paragraph the change in fluvial style between BA 1-4, MB1 and MB2 (mainly an increase in sinuosity) can be correlated with climatic events contemporary to the last pleniglacial and late glacial Würm as indicated by datings and correlations with sedimentary dynamics in glacial lakes (Stange et al., 2013; Andrieu-Ponel et al., 1988) and vegetation evolution shown by palynology (Andrieu-Ponel et al., 1993; Andrieu-Ponel, 1991; Jalut et al., 2006). Nevertheless, we can wonder how these events controlled the morphology of the Garonne River. Such kind of data gives us indication of the climatic context but they cannot be interpreted in terms of river hydrologic dynamics.

The braiding/meandering transition generated, a huge literature since the 50's (see review by Métivier and Barrier 2012). Through years influence of several parameter was discarded. Bridge (1993) pointed out the lack of influence of discharge: "Discharge variability does not exert a major influence on the existence of the different channel patterns because they can all be formed in laboratory channels at constant discharge". More recent studies confirmed this statement (see review in Métivier and Barrier, 2012).

Channel slope was also invoked as a key parameter in the transition braided/meandering. Lane (1957) ; van den Berg, (1995) stated that threshold slope values controls this transition with meandering channel below the threshold value and braided channels above. Schumm and Kahn (1972) showed with analog modelling of channels that stable meanders could occur for higher slope values than braided streams, depending on sediments grain size and discharge. Other studies showed that channel slope is the result of the combination of other parameters and cannot be considered as an independent parameter (Carson, 1984 ; Lewin and Brewer, 2001; Métivier and Barrier, 2012).

Grain size can also play a role in the braided meandering transition (Schumm and Kahn, 1972 ; Métivier and Barrier, 2012). In the case of the Upper Pleistocene Garonne River, grain size is not likely to play a role in the braided/meandering transition because grain size of material observed in braided streams (Fig. 5) and in meanders (Fig. 6) is the

same. It seems the gravel meanders only reworked material previously deposited by braided streams. This observation seems to be quite common in gravel meandering rivers and was yet proposed by Brierley and Hickin (1991).

In the last years, two parameters referred to play a role in this transition were object of attention: 1) cohesive material on channel banks increasing resistance to erosion (Smith, 1998; Rowntree and Dollar, 1999) and 2) role of vegetation and its role in fixing bedforms and pointbars (Tal and Paola, 2007; 2010; Brauderick et al., 2009; Ghibling and Davies, 2012).

The occurrence of cohesive materials in the terrace T1 infill is scarce. As shown on figure 5 and 6, channel deposits are made of pebbles and sands. The only silty or clayish sediments are observed at the top of the channel deposits. The silts observed above the channel deposits (Fig. 5 and 9) are widespread all over the terrace covering both the braided and meandering channels. outcrops exposed in quarry pits do not exhibit silt or clay within channels but only at the top of both channels and pointbars (Fig. 6). Moreover when present, silts and clay represent only rather thin beds (< 50cm). Anyway, at least part of these silts deposited after the abandonment of the terrace by low order tributaries superposed to the terrace. Another part is contemporary to the progressive abandonment and wandering of channels, silts and clays filling former channels during floods. Cohesive sediment such as silts or clays are classically not observed in braided channels, which suggests that silts and clays covering the braided channels are not contemporary to the channel activity but deposited after the braided channels abandonment. In the case of meanders, gravel meandering rivers were poorly considered (Bluck, 1971; Ori, 1979; Arche, 1983; Brierley and Hickin, 1991) but facies models for gravel meandering rivers (Miall, 1996) show silts and clays are scarce in such rivers and play no major role in increasing bank stability (Rowntree and Dollar, 1999).

The role of vegetation in the stabilization of meander at the onset of MB1 (Fig. 2) is more difficult to evidence. The change in vegetation at 30 000 yrs Cal BP (Andrieu-Ponel et al, 1988) is registered in the Barbazan Lake. It indicates a change in vegetation at regional scale correlated with a dry event known in whole Europe (Van Campo, 1985). Nevertheless this regional change in vegetation does not depict the characteristics of the riparian vegetation, which, even if the climate becomes dryer, remains in moist condition due to the water discharge in the stream. In their studies dedicated to the conditions stabilization of meanders, Tal and Paola (2007; 2010) and Brauderick et al. (2009) showed the role of vegetation in stabilizing meanders. Indirectly, they also show it is important to have fluctuations in

water discharge in streams. Indeed, with fluctuating discharge, the top of bedforms remains uncovered between discharge peaks allowing germination and the growth of vegetation. This vegetation helps then the bedform to resist erosion during the following flood. In studies presented by Tal and Paola (2007; 2010) and Braudrick et al. (2009), meanders could not be stabilized because, the discharge being constant, sand bars remained under water which did not allow germination and sufficient growth of plants. Considering the time needed for germination and growth of vegetation on bedforms, it would indicate the fluctuations of discharge varies from an annual to pluri-annual cycles, which is the typical time scale of an hydrological regime of a river. In the modern Garonne River, sand or gravel bars need at least to years for germination of seedling of a pioneer specie such as *Populus nigra* and even more time in order to stabilize the bedform (Corenblit et al., 2013).

Another key point in the role of the vegetation for stabilizing meanders is the relationship between time of germination and the high water stage in the river. Indeed, germination and growth start generally in spring. In rivers exhibiting a glacial hydrologic regime in Western Europe, high water stage occurs in July and August with discharge starting to increase in April (case of swiss alpine rivers). This would indicate that bars in channels are covered by water by the time of germination. On the contrary, in pluvio-nival hydrologic regime (such as the modern Garonne River), high water stage occurs in February and March and low water stage occurs in summer. This indicates that bars remain uncovered within the time of germination of the vegetation. Hence, we can think that, at the end of the last glaciation, the hydrologic regime of the Garonne River progressively changed from a glacial to a pluvio-nival hydrologic regime and, as a consequence, the shift of the high water stage from summer to winter allowed the vegetation to settle the gravel bars and stabilized meanders.

Thus, in the case of the transition from BA 1-4 to MB1, the stabilization of meanders may result from a change in the hydrological regime allowing sand bars to remain uncovered by flow during dry periods and to be colonized by pioneer vegetation. In the case of the transition between MB1 and MB2, the change in hydrologic and vegetation characteristics allowing new species growing faster to develop in the riparian vegetation, increasing meanders stability and sinuosity.

As whole, morphological adjustments of the Garonne River could be better a response of the river channels to changes in hydrological regimes passing from a glacial hydrological regime to a pluvio-nival regime shifting the high water stage to the end of winter and spring and putting it in phase with the cycle of germination and growth of the vegetation.

8 – Conclusions

The mapping of the paleochannels preserved in the infill of the lowest terrace of the Garonne by mean of remote sensing based on aerial photographs and field data allows us to reconstruct the evolution of fluvial styles in time and space at the end of the Würmian glaciation. Fluvial aggradation on top of the strath started after 35,000 BP associated with a braided morphology (BA 1 to 4 on Fig. 2 and 10), contemporary to the retreat of Pyrenean glaciers (Andrieu et al., 1991, Delmas et al. 2011; Stange et al. 2013) and the increase of water discharge at some periods of the hydrologic cycle allowing more bedload transport. The Garonne changed its morphology to a low sinuosity gravel bed meandering stream (MB1 on Fig. 2 and 10) contemporary to the intensification of glacial melting identified in the Barbazan Lake around 25 600 +/- 800 yrs¹⁴C (30 456 +/- 831 yrs Cal BP, Andrieu-Ponel et al., 1988). This change in morphology would be the consequence of the change in hydrologic regime of the Garonne River passing from a glacial to pluvio-nival hydrologic regime associated to the development of bushy vegetation on pointbars at low water stage provoking meander stabilization of meanders. MB1 was abandoned after 15,000 BP. The Garonne evolved then toward a high sinuosity gravel meandering river contemporaneous of MB2 which was active till the end of the Younger Dryas. This drastic change in morphology could be the consequence of changes in hydrologic regime at the end of the Younger Dryas associated to the end of the “dry climate” allowing the development of denser riparian vegetation.

The abandonment of MB2 and final abandonment of Terrace T1 is so younger than the Younger Dryas.

Our study shows this terrace is composite, recording below an only flat surface a complex history made of partial abandonments and reworking contemporaneous of hydrologic regime changes and interplay with vegetation changes related with the end of the last glaciation.

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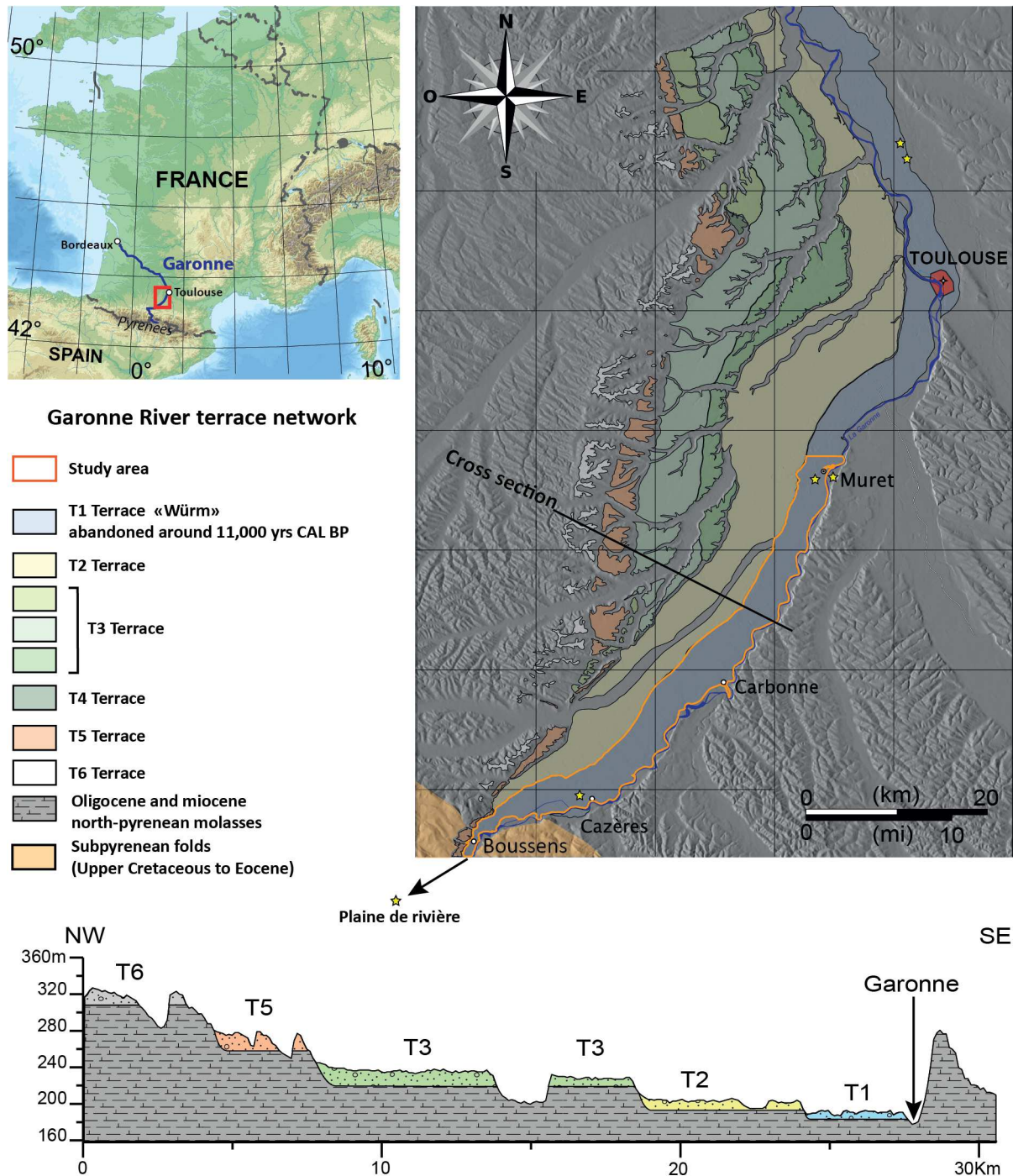


Figure 1: Geological map of the north-pyrenean foothill along the Garonne, location of the study area and geological cross section (modified from Hubschmann, 1975a, b; Courbouleix and Barnolas, 2008). Yellow stars: datings (north: Bruxelles et Jarry 2011, south of Muret: Bourgeat et al., 1984, Cazères and out of the map: Stange et al., 2013). Yellow stars: datings sites exhibited on figure 8.

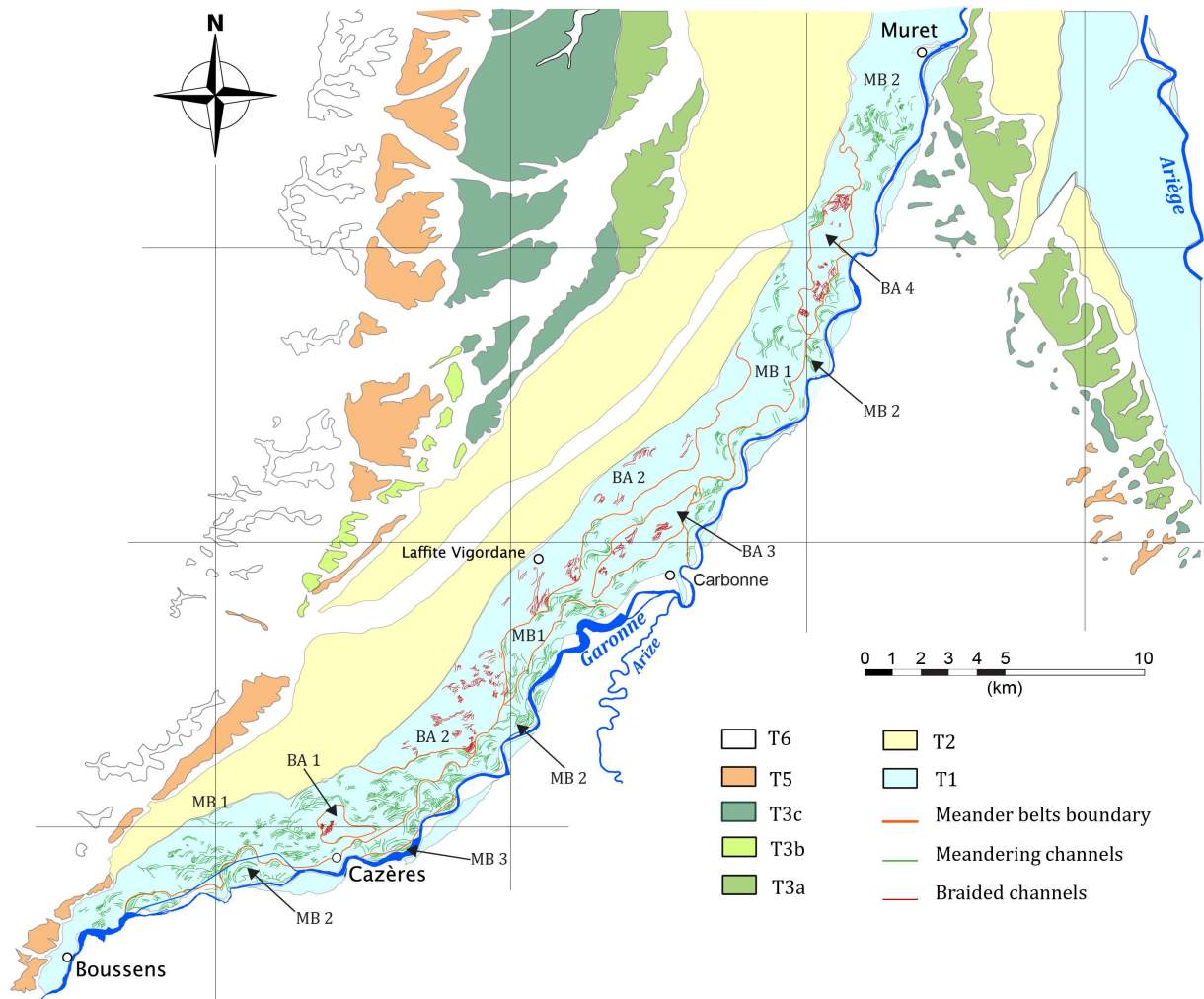


Figure 2: Map of the fluvial planforms of the Garonne river preserved below the lowest terrace (T1). In yellow: boundary of the lowest Terrace (T1), in red: braid channels, in green: meandering channels, in orange: boundaries of the main fluvial belts, in blue: channel preserved below the second terrace (T2), in light blue: modern Garonne river boundary. BA 1 to 4: Braided areas. MB 1 to 3: Meander Belts.

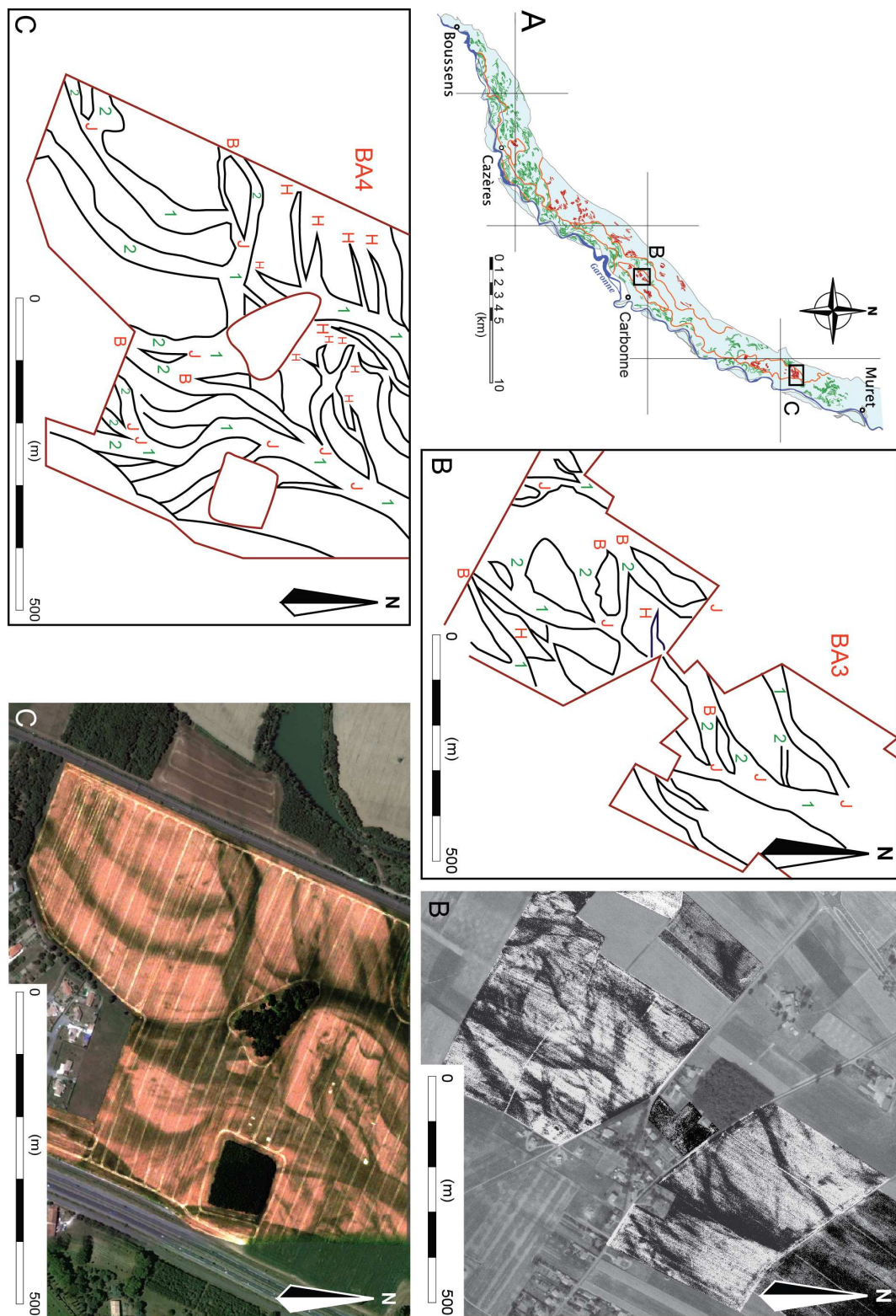


Figure 3: Braided pattern of the Garonne lowest terrace highlighted by remote sensing based on aerial photographs. A: Location of B and C. B: Braiding pattern of BA3. C: Braided channel in BA4; note that the difference in shape of the channels: they are more sinuous than B. Topological classifications of channel nodes (Ferguson, 1993): J: junction; B: bifurcation, H: channel head. Channels orders: 1 and 2 (Bridge, 1993).

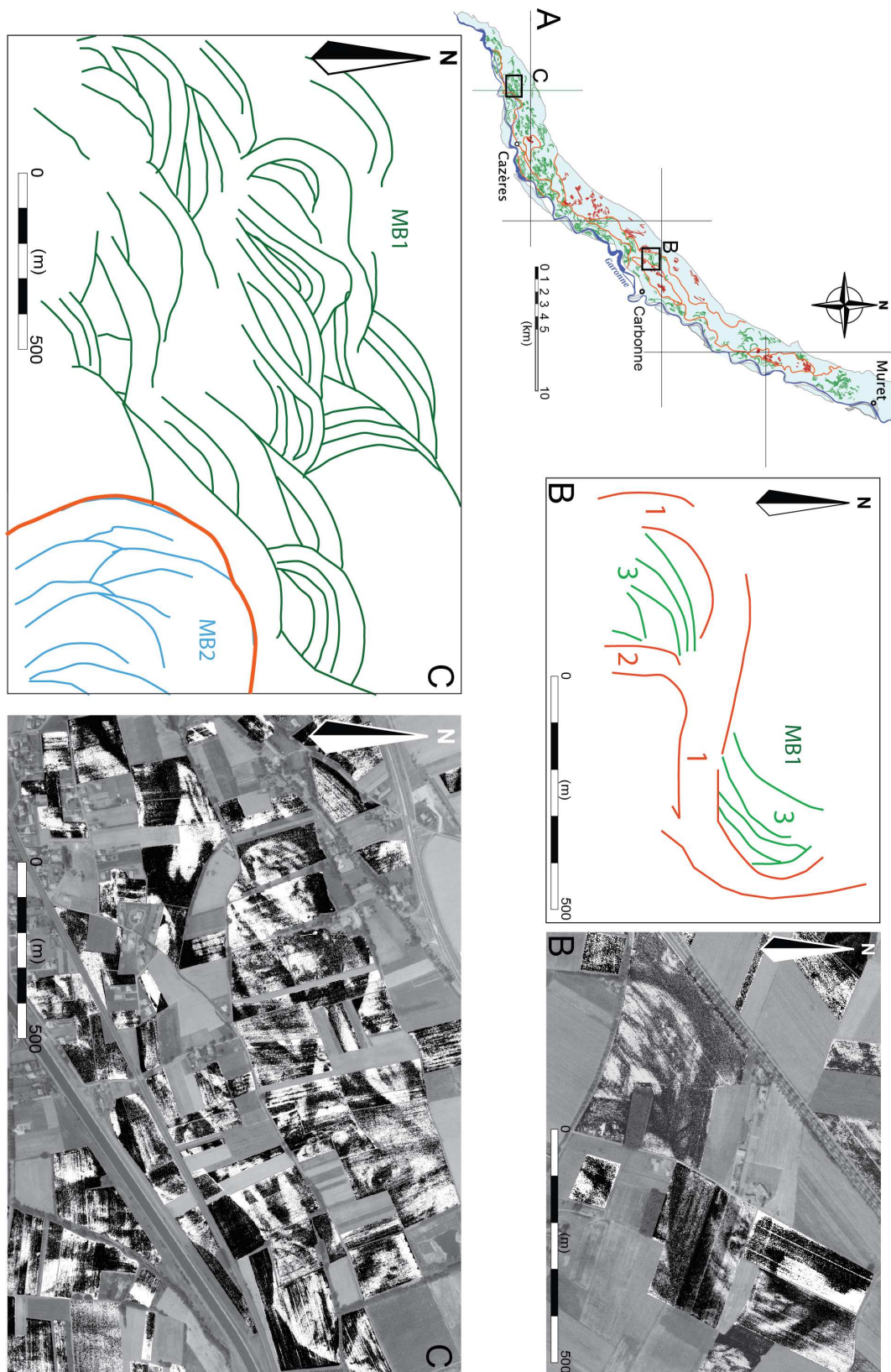


Figure 4: Meandering planforms of the Garonne lowest terrace evidenced by remote sensing based on aerial photographs. A: Location of B and C. B: Meander of MB1. C: Meander loops of MB1 between Cazères and Boussens.

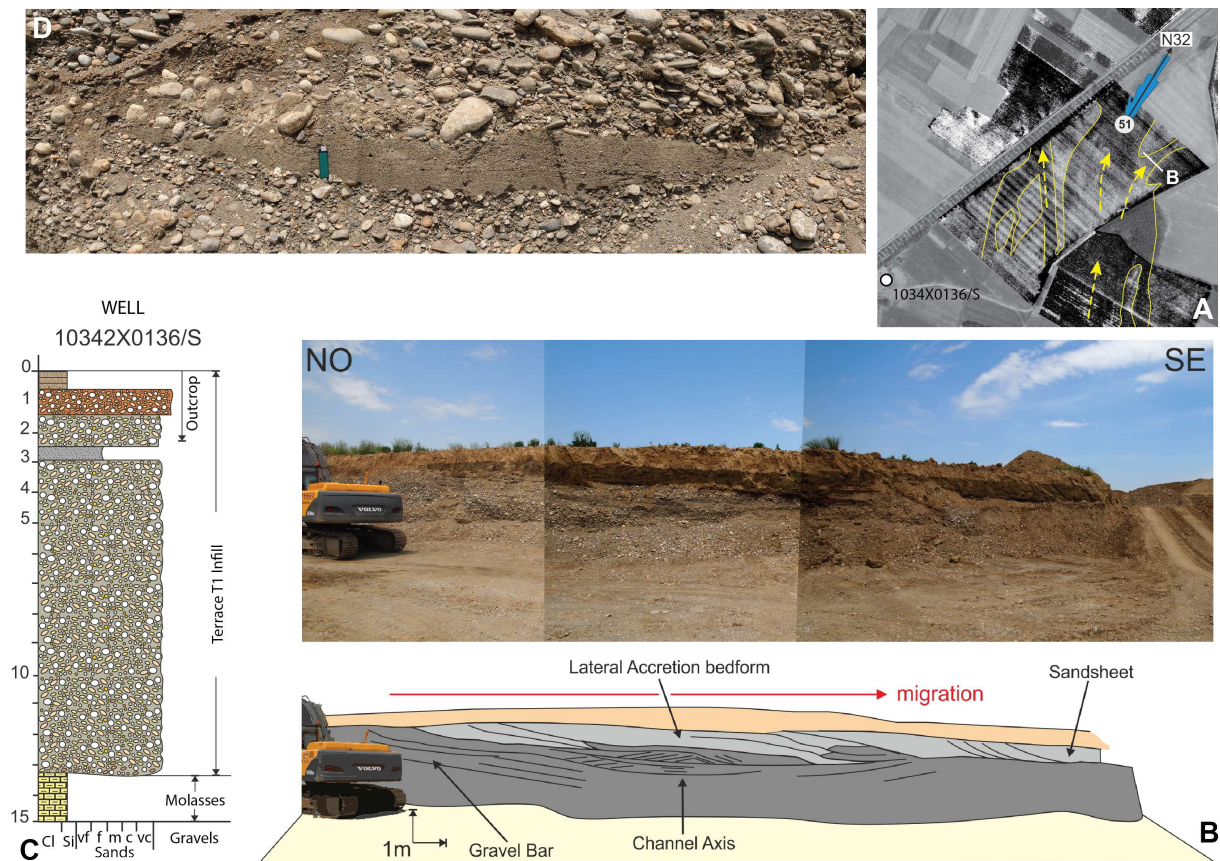


Figure 5: Outcrops of the braided channels of the Garonne lowest terrace. A: location of the outcrops in the pit-quarry and paleocurrents. B: Well log cored previous to the exploitation of the quarry (location on A). C: Outcrop showing the transition between the two main channels identified on aerial photographs. Channels. D: Structure of the southeastern channel. E: Gravel bar preserved in the northwestern channel. Paleocurrent rose diagram on A was measured on this outcrop. F: Detail of a sandy lens.

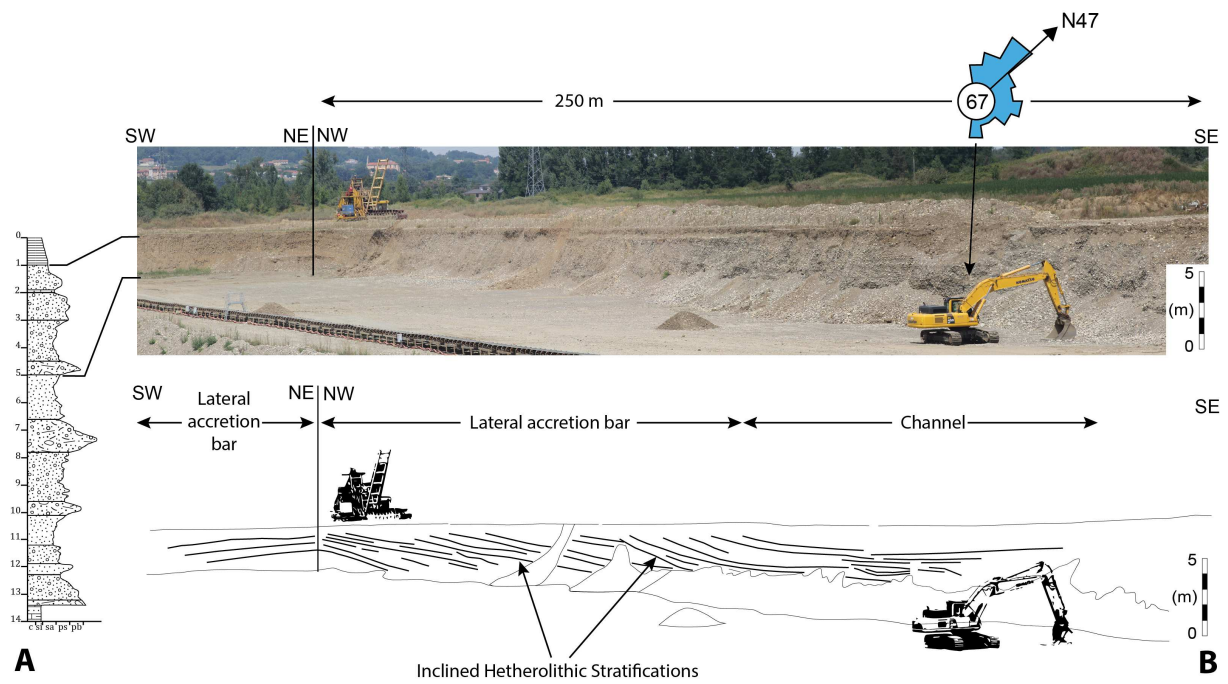


Figure 6: Outcrop of the gravel meandering channels of the Garonne lowest terrace in Cazères. Channels belong to MB1 (Fig. 2). Remark the increasing depth of channel and the steep slope of IHS compared to braided channel exhibited on Figure 5.

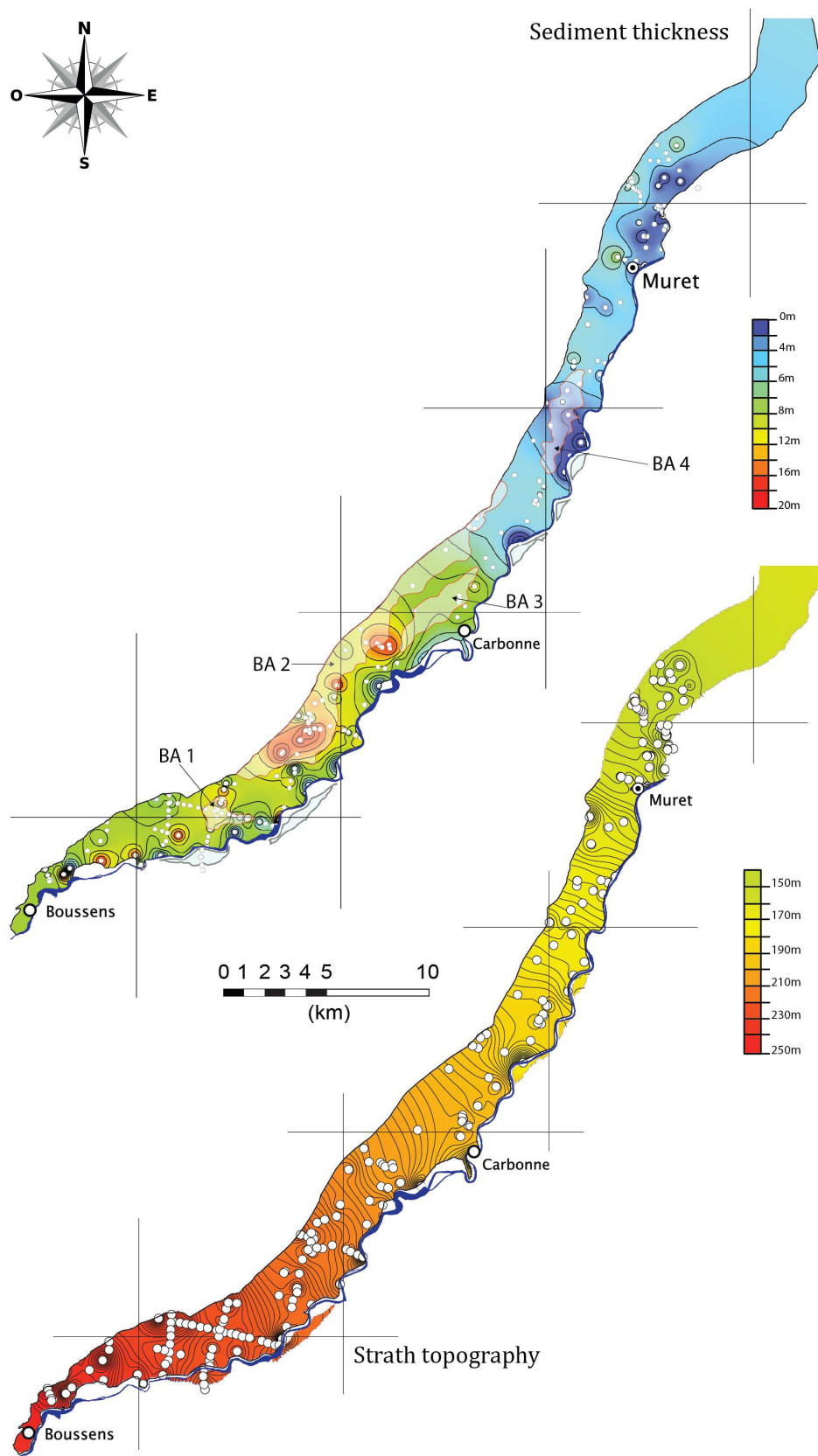


Figure 7: Strath topography and Isopach map of the sediments preserved below the lowest terrace of the Garonne River. White dots: boreholes, curves spacing: 2 m.

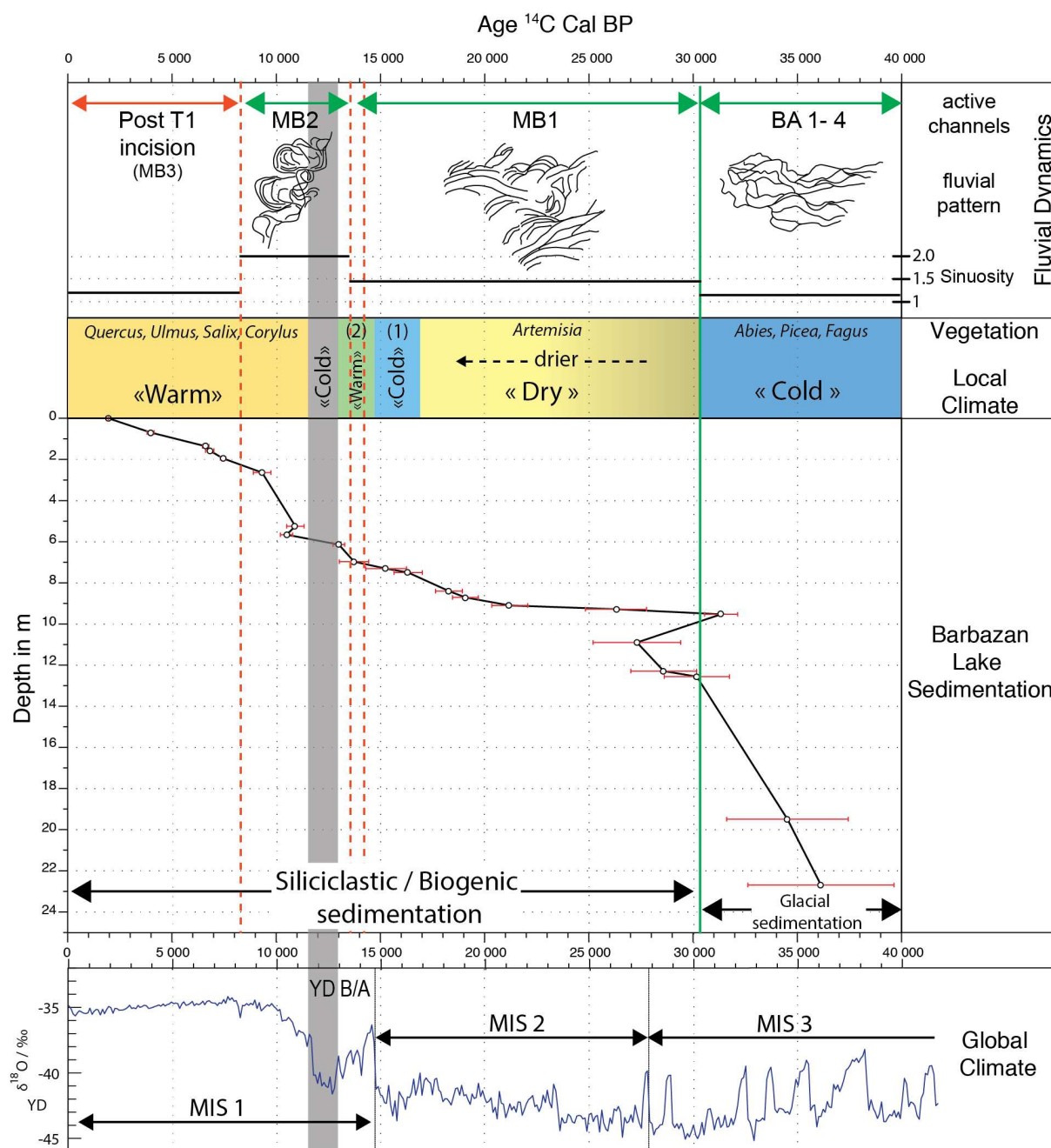


Figure 8 : Correlation between sedimentation rates in the Barbazan glacial lake (modified from Stange et al., 2013). $\delta^{18}\text{O}$ curve from Lisiecki and Raymo (2005), Martinson et al., (1987). Sedimentation data after Andrieu-Ponel (1991). ^{14}C ages calibrated with CalPal2007_{online} (Danzeglocke et al., 2013). Vegetation and climate from Andrieu-Ponel et al. (1988), Reille and Andrieu, (1995) Jalut and Turu i Michels (2006), Rius et al., (2012), Carozza et al., (2014). (1) Vegetation between 16 900-14 700 yrs Cal BP: *Artemisia*, *Juniperus*. (Jalut et Turu i Michels, 2006), (2) Vegetation between 14 700 – 12 895 yrs Cal BP: *Abies*, *Betula*, *Quercus* (Jalut et Turu i Michels, 2006).

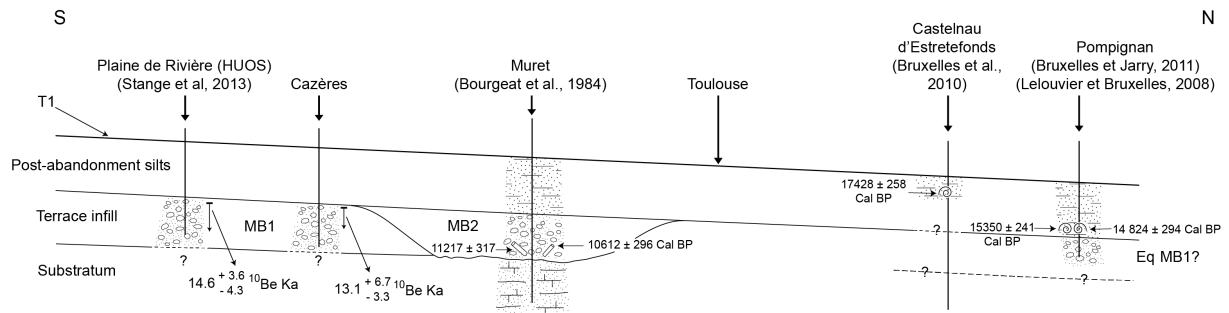


Figure 9 : Downstream correlations of datings of the terrace T1 of the Garonne River.¹⁰Be exposure ages after Stange et al., (2013). Radiocarbon datings from Bourgeat et al., (1984), Bruxelles et al., (2010), Bruxelles and Jarry, (2011), Lelouvier and Bruxelles(2008). ¹⁴C ages calibrated with CalPal2007^{online} (Danzeglocke et al., 20013). Location of dated sites : yellow stars on Figure 1. No scale.

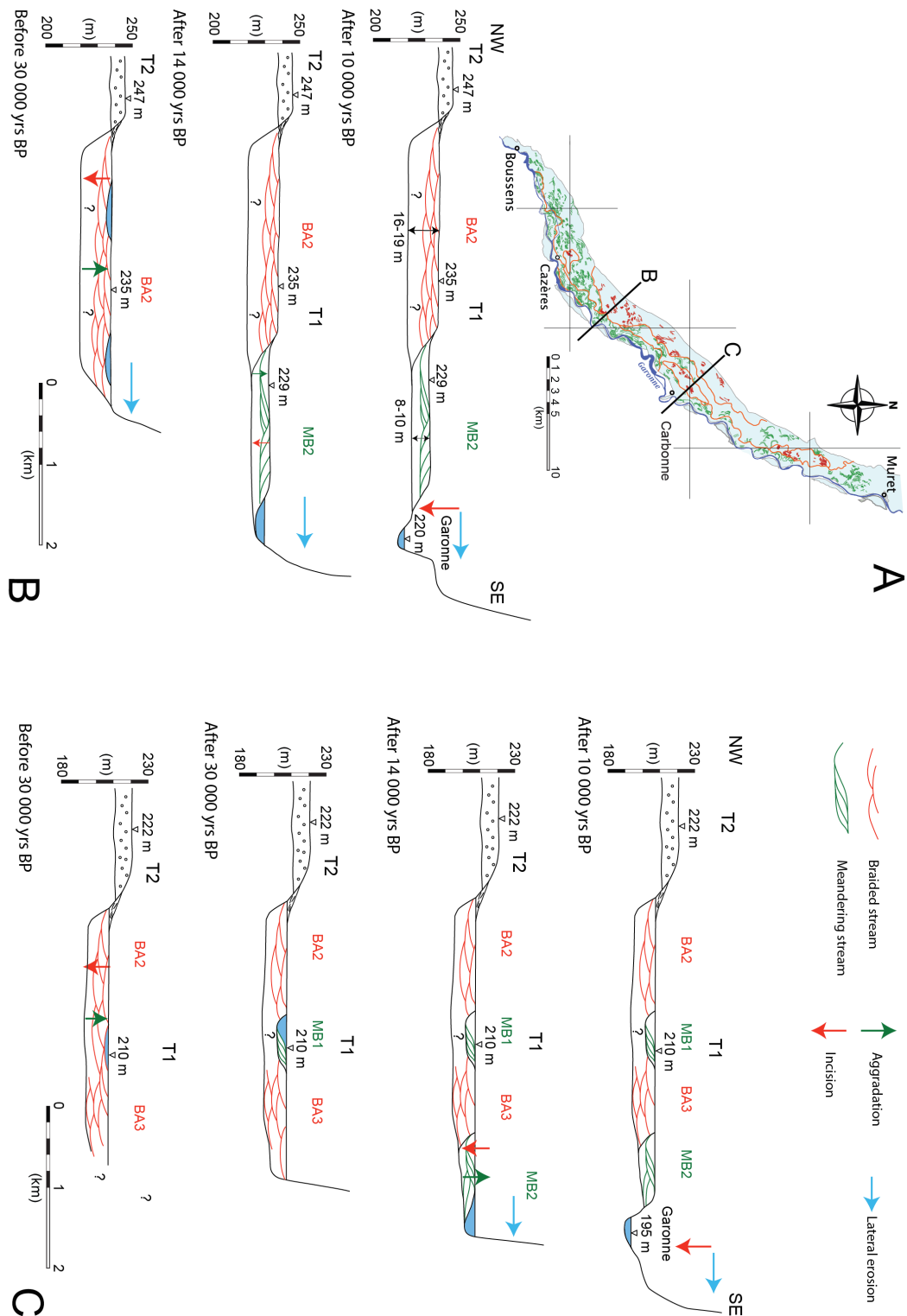


Figure 10 : Upper Pleistocene and Holocene evolution of the last terrace of the Garonne River along two transverse cross sections. Channel belts refer to figure 2. Sediment thicknesses represented correspond to Figure 7. Observe the weak incision between the base of the terrace infill and the modern Garonne River (bottom not constrained)