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The Pleistocene terrace staircases of the present and past rivers downstream from the Vosges Massif (Meuse and Moselle catchments)

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Abstract

This paper aims to provide a synthesis and update concerning the fluvial terraces of the rivers flowing from the Vosges Massif (Moselle and palaeo Upper-Moselle-Meuse, Meurthe, Sarre). The terraces of these rivers are especially well-developed in the marly depressions of the Eastern Paris Basin, justifying an extensive field mapping expedition. The main rivers exhibit terrace staircases with 8 to 13 stepped terrace steps within 100m of the present valley floor. The fluvial sediments mainly originate from the Vosges Massif (crystalline basement and Permo-Triassic sandstones and conglomerates). Another peculiarity of the study area is the presence of several palaeovalleys, typically related to fluvial capture events which occurred to the detriment of the River Meuse. Many palaeomeanders have also been recognised in the Paris Basin (Meuse catchment), and the Rhenish Massif (Moselle and Sarre valleys). Despite some similarities, palaeoenvironmental reconstructions provide evidence for the terrace staircases being distinct from one valley / section of valley to another. These differences are related to the morphostructural framework and to the climate forcing (presence/absence of glaciers in the upper catchment of the rivers). The chronological framework suggests that the terrace sequences and the main capture events may be older than previously thought.

Keywords: fluvial captures, fluvial terraces, Moselle, Meuse, palaeovalleys, Pleistocene

Introduction

The study of fluvial archives (sediments and landforms) was one of Jef Vandenberghe's main research topic, as shown by his involvement in the Fluvial Archives Group (FLAG) activities. Fluvial systems are largely dependent on internal (tectonic) and external (climatic and anthropogenic) driving mechanisms and are thus excellent indicators of palaeoenvironmental changes (Bridgland, 2000). The fluvial response to tectonic is shown by the location of the sediments, forming thick accumulations in subsiding areas (e.g. the Upper Rhine Graben and Lower Rhine; Busschers et al., 2007; Lauer et al., 2010) and terrace staircases in uplifted areas. The climatic control is both direct (variations in precipitations and evaporation) or indirect (influence on the sea-level, the glaciers or the vegetation). Furthermore, the fluvial response to such environmental changes depends on geomorphic thresholds (Schumm, 1979) which can vary from one river/section of river to another one.

The question of forcing has remained a main point of debate over the past decades in the Meuse and Moselle systems: as their catchment is developed through five countries (France, Luxembourg, Belgium, Germany, the Netherlands), the first reconstructions focused either on one part or the other of a valley. Furthermore, French research mainly focus on the correlation between the fluvial terraces and the glaciers in the Vosges Massif (Flageollet, 1988, 2002; Harmand and Durand, 2010), while Germans and Belgians focus on the influence of uplift in the Rhenish Massif (Negendank, 1983; Van Balen et al., 2000). To allow a better understanding of the driving mechanisms and reconstruct their Pleistocene evolution, the main valleys draining the northwestern part of the Vosges Massif (Moselle and Meuse catchments, Fig. 1) have been extensively studied during the last decade, as part of the IGCP 449 programme (Bridgland et al., 2009).

Complex terrace staircases have been recognised in the valleys of the Upper-Moselle (Losson, 2003; this study), the Meurthe, the Middle and Lower Moselle (Cordier, 2004, Cordier et al., 2005, 2006a, b, 2009), and the Sarre (Harmand, 2007). River terraces are well preserved in the Eastern Paris Basin, especially in the marly depressions developed in Triassic rocks and located in the vicinity of the Vosges Massif. Fluvial archives have also been widely recognised in the Rhenish Massif (Ardenne, Eifel, Hunsrück). Well preserved palaeovalleys and palaeomeanders occur in the Paris Basin (palaeovalley of the Upper Moselle in the Toul area), in the southern margins of the Rhenish Massif in the Meuse and Sarre valleys (Charleville and Saarburg-Konz areas, respectively), and in the Rhenish Massif (Moselle valley between Trier and Bernkastel). Research provided the first correlations with the fluvial systems located further downstream (Lower Meuse and Rhine; Pissart et al., 1997, Cordier et al., 2009). It also allowed a better understanding of the fluvial response to autogenic and allogenic forcings. Terrace formation is actually assumed to be the result of climate change superimposed onto a general trend to tectonic uplift. Research

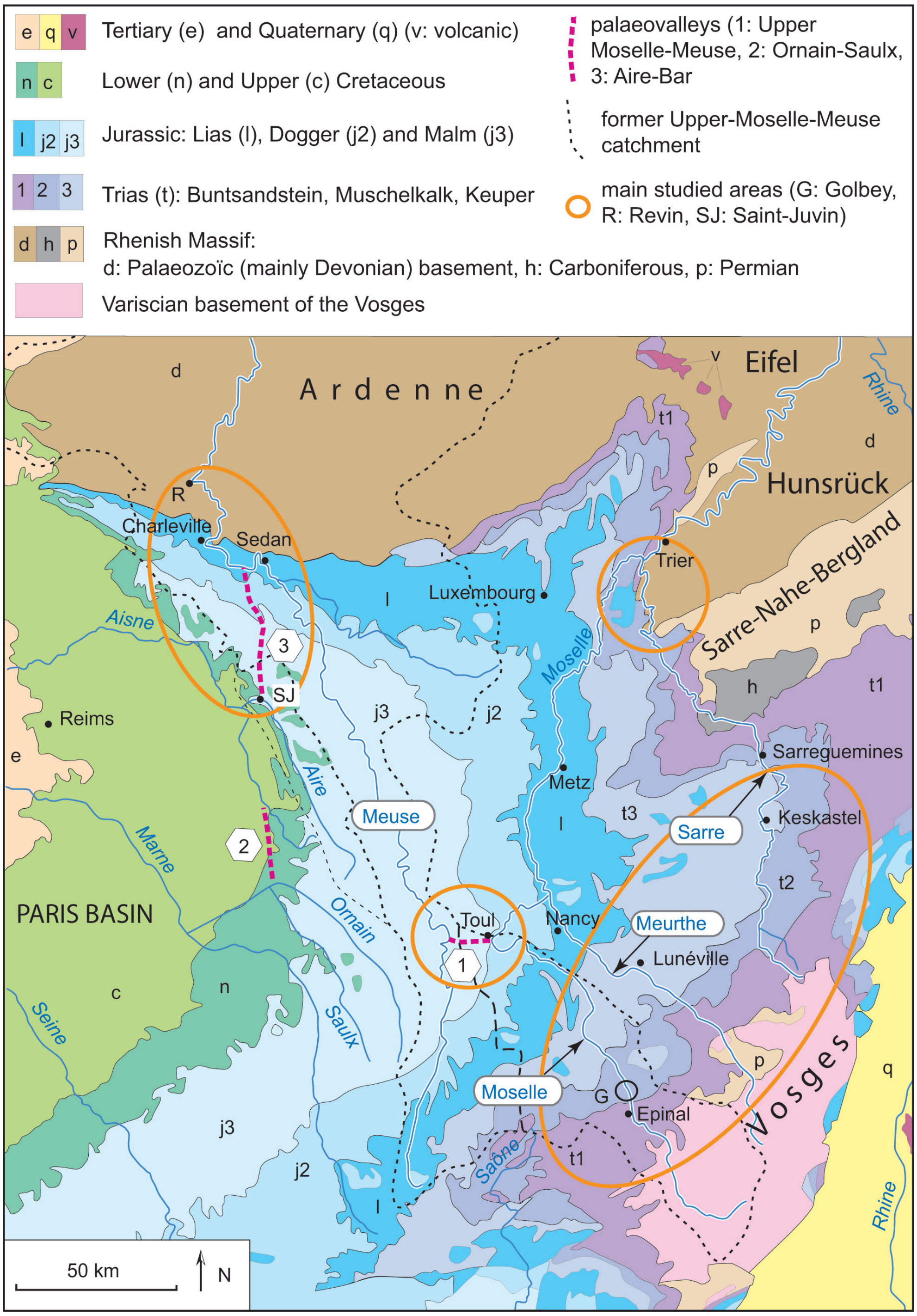


Fig. 1. General map of the study area, highlighting the geological context and the location of the main valleys and capture events.

also focused on several capture events that took place during the Middle Pleistocene in the study area. The main one concerned the Upper-Moselle, which before its capture by a tributary of the Rhine was an upstream continuation of the Meuse (Harmand et al., 1995; Harmand and Le Roux, 2000). The study of captures is of great importance not only in terms of chronostratigraphy (recognition and correlation of the pre- and post-capture terraces) but also because changes in the catchment area have had significant influence on fluvial evolution (increase or decrease of water input).

The present paper provides a synthesis of this research. It includes results of recent field work and numerical dating in the Upper Moselle valley and in the Meuse catchment. Two main topics will be discussed: 1) the recognition of a regional terrace system (e.g. from the Meuse to the Sarre, Fig. 1), and 2) the question of the linearity of fluvial response to climate change through space and time. These topics will be discussed by providing correlation between the fluvial terraces of the valleys under study, using numerical dating but also lithological changes in sediment composition related to the main captures, and by the analysis of some key-sections. After a presentation of the study area and methods, the terrace staircases and sediment characteristics will be described. Hereafter the main results concerning the fluvial captures and changes in drainage courses will be presented. Finally, the correlations between fluvial terraces and the role and inprint of climate change will be discussed.

The authors are indebted to the research conducted by Jef Vandenberghe during recent decades. Research focusing on the Maas terraces (e.g. the Maastricht-Belvédère terrace; Vandenberghe et al., 1985; Vandenberghe, 1995) contributed to provide the first absolute chronology for the fluvial evolution in the study area (Moselle and Meuse catchments). Research dealing with the periglacial features (e.g. Vandenberghe, 1983, 1992) provided a robust background for the palaeoenvironmental reconstructions in the study area. Finally the contribution of Jef Vandenberghe to improve understanding of the fluvial response to climate forcing (Vandenberghe, 2003, 2008; Vandenberghe et al., 2010) provided valuable guidance in the unraveling of the fluvial evolution in the Moselle and Meuse catchments.

Study area and methods

The Meuse, Moselle, Meurthe and Sarre rivers flow in south-north to SSE-NNW direction (Fig. 1). They drain, successively, the Vosges Massif (excluding the Meuse since the Upper Moselle capture), the Eastern Paris Basin and the Rhenish Massif (excepting the Meurthe which joins the Moselle to the north of Nancy). The Vosges and Rhenish massifs are blocks of Variscan basement that have been uplifted since the Tertiary. This slow but general uplift explains the presence of terraces staircase in the whole study area. The massifs are major sources for fluvial sediments, which are mainly siliceous. In the Vosges Massif, sediment supply was enhanced during the Pleistocene by the presence of glaciers during the cold periods. The glaciers covered large parts of the upper catchment of the Moselle, and, to a lesser extent, that of the Meurthe River. Sediments have been deposited in fluvial basins downstream from the Vosges Massif (Figs 2, 3 and 4). Even if they may relate to structural conditions, these basins are typically allocated to the presence of less resistant rocks. The widest basins (25 to 30 km long in the Upper Moselle and Meurthe valleys, Fig. 2) are preserved in the vicinity of the Vosges massif, and correspond with outcrops of Muschelkalk (Upper Anisian) and Keuper (Upper Ladinian, Carnian and Norian) marls (Durand, 2010). Further downstream, the fluvial basins are smaller due to the predominance of Jurassic limestones. The main ones can be found in the Moselle valley in the vicinity of Toul or downstream from Metz, and in the middle Sarre valley (Sarre-Nahe basin in the Permian and Triassic soft sandstones and clays; Harmand, 2007). The alternation of resistant and less-resistant rocks is also very important to explain the location and preservation of the fluvial terraces in the Paris Basin. It is less significant in the Rhenish Massif due to the homogeneity of the rocks (predominance of schists and quartzites in the Eifel and Hunsrück, associated with limestones in the Ardenne) and to the importance of the local sediment supply.

Research on the fluvial terraces first includes a high resolution morphological mapping of the terraces (scale 1 : 25 000), on the basis of intensive field work coupled with the analysis of previous boreholes. The boreholes provided useful information on the thickness of the fluvial terraces and the height of the bedrock. Due to the predominance of erosion against aggradation in the study area, such a detailed work was fundamental to enable longitudinal correlations (Meikle et al., 2010). This work was complemented by sedimentological, stratigraphical, grain-size, mineralogical and petrographical analyses of sediments exposed in sand- and gravel pits. The sedimentological analysis was important to identify major changes in sediment composition and therefore possible fluvial capture events. Special attention was also given to the construction of a numerical chronological framework using Optically Stimulated Luminescence (OSL) method on quartz and feldspars (IRSL), and the Electron Spin Resonance (ESR) method.

The fluvial valleys of the Meuse, Moselle, Meurthe and Sarre rivers

Terrace staircases

Mapping of the terraces focused primarily on the main fluvial basins preserved downstream from the Vosges Massif. It was conducted in several phases and included the Upper Moselle (Fig. 2, this study), the Sarre (Fig. 3, Harmand, 2007), and the Meurthe with its main tributaries the Mortagne and the

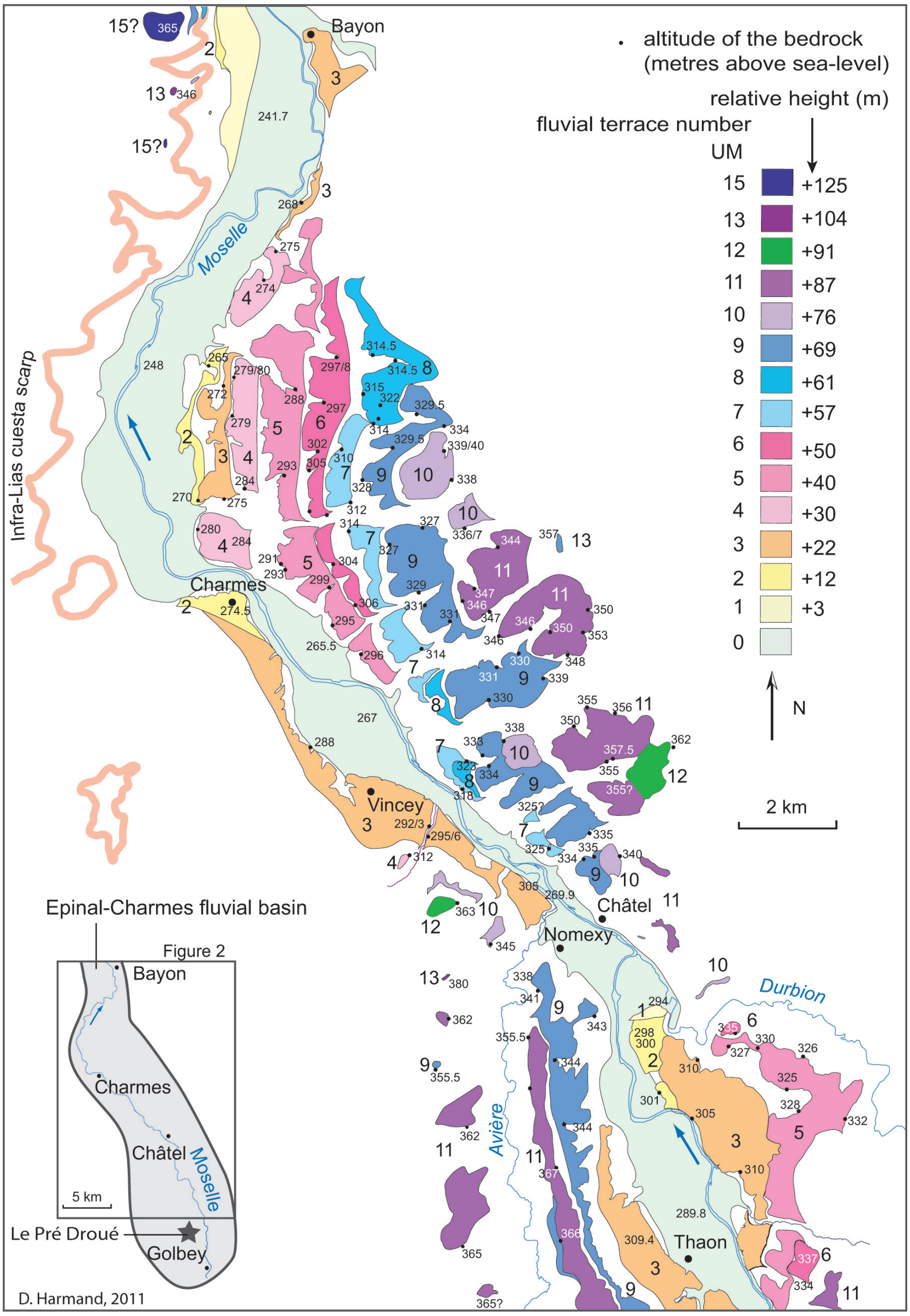
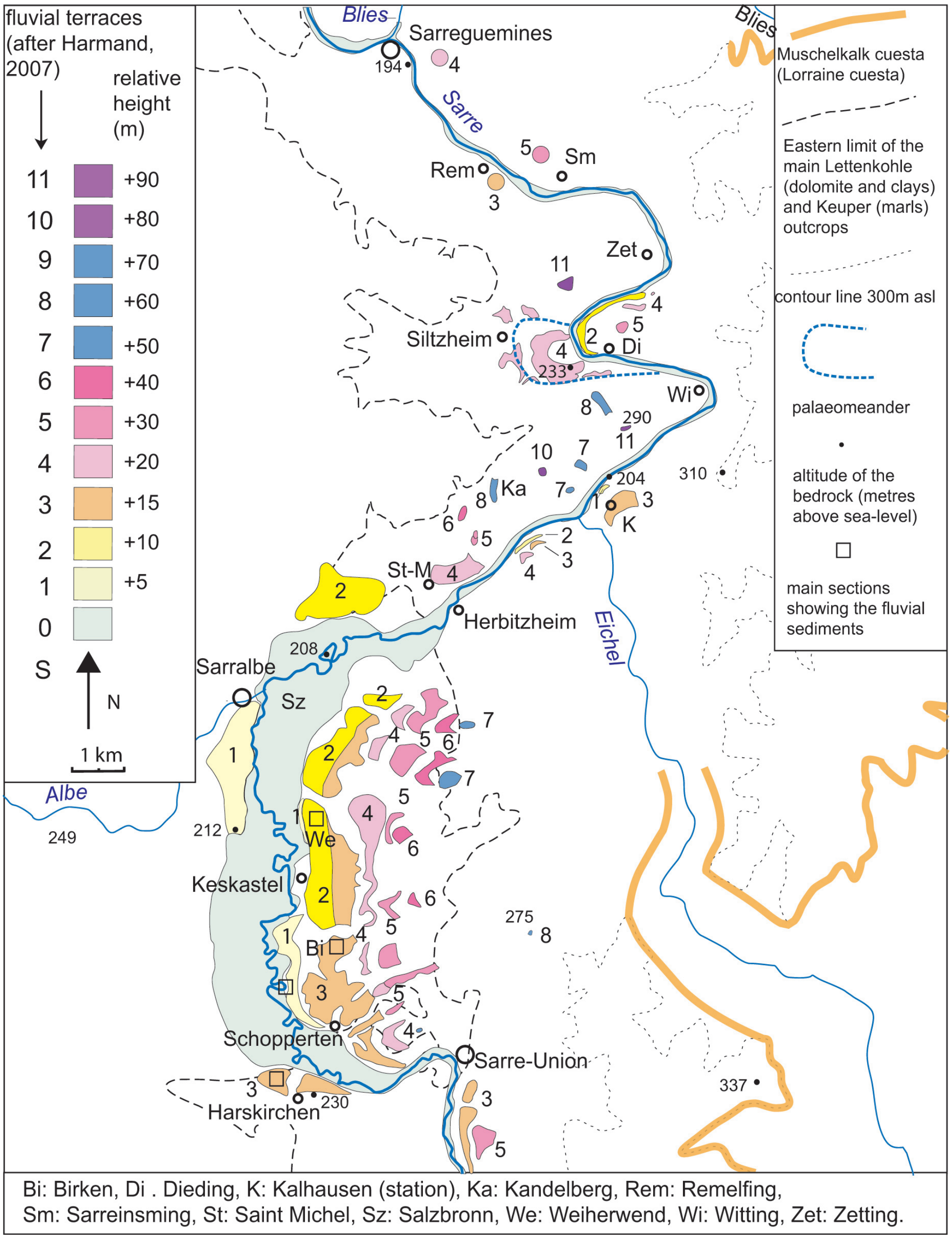


Fig. 2. The fluvial terraces of the Upper Moselle between Epinal and Bayon.

Vezouze (Fig. 4; Cordier, 2004; Ménillet et al., 2005). The number of well-preserved terraces in the whole study area strongly depends on the lithology of the bedrock, as the most preserved landscape associated with thick fluvial sediments are to be found on less resistant rocks such as clays or marls. However, the terrace staircase may vary from one valley to another, in relation with the morphostructural framework.

The most preserved terrace staircase has been recognised in the Upper Moselle valley downstream from the Vosges Massif: Between Epinal and Charmes, the terraces are preserved on a 30 km long and up to 7 km wide area. South of the Châtel dome, the fluvial terrace are developed on the faulted Muschelkalk and Lettenkohle limestones and dolomites. The oldest terraces (UM 9 and UM 11) are assumed to be proglacial fans (Minoux, 1978; Flageollet, 1988; Vincent et al., 1989). The well-preserved terrace UM 3 (10 km long) also corresponds to a younger proglacial fan (Taous 1994). Field work conducted in 2011 north of Châtel showed thirteen terraces, mainly preserved on the eastern part of the present Moselle (Fig. 2). The morphology of the terrace is well preserved and the thickness of the sediments commonly reaches several metres. This terrace staircase clearly suggests that the Moselle moved westwards as the river was



Bi: Birken, Di . Dieding, K: Kalhausen (station), Ka: Kandelberg, Rem: Remelfing, Sm: Sarreinsming, St: Saint Michel, Sz: Salzbronn, We: Weiherwend, Wi: Witting, Zet: Zetting.

Fig. 3. The fluvial terraces of the Upper Sarre.

forming its valley. Downstream from Charmes, the fluvial sediments are less well-preserved on the Jurassic limestones. Some relict terraces have been found in the Moselle valley up to +120 to +140 m near Bayon, on the lower Liassic limestones, and even at +200 m on the top of the Dogger cuesta (Allouc, 1977; Harmand, 2004; Figs 1, 2). Similarly, in the Meuse valley, relict fluvial deposits of the Upper-Moselle-Meuse have been observed at +180 m above the present valley floor on the Oxfordian limestones (Harmand, 1989).

In the Palaeo-Meurthe valley (Moselle valley north of the present Moselle-Meurthe confluence), as in the Meurthe and Sarre valleys, only the lowest terraces are more or less preserved in the depressions formed in the Liassic marls (Cordier, 2004; Le Roux, 1999, 2000; Fig. 4). Older and higher terraces have been weathered and only show relict deposits, for example on top of the Dogger cuesta (Cordier, 2004). The Meurthe valley and its two main tributaries the Vezouze and the Mortagne flow through the Triassic and Liassic marls and clays between the Vosges Massif and from Lunéville. This led to the recognition of eight terraces in the Meurthe valley (Cordier 2004), 4 in the Vezouze and 5 in the Mortagne. Well preserved terraces have been recognised up to +35m in the Meurthe valley, due to this predominance of marls (Fig. 4) that are more sensitive for lateral erosion. Finally the South-North Sarre valley exposes various terrace staircases due to the morphostructural context: in the Sarrebourg and Sarreguemines areas, the valley is narrow due to the presence of Muschelkalk (Middle Trias) limestones (Harmand, 2007; Fig. 3). Up to 11 terraces have been recognised,

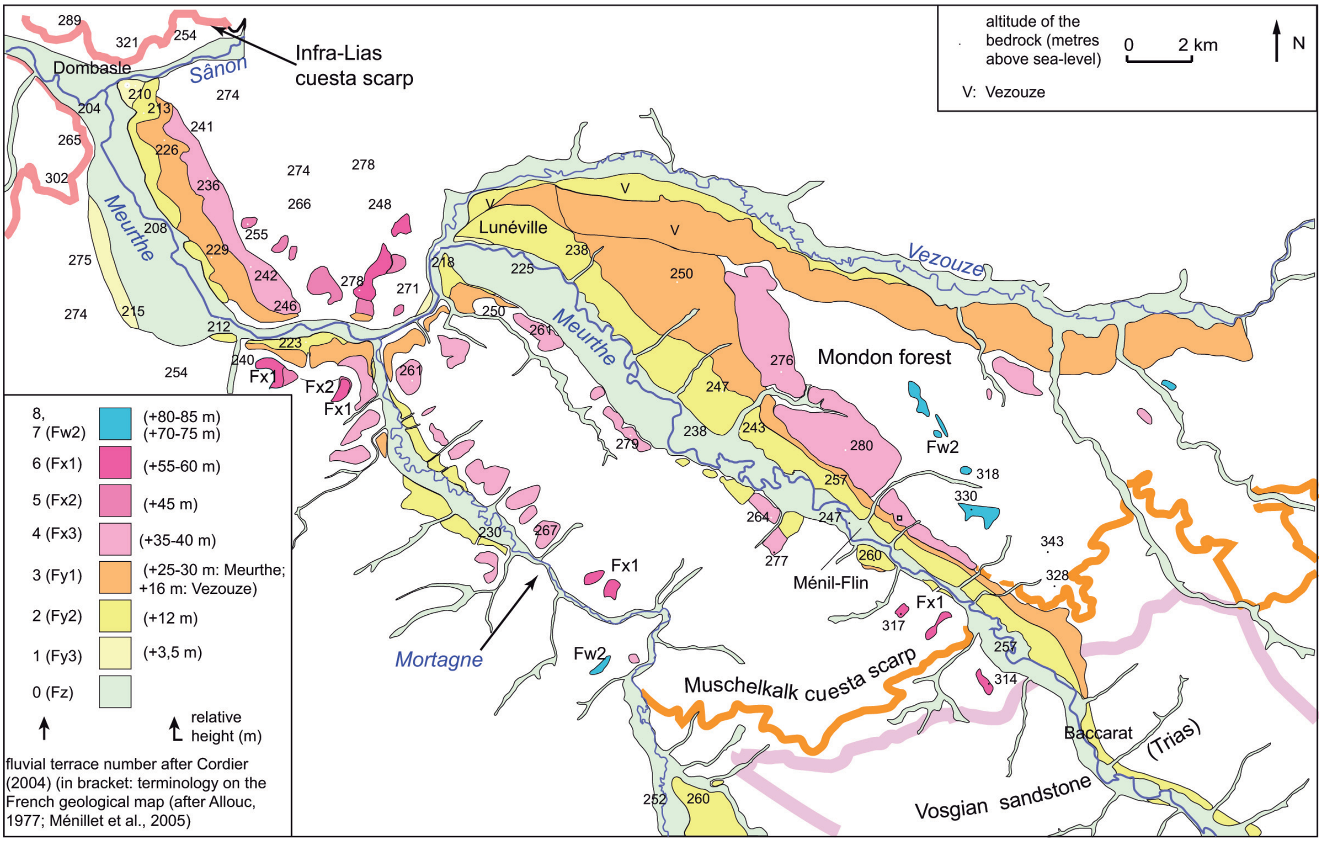


Fig. 4. The fluvial terraces of the Meurthe and its main tributaries the Mortagne and the Vezouze downstream from the Vosges Massif.

but most of them are residual. In contrast, a well preserved staircase is exposed in the Triassic marls and clays south of the Sarreguemines syncline, with 7 terraces up to +50 m. The terrace system is similar in the Middle Sarre valley (Sarre-Nahe fluvial basin), developed on sandstones, clays and limestones of Carboniferous to Triassic age (Harmand, 2007).

Sedimentary characteristics and climatic significance of the fluvial deposits

The study of several sections allowed the identification of depositional facies as well as petrographical and mineralogical analyses. Several lines of evidences from the fluvial terraces of the Upper Moselle (showing an alternation of coarse and sandy layers, each of one being several dm thick; Taous, 1994; Harmand, this study; Fig. 6), the Meurthe (showing channel fill cross bedding; Cordier, 2004) and the Sarre valleys (showing cross bedded structures and erosional features; Harmand, 2007) suggest that the deposition of the coarse and sandy sediments occurred in braided systems.

Special attention was given to the fluvial sediments preserved in the depressions of Triassic rocks of the Eastern Paris Basin. This made it possible to confirm the role of the Vosges Massif as main source for sediment supply but also to recognise distinct lithofacies on the basis of the lithology, mineralogy and grain-size of the sediments. The Meurthe and Sarre terraces are characterised by a predominance of sediments originating from the Permo-Triassic rocks of the Vosges Massif: in the Sarre valley (which only drains the Permo-Triassic strata), the sediments are typically sandy and originate from the Buntsandstein (Lower and middle Triassic) sandstones (Beiner et al., 2009), as indicated by the homogeneous heavy mineral composition (predominance of tourmaline, associated with zircon; Wolf, 1982, in Konzan et al., 1992). The coarser sediments (quartz and quartzites pebbles) originate from the conglomerates (Senones layers, Upper Permian; basal conglomerates of the Vosgian Sandstone; main Conglomerate of the Olenekian (Lower Trias); Durand, 2010). In the Meurthe valley (Cordier et al., 2005), the sediments are also mainly sandy. The sands originate from the Buntsandstein (presence of tourmaline and zircon as for the Sarre valley), but also from the crystalline basement, as indicated by the presence of hornblende. In the Mondon basin located between the Vosges Massif and Lunéville (Figs 1 and 4), the top of the sands is (as observed in terraces Me2, Me3 and Me4) eroded and overlain by a coarse unit which also includes a significant component of crystalline sediments. The presence of such deposits (granites, gneiss, etc, and associated minerals such as hornblende) is explained by the fact that about 25% of the Vosgian drainage area of the Meurthe (especially in the upper Meurthe) is developed in the crystalline basement. Their increasing presence in the top of the fluvial sequence is related to the melting of the glacier in

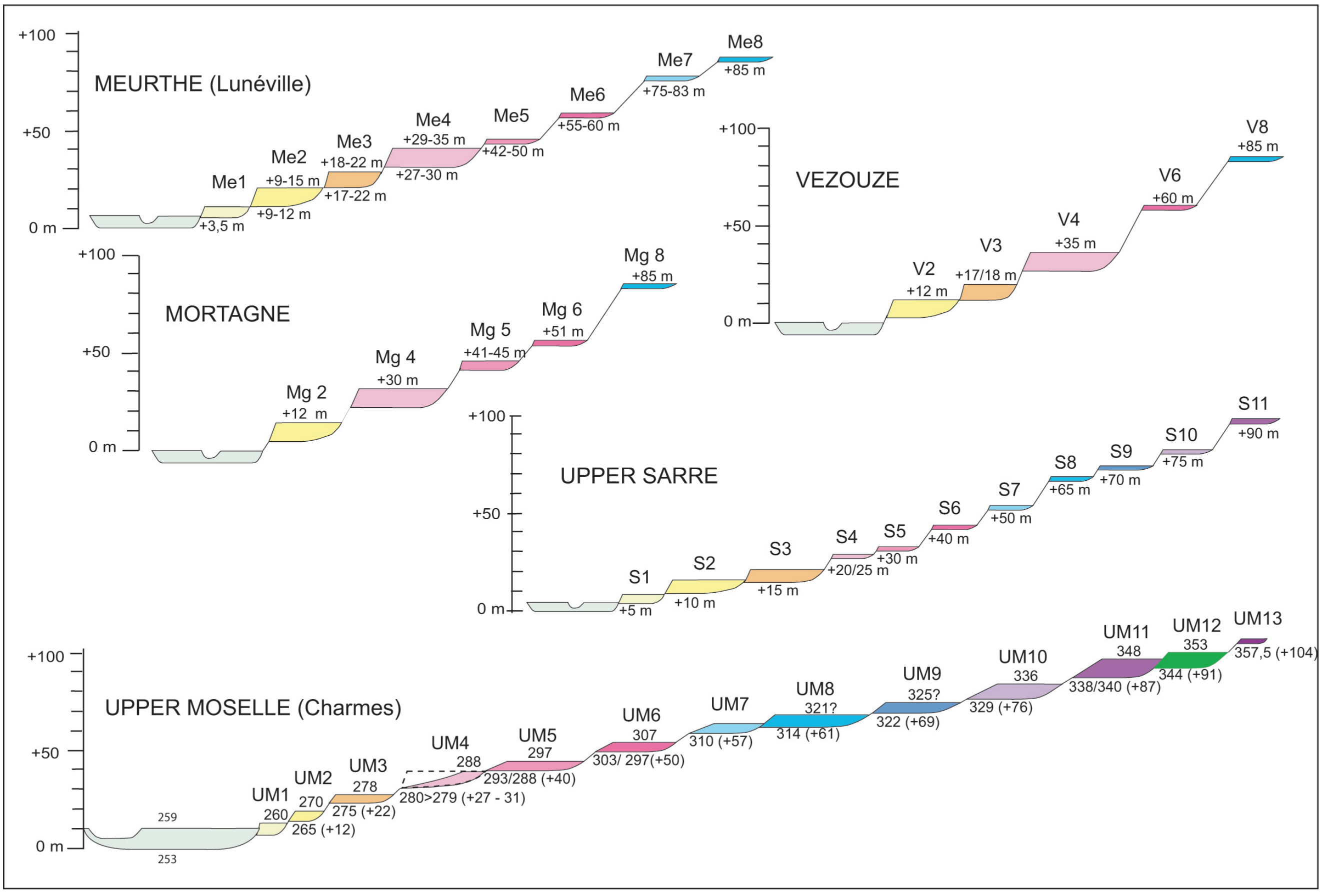


Fig. 5. Idealised sketch of the terrace staircases for the main rivers under study. Mapping performed during the past decade has made it possible to provide evidence for a significantly higher number of terraces than previously recognised.

the upper Meurthe valley. In the Upper Moselle valley, several sections have been studied, especially in the Golbey-Chavelot alluvial fan (Pré Droué and Cobrelle gravel-pits; Taous, 1994) and in the vicinity of Toul (Beiner in Losson, 2003; Cordier et al., 2004). The Moselle sediments include both sandy and coarse units. Mineralogical and petrographical investigations showed that most of the sediment have a crystalline origin (predominance of granite and gneiss pebbles associated with hornblende and garnet typical from the Vosges basement). This result is consistent with the lithology of the Upper Moselle

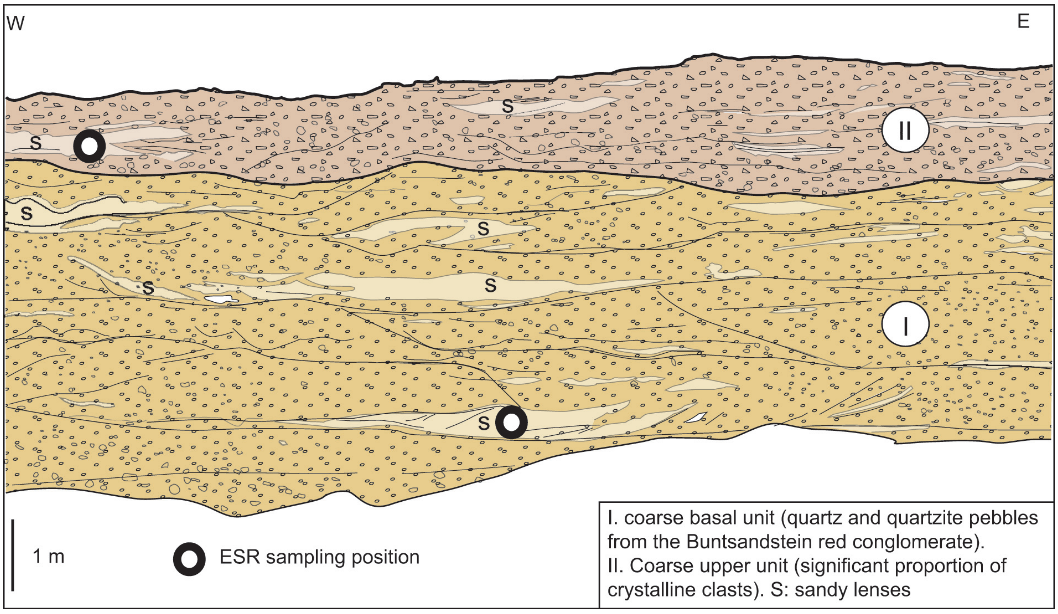


Fig. 6. General description of the Pre-Droué section (Golbey-Chavelot alluvial fan, terrace UM3) with location of the ESR sampling positions.

catchment (75% of the surface being composed of crystalline rocks). Following this, the Moselle and Meurthe sediments are characterised by clearly distinct sediment compositions. The lithology of the sediments should hence be considered as a reliable tool to recognise the pre- and post-capture terraces downstream from the present Moselle-Meurthe confluence (Cordier et al., 2004).

Captures and changes in river course

The study area is characterised by several capture events, with the main one being that of the Upper Moselle. In addition, local captures as well as changes in fluvial courses (e.g. meander downcutting) have been recognised at the border between the Paris Basin and the Rhenish Massif, in the Meuse valley (vicinity of Charleville-Mézières) and near the Moselle-Sarre confluence.

Impact of the Upper Moselle capture

Recognised more than one century ago and made famous by Davis (1895), the Upper-Moselle capture has been extensively studied (Harmand et al., 1995; Le Roux and Harmand, 1998; Losson, 2003). Recent research has shed new light on this event (Pissart et al., 1997; Losson, 2003; Harmand, 2004; Cordier et al., 2005). It led to the recognition of six well-preserved stepped terraces in the vicinity of Toul (Figs 7, 8). The older terraces (UM 6 to 4) correlate with terraces in the Meuse valley (pre-capture terraces. Upstream from Toul, in the Bajocian limestones, these terraces are residual. However, fluvial sediments associated to these terraces have been found in karstic caves, which provide evidence for partial defluviation of the Moselle towards the North (Losson 2003). In contrast, pre-capture terraces cover large areas in the Callovian clays near Toul, and the associated sediments are up to 10 m thick (Justice terrace, UM 5). Further West, the Val de l'Asne palaeovalley (connecting the Moselle and Meuse valleys) is also well preserved and exhibits beautiful palaeomeanders entrenched in the Oxfordian limestones. The relative height of the terraces is significantly different between Toul and the Meuse valley: the UM4 terrace, which is preserved a +30m near Toul, corresponds with the valley floor in the Val de l'Âne and in the Meuse valley. In the latter area, however, a significant reworking of the sediment took place: the valley floor sediments are actually mainly calcareous (in keeping with the lithology of the post-capture Lorraine Meuse catchment, which only drains the Jurassic limestones and marls of the Eastern Paris Basin). Their age ranges from the Weichselian Pleniglacial and Late Glacial (Lefèvre et al., 1993, 1995) to the Holocene for the top of the deposits (Harmand, 2004). This result clearly demonstrates that the Meuse and Moselle (Rhine) catchments have evolved very differently since the capture event: while an incision of ca 30 m took place in the Moselle valley and its tributaries, no vertical incision occurred in the Meuse valley. This is explained by the strong decrease of water input and by the predominance of hard rocks (Mesozoic limestones in the Eastern Paris basin, sandstones and quartzites in the Ardenne Massif).

In contrast with the pre-capture terraces, the three lowest terraces (UM3 to UM1) follow the present Moselle valley (post-capture terraces) from Toul to the Meurthe confluence. Recent field work (Harmand, this study) demonstrates that these terraces (and especially the first post-capture terrace UM3, located at +20 m relative height) are also well preserved between Epinal and Charmes. The post-capture terraces have also been correlated firmly with the terraces preserved downstream from the Moselle-Meurthe confluence, both in the Paris Basin and in the Rhenish Massif downstream from Trier. An important change in sediment composition (petrography of pebbles and gravels, heavy-mineral spectra) has been recognised between terraces M4 and M3: the fluvial deposits of terrace M4 (and older terraces) are very similar to those of the Meurthe, with a predominance of sediments originating from the Permo-Triassic cover of the Vosges Massif (quartz and quartzite pebbles, tourmaline and zircon). In contrast, the sediments of terraces M3 and youngest (M2 to M0) include a significant proportion of crystalline sediments (granite pebbles, hornblende and garnet). A comparison with the lithology of the upper catchments of the Moselle and Meurthe (see above) allow this major change to be related to the Upper-Moselle capture (Cordier et al., 2005, 2006b).

Changes of river course in the Southern Rhenish Massif

Charleville-Mézières area (Southern Ardenne)

Three significant drainage changes have been recognised in the vicinity of Charleville-Mézières (Fig. 1; Harmand, 2004, this study). The drainage change are associated to the Aire-Bar-Meuse palaeovalley (Fig. 9), the Meuse of Gespunsart palaeovalley, and the Sormonne valley (Figs 10 and 11).

Aire-Bar-Meuse palaeovalley

The River Aire is a tributary of the Seine, that previously flowed through the Bar valley to join the Meuse north of Charleville (Aire-Bar-Meuse, Harmand, 2004). A first capture event occurred when the Meuse of Gespunsart (corresponding to the Upper Moselle-Meuse) was captured by the Aire-Bar-Meuse between Sedan and Charleville (see below). The upper part of the Aire-Bar (the Aire) was subsequently captured by the Aisne. Mapping of the terraces in the area of the Aire capture allowed the recognition of one pre-capture (Aire-Bar terrace AB 5) and four post-capture terraces (Aire terraces from Ai4, the oldest, to Ai1, the youngest; Fig. 8; Harmand and Le Roux, 2009). In contrast to the post-capture sediments which occur in the modern valley towards the Aisne, the pre-capture sediments are preserved along a large meandering valley (present valleys of the Agron, Briquenay and Bar), which

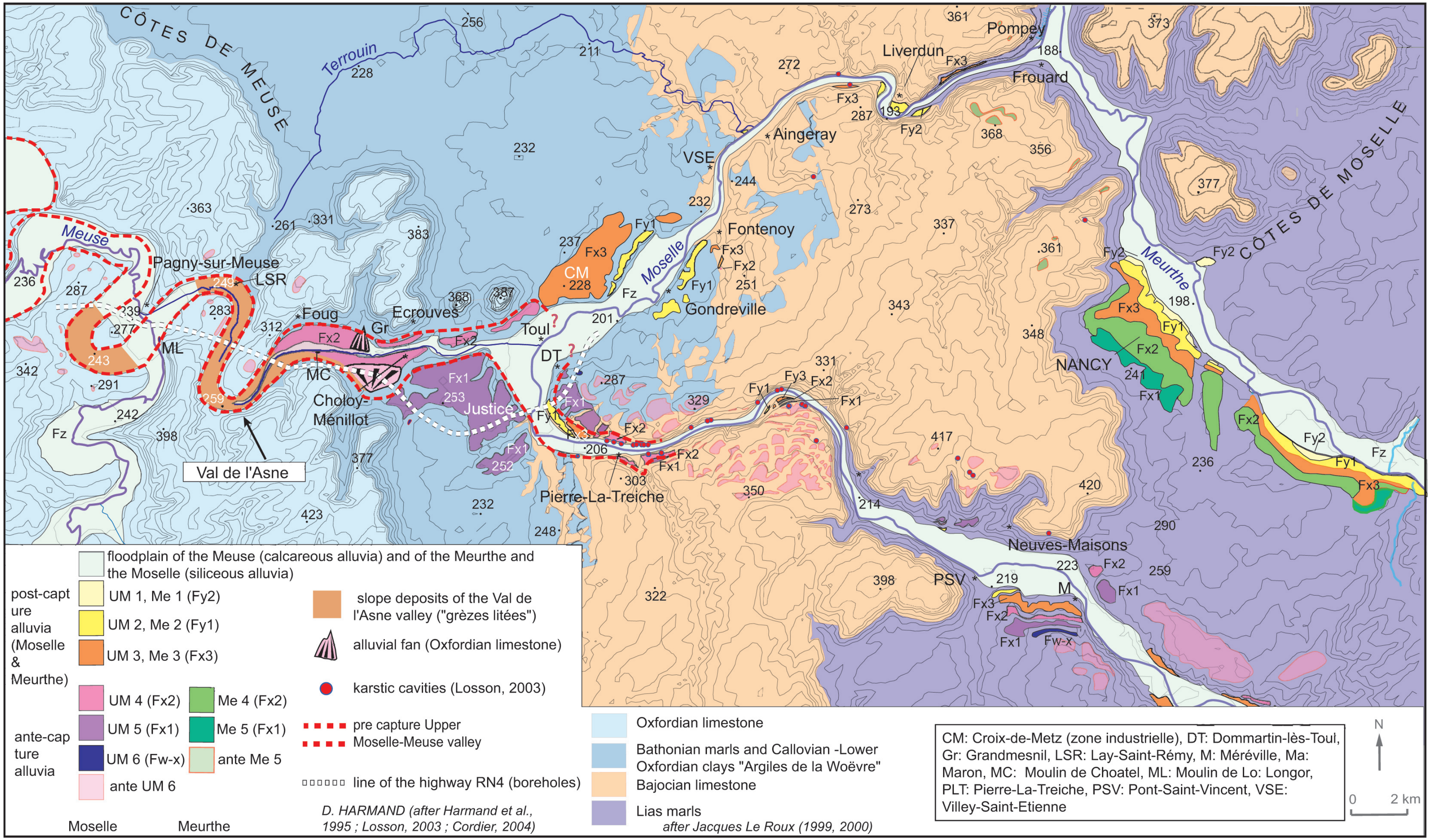


Fig. 7. The Upper Moselle capture area.

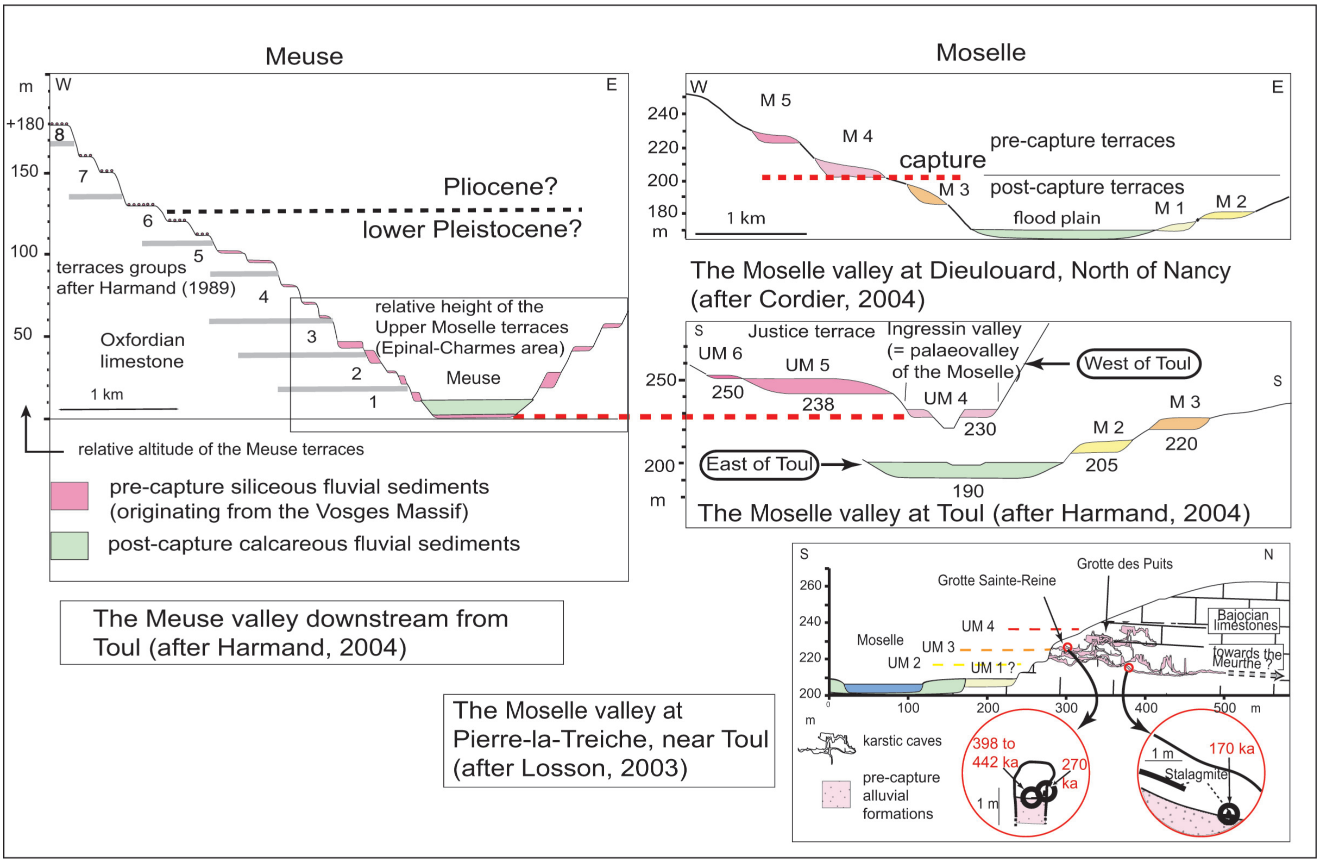


Fig. 8. The Upper Moselle capture and its record in the Meuse and Moselle valleys and in the karstic systems in the vicinity of Toul.

cannot have been formed by the present small rivers. Due to subsequent incision, the bedrock surface of terrace AB5 is ca 45 m above the present Aire valley. The incision was less pronounced in the palaeovalley due to the lower water input: the relative height of the basis of AB5 is only 2-3 m above the Agron floodplain at Verpel. Further North, at the border between the present Aire and Meuse catchments (Buzancy area), a borehole recorded by the French Geological Survey (BRGM; borehole 110.4.7) suggests that the sediments of terrace AB5 (8 m thick) are even covered by 14 m of slope deposits. Modern wetland covers the sediments of AB5 as well as the present floodplain. As the Aire and Aisne Rivers flows through the same Mesozoic strata (Jurassic limestones and Cretaceous siliceous sands), there is no lithological signature in the fluvial deposits that records the capture (Harmand, 2004). However, a minimum age estimate for the Aire capture event is provided by ESR dating of Aisne terrace As3 (correlated with Ai3), which yielded an age of ca 220±15 ka (Cojan et al., 2007). The AB 5 terrace formation and the Aire capture are thus significantly older than MIS 7.

Meuse of Gespunsart palaeovalley

The Gespunsart Valley is situated east of Charleville-Mezières and joins the present Meuse valley at Nouzonville (fig 9). The size of the palaeomeanders along the Gespunsart valley is comparable with that of the Meuse meanders. Previous study allowed the recognition of eight fluvial terraces, the highest being located at 315 m a.s.l (+180 m above the present Meuse river; Fig. 10). Furthermore, a significant proportion of the relict sediments preserved in this valley originated from the Vosges Massif (crystalline basement and Permo-Triassic cover; Pissart, 1960; Voisin, 1980). Paleoenvironmental reconstructions derived from this evidence indicate the presence of two parallel palaeorivers joining to the North of Charleville (Fig. 9): the Aire-Bar-Meuse and the Upper-Moselle-Gespunsart Meuse. The capture of the Upper-Moselle-Meuse by the Aire-Bar-Meuse is well recorded in the Meuse sediments at Charleville (Pissart et al, 1997): the sediments from below the Mont-Olympe terrace (+15 m above the present Meuse) mainly contain tourmaline and zircon originating from the Ardenne and Cretaceous rocks, while hornblende typical of the Vosges crystalline basement is lacking (Fig. 10c; Voisin, 1980). In contrast, the sediments from below the +10 m terrace preserved at Warcq and Montcy-Notre-Dame (upstream and downstream from Charleville, respectively) contain a significant proportion of hornblende. The six terraces located between +80 m and +15 m must therefore have been formed by the Aire-Bar-Meuse, in contrast to the lowest terrace, which has been formed by the Upper-Moselle-Meuse (Harmand, 2004).

Sormonne valley

West of Charleville, a third change of river course was recognised (Voisin, 1972). The Ruisseau de Faux is a 10 km long tributary of the Meuse which flows through the Liassic strata of the Pre-Ardenne depression and the Ardenne basement (Fig. 9). A terrace is preserved at 60m above the present river (220 m a.s.l, Fig. 10). The section exposes a coarse basal unit (1.20 m thick) with quartzite pebbles, overlain by yellow sands (2 m thick) and slope deposits. The presence of glauconite and sponge spicules in the sands indicates that they originate from Cretaceous outcrops, which occur a few kilometres further to the south, in the present Sormonne catchment (Fig. 9). Taking into consideration the great width of the present Ruisseau de Faux valley, we assume that the sediments from below the +60m terrace were deposited by a palaeo-Sormonne before the river eroded the Pre-Ardenne depression during the Pleistocene.

The palaeomeanders in the Lower Sarre valley

The Lower Sarre valley is developed through the Devonian schists of the Hunsrück Massif (Figs 1 and 12). The presence of hard rocks has allowed the preservation of the fluvial terrace sequence (as lateral erosion is restricted) and a staircase of ca 15 terraces (up to +200 m relative height) has been recognised. The fluvial sediments are thick, especially for the older terraces: terraces S9 (+85 m) and S12 (+125 m) expose up to 14 and 9m of sediments, respectively (Fischer, 1957; Müller, 1976; Zöller, 1985; Harmand, 2007, Fig. 13). Fluvial deposits are also preserved in several palaeomeanders such as the Ayl-Wawern palaeomeander (relative height +7 m), the Irsch-Ockfen palaeomeander (+85 m) and the Konzer Tälchen palaeomeander (+100 m). The last (which may be older than 1 Ma as suggested by the ESR datings, see above) has been formed not only by the Sarre but also by the Palaeo-Meurthe, as indicated by the presence of iron ooliths originating from the Toarcian layer of the Dogger cuesta (Müller, 1976). The presence of several generations of palaeomeanders (Figs 12, 13), allocated to the Early to Middle Pleistocene (Irsch-Ockfen, Konzer Tälchen) or to the Upper Pleistocene (Ayl-Wawern), provides evidence for a complex evolution of the river's course, which may have been controlled not only by the tectonic activity (uplift of the Rhenish Massif) but also by climatically driven fluvial erosion.

The preservation of the terrace staircase allows correlation with the Moselle valley in the Rhenish Massif. In particular terraces S5 to S1 (+50 to +5 m relative height) are located at relative height similar to the Moselle terraces M5 to M1. At higher relative heights, the number of terraces is higher in the

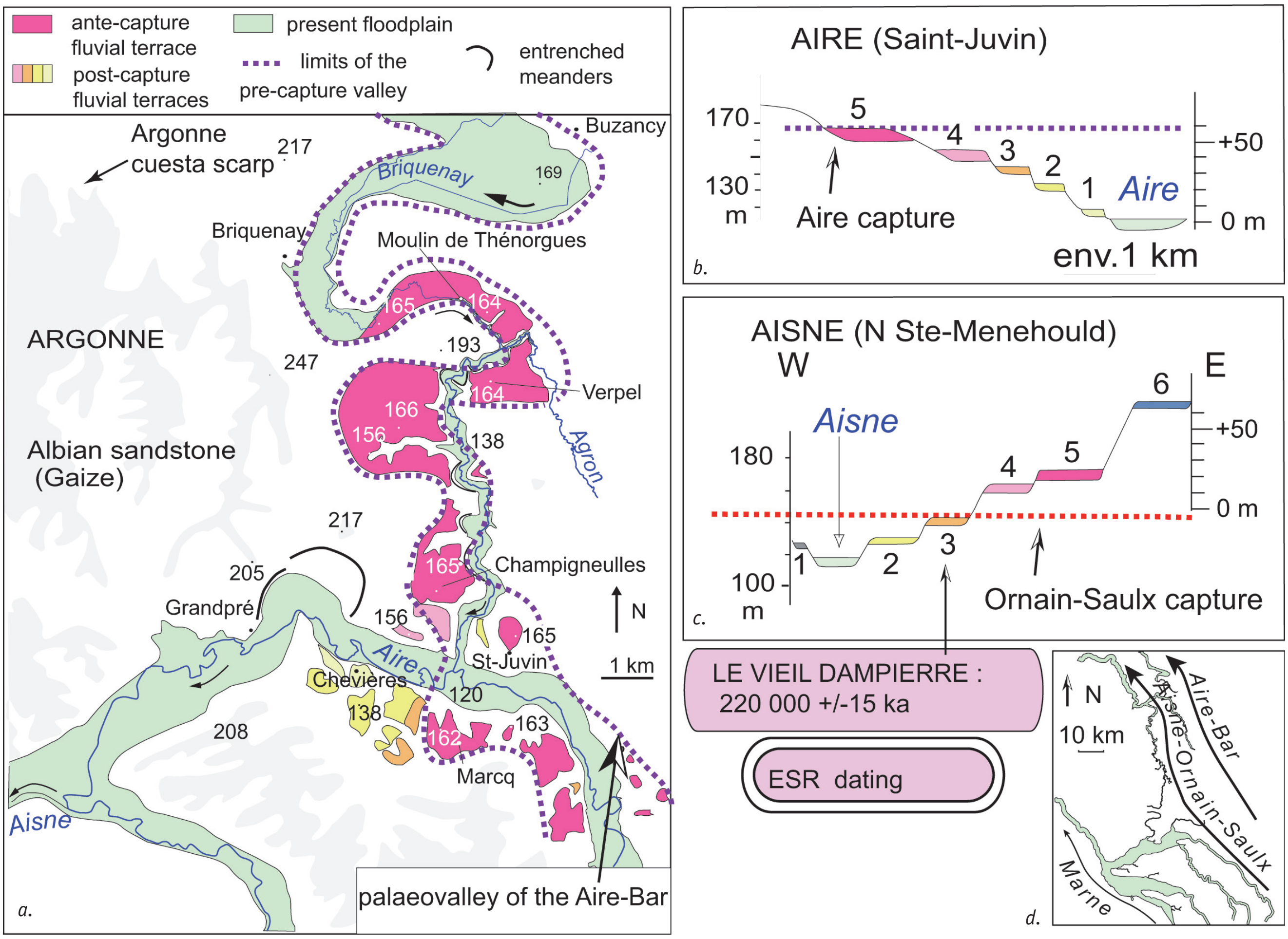


Fig. 9. The Aire-Bar capture and its chronostratigraphical framework. a. Morphological map; b. Terrace staircase of the Aire valley; c. Terrace staircase of the Aisne valley; d. Location map with indication of the palaeorivers.

Sarre valley. In contrast, the Moselle valley is characterised by a hiatus between what is called the 'lower and middle terraces' (less than 100 m relative height) and the 'main terrace' complex (above 100 m).

Discussion

The timing of terrace formation and river capture events

Ages of the lower terraces

The chronological framework of the fluvial sediments in the study area has been significantly enhanced during the last decade, using OSL, ESR and radiocarbon dating methods, especially for the youngest terraces. This makes it possible to correlate the youngest terraces (terraces 2 and 1, Fig. 5) and the present valley floor within the last glacial cycle (Weichselian to Holocene). The present floodplain of is allocated to the Late Glacial to Holocene period, on the basis of radiocarbon dates performed in the Meurthe and Moselle (Carcaud, 1992) valleys. In the Meuse valley, radiocarbon dating underlined the Holocene filling of channels cut into the older coarse gravel (Harmand, 2004). The incision from terrace M1 to M0 is likely to have occurred at the beginning of the Late Glacial. OSL dates from Moselle terrace M1 in Luxembourg and Sarre terrace S1 actually suggest that the main aggradation period occurred during MIS 3 (and possibly MIS 2; Cordier et al., 2010). Similarly OSL dating of terrace 2 in the Meurthe valley indicates that it was deposited during MIS 4. The MIS 3 age proposed for this terrace (Cordier et al., 2006a) should, in contrast, be considered with caution, due to methodological problems. Furthermore, comparison with the other major rivers of the Eastern Paris Basin (especially the

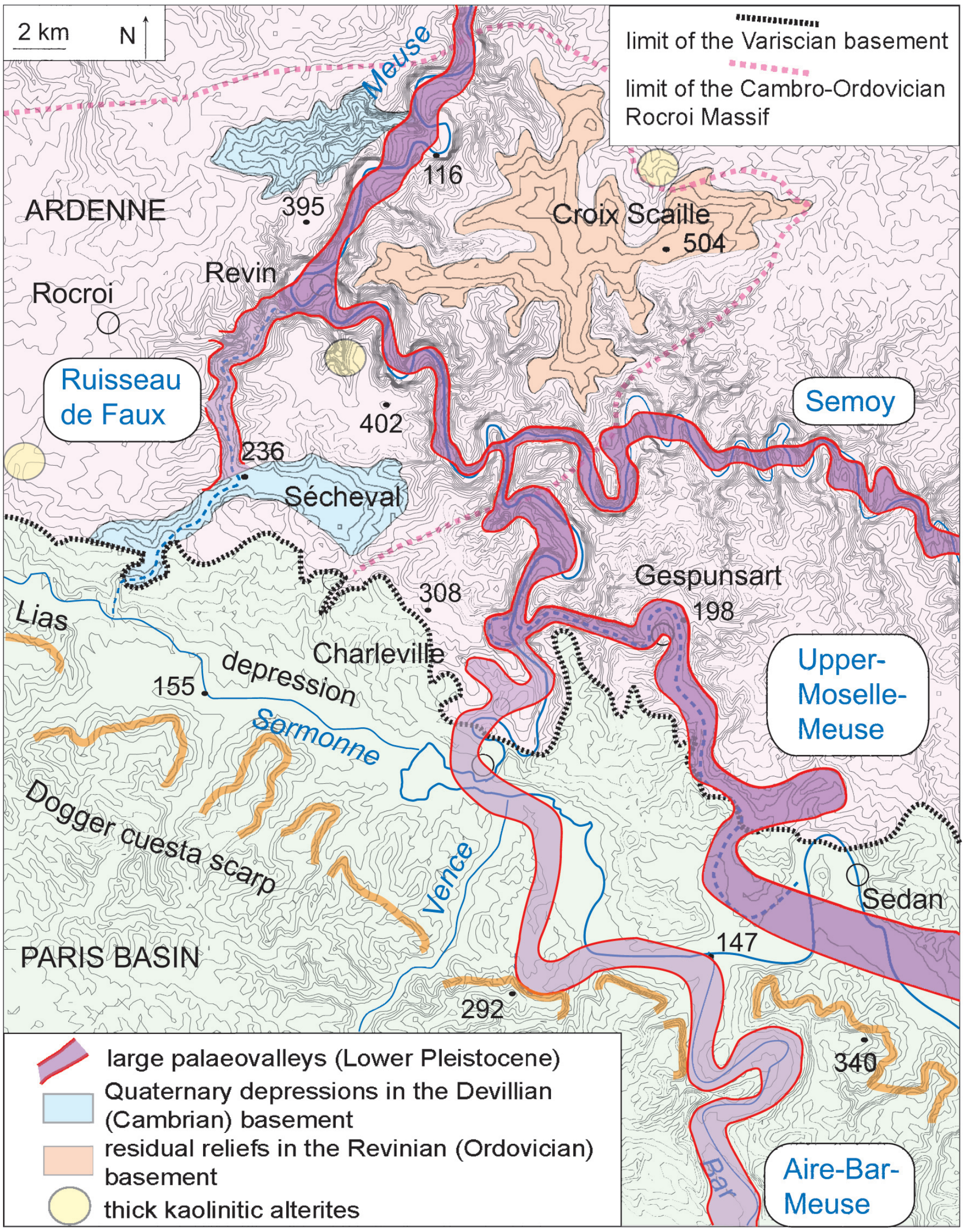
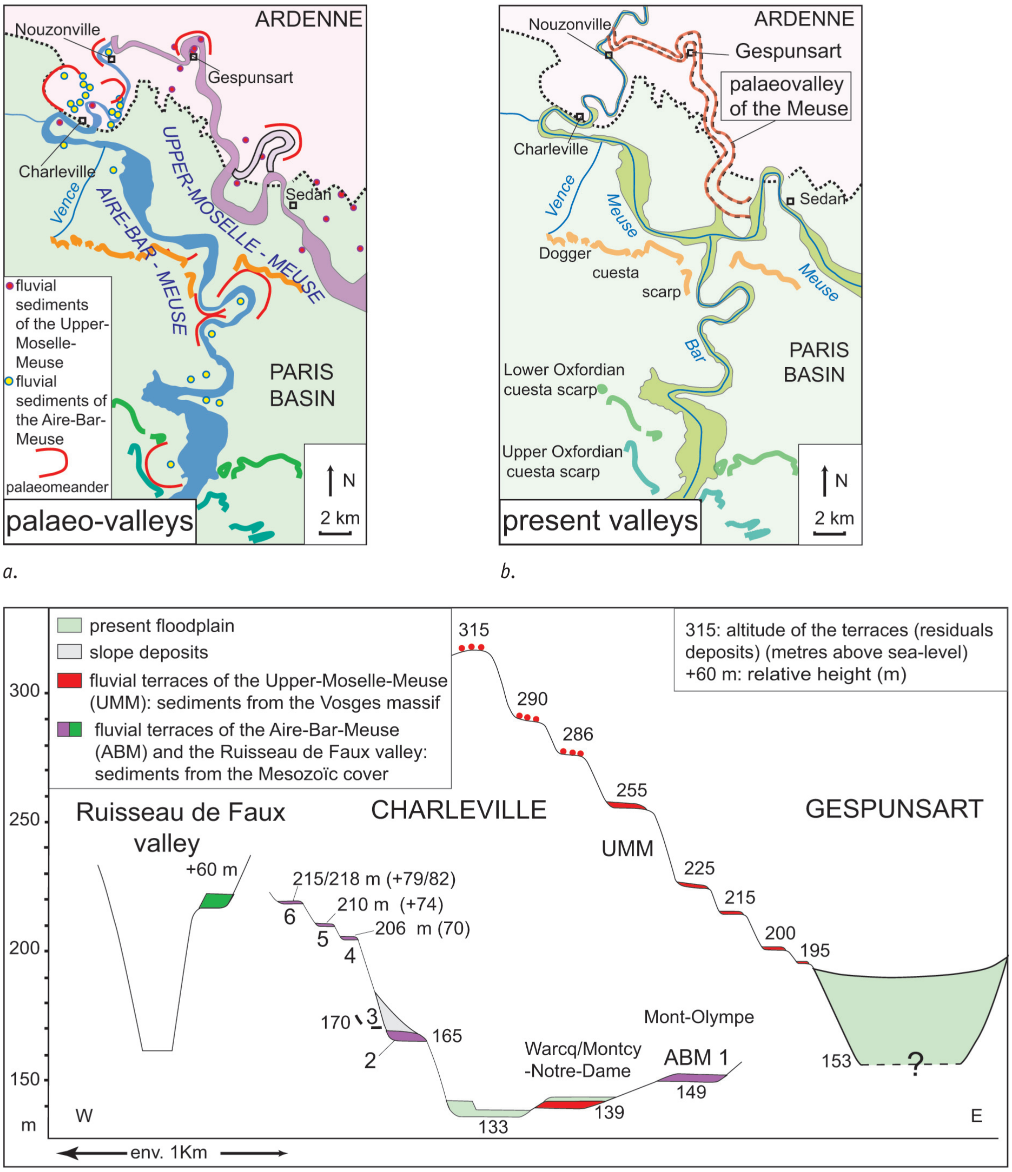


Fig. 10. Valleys and palaeovalleys in the Southern Ardenne.



a.

b.

c.

Fig. 11. The palaeovalleys and valleys in the vicinity of Charleville: location and stratigraphical location of the Gespunsart Meuse capture. a. the palaeorivers in the Charleville area; b. the present valleys; c. cross profile of the terraces in the Meuse and palaeo-Meuse valleys (after Pissart, 1961; Voisin, 1980; Pissart et al., 1997; Harmand, 2004).

Marne, tributary of the Seine, in which ESR dating yielded an age estimate of 93±9 ka; Cojan et al. 2007) suggests that MIS 5 sediments could also occur in terrace 2. This reconstruction for the terraces 2 to 0 is in excellent agreement with the reconstruction for the Lower Moselle valley at Trier (Zolitschka and Löhr, 1999). The proposed chronology is also consistent with the numerical datings from terrace 3. In the Meurthe valley, Infra-Red Stimulated Luminescence (IRSL) dates have indicated ages in MIS 6 (between 170 and 130 ka; Cordier et al., 2005). These should however be only considered as minimum ages, due to the lack of a fading correction. However, they are in good agreement with the recently obtained ESR dates from Upper Moselle terrace 3 at Golbey (Pré Droué section), which yielded ages of 191±30 and 218±30ka. This result makes it possible to overturn the reconstruction of Taous (1994), who recognised three main Saalian periods of aggradation within the Golbey alluvial fan deposits. Although further dating is required to improve knowledge about the formation of terrace 3, these results are comparable with two dates from sediments undertaken for sediments from terrace 3 in the Aisne and Marne catchments, which yielded age estimates of 220±21 and 150±18 ka (Cojan et al., 2007). Taking into consideration the results obtained from the youngest terraces, a relation can be identified between the Pleistocene cold periods and terrace formation. This fact is consistent with the recognition of periglacial features in the fluvial sediments of the main studied rivers (see below).

Ages of the Upper Moselle capture (M4, UM4 and Sa4 terraces)

The age of the Upper Moselle capture event remains a matter of debate. A first chronological control on the event was obtained in the Maastricht-Belvédère terrace of the Meuse (the Netherlands).

In this terrace the pre-capture sediments (including sediments from the Vosges Massif) are overlain by post-capture sediments and by a palaeosoil. Thermoluminescence dating of burnt flints preserved in this palaeosoil yielded an age of ca 250-270 ka for the capture event (Huxtable and Aitken, 1985; Krook, 1993). This age is in good agreement with the relative chronologies proposed for the Moselle terrace and the end of the 20th century (Harmand et al., 1995), as well as with the numerical dating of the youngest terraces. However, it should, for methodological reasons, be considered cautiously. More recently, two speleothems found near Toul, in a cave containing fluvial sediments related to the UM4 terrace have been dated using U/Th (Losson & Quinif, 2001; Losson, 2003). A first dating yielded an age of 270 ka for a speleothem preserved in a cave

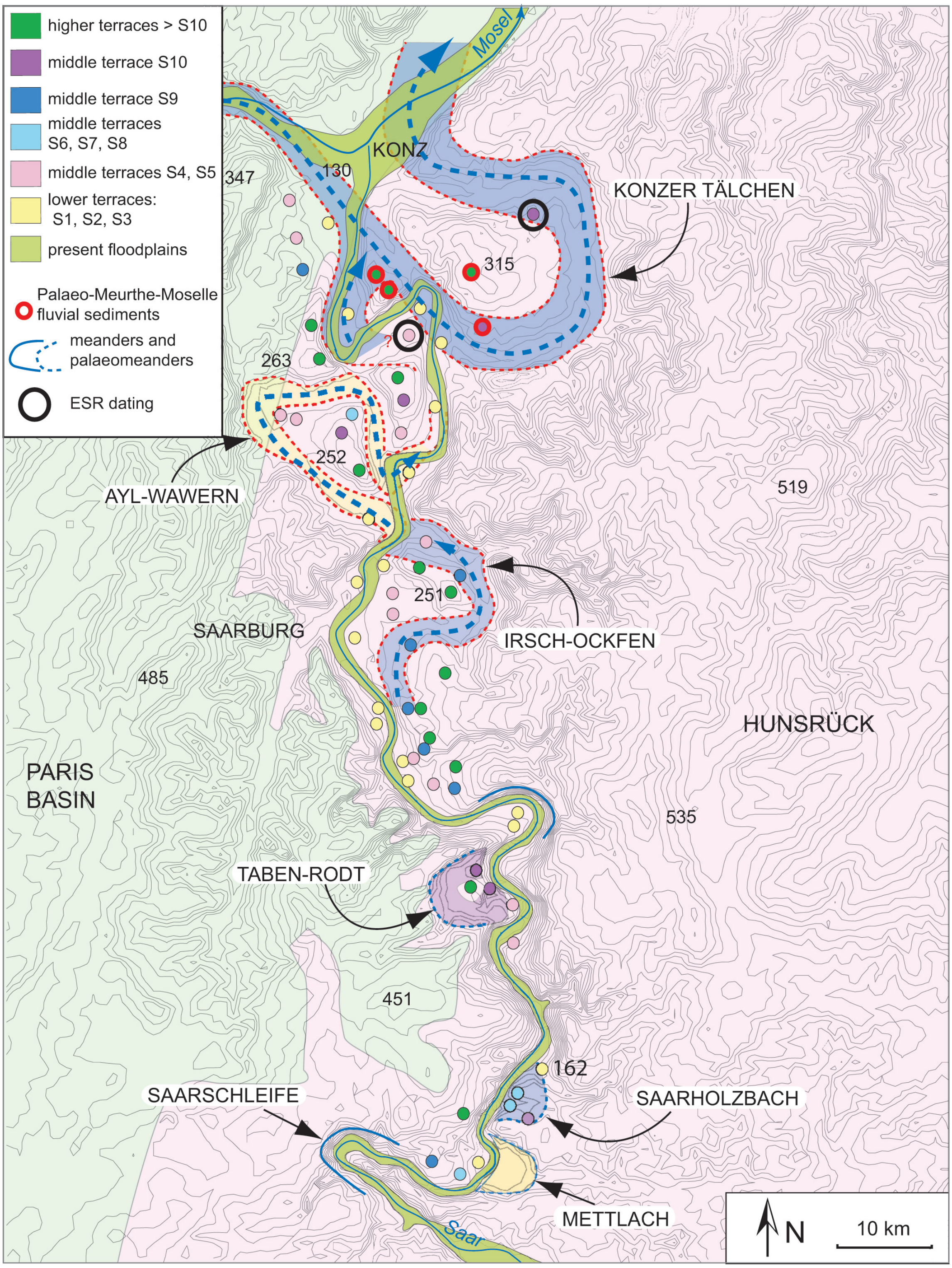


Fig. 12. The meanders and palaeomeanders of the Lower Sarre (after Müller, 1976; Zöller, 1985; Harmand, 2007).

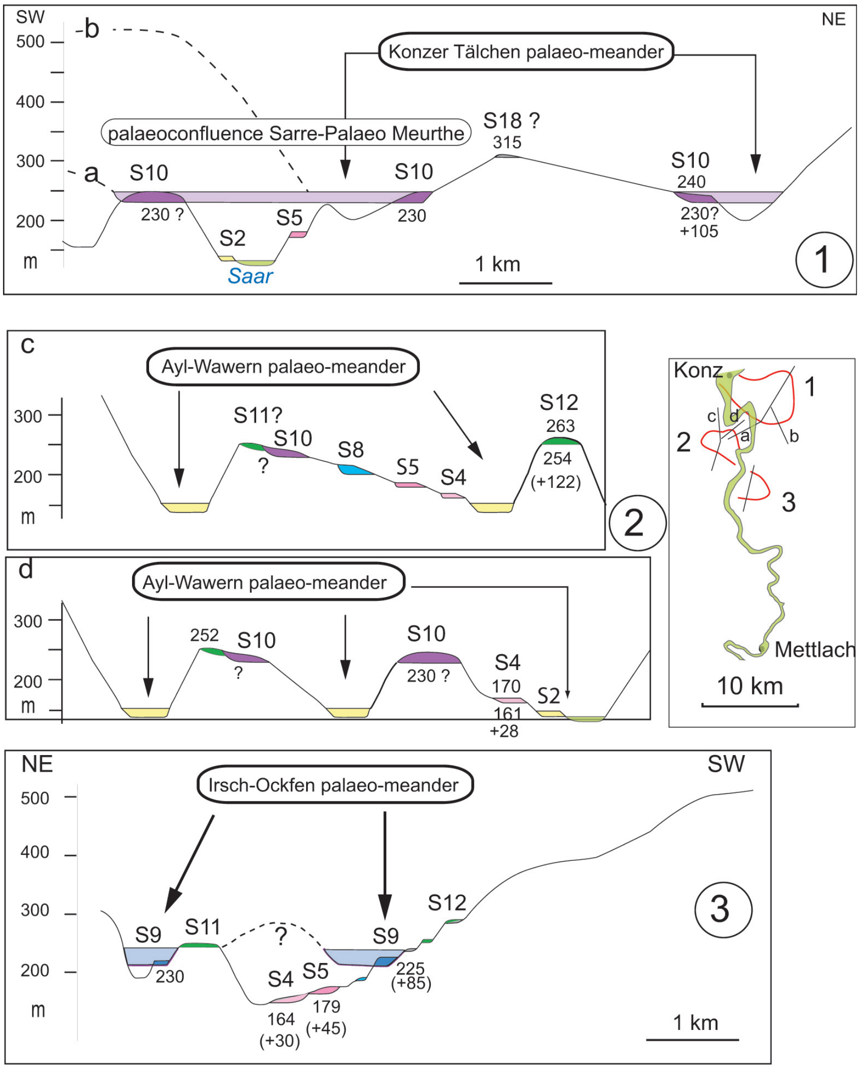


Fig. 13. *Palaeomeander and terraces staircase in the Lower Sarre.*

formed by the Moselle water contemporaneously with the UM4 terrace. The presence of this speleothem demonstrates that the cave was dewatered 270 ka ago, and therefore that the capture is older than 270 ka. However, the dating of a second speleothem sampled in the same cave yielded an age of 398-442 ka which should similarly be considered as a minimum age for the capture. Following from this, the capture event may be significantly older than previously expected. This observation is consistent with other U/Th dating of speleothem performed in the Meuse catchment in the Ardenne (Quinif, 2002), which demonstrated that the Meuse and its tributaries had not carved their valley significantly since 400 ka. It is also consistent with the ESR dating of the Sarre terrace Sa4 at Kanzem, which yielded an age of 340 to 410 ka, suggesting a correlation with MIS 11-10 (Cordier et al., 2012). On the base of morphological correlations, this age could be extrapolated to the last pre-capture terrace of the Moselle (M4) and to the UM4 terrace. However, both the ESR age and this correlation needs to be confirmed : further datings are obviously necessary to obtain a reliable age estimate for this major capture event and the associated terraces.

Age of the older terraces

If we follow the assumption (derived from the chronology for the youngest terraces, see above) that each cold period corresponds with a terrace formation, the presence of about ten pre-capture terraces in the Upper Moselle valley (Harmand, this study) suggests that the formation of the oldest terraces could be significantly older than 1 Ma. This reconstruction is consistent with the ESR dating on samples from the Sarre terrace Sa10 at Kommlingen (palaeo Moselle-Sarre confluence), which yielded ages of ca 1100-1250 ka, suggesting an Early Pleistocene age for Sa10 (Cordier et al., 2012). It is also consistent with previous research in the German Moselle valley (Cordier et al., 2006b), and in the Upper-Mselle-Meuse where Pissart et al. (1997) proposed age ranges from 2.2 Ma to 260 ka for the terraces between Toul and Maastricht. In contrast, it is in contradiction with the modelling of Westaway et al. (2009), who proposed that the middle and lower terrace formation (terraces located at less than 100 m relative height) took place after the Mid-Pleistocene revolution: following this reconstruction, the incision in the Moselle valley in the Rhenish Massif during the last 900 ka would have largely exceeded 100m, against less than 15m for the Meuse in the Southern Ardenne. Further dating of the older terraces is consequently required to provide a reliable reconstruction of long-term valley evolution in the Moselle and Meuse basin, taking account of regional uplift, morphostructural local conditions, and the incidence of the capture events.

Mechanisms for the fluvial captures

The occurrence of fluvial captures in the Eastern Paris basin results from a combination of lithological, palaeoclimatic and (at a larger scale) structural factors (Harmand et al., 1995; Harmand et Le Roux, 2009). The lithological factor is fundamental: all the capture events actually took place in marly or clayey depressions (Liassic clays and marls for the Gespunsart Meuse and the Palaeo-Sormonne; Callovian clays for the Upper Moselle; Lower Cretaceous clays for the Aire). These depressions are systematically located (following the pre-capture rivers) upstream from gorges sections: Ardenne basement for the Charleville area, Jurassic limestones for the Aire-Bar and Upper-Moselle. The presence of limestones in the latter areas has enabled seepage processes that have been recognised in the Upper Moselle, and are possible in the Aire-Bar area. However, infiltrations are not expected to have had a major influence on capture events, as demonstrated by the research of Losson (2003) in the Toul area and by the fact that capture events also occurred in non-karstic area (e.g. Charleville area). In contrast, the downstream sections following post-capture rivers are typically developed in soft rocks: easily eroded Chalk of Champagne for the Aisne river, Liassic marls for the Palaeo-Meurthe. The captures were finally realised by tributaries of these rivers, such as the Palaeo-Terrouin (tributary of the Palaeo-Meurthe; Figure 7) for the Upper Moselle (Le Roux and Harmand, 1998).

The second main factor relates to the climatic conditions: palaeoenvironmental reconstructions suggest that most of the capture took place at the end of cold periods. Recent research (Cordier et al., 2006a, b) demonstrated that most of the sedimentation took place during pleniglacial conditions (deposition of coarse deposits originating from the Vosges massif for the Upper-Moselle-Meuse valley, from the Barrois frost-shattered limestones for the Aire). Following from this, it is likely that the pleniglacial sedimentation led the river (and their tributaries) to raise the level of water, allowing diversion into another catchment. This process requires sufficient erosion of the marly interfluves, hence determining the timing of the capture event.

At a larger scale, the influence of the structural Barrois threshold was fundamental. The Barrois threshold corresponds to the border between the Paris basin (*stricto sensu*) and the Lorraine Triassic basin. It was active during the Jurassic and the Early Cretaceous, but corresponded to a depressed area during the formation of the hydrographic network at the end of the Cretaceous (Le Roux and Harmand, 2003). The Barrois threshold broadly corresponds to the present Meuse and Aire catchments in Lorraine (Fig. 1). These rivers also have a surelevated location in comparison with the Seine and Moselle catchments. The capture events that took place in the Eastern Paris basin should therefore be interpreted as readjustments of the hydrographic network to the Cenozoic structural conditions.

Climate forcing on fluvial evolution

The terrace staircases described above obviously reflect an internal forcing corresponding with a general tectonic uplift since the Tertiary. However, change in the fluvial system functioning (alternation of depositional and erosion periods) has to be interpreted in terms of climate change (Cordier et al., 2006a, b), as suggested by sedimentological and geochronological evidences. The study of several sections that expose the fluvial sediments shows that the main depositional phases correlate with the cold periods (e.g. pleniglacial and lateglacial periods of the glacial-interglacial or stadial-interstadial cycles). Periglacial features have actually been recognised in the fluvial sediments in the Meurthe valley (involutions in the fluvial sediments related to the presence of a continuous permafrost; J. Vandenberghe, pers. comm.), in the Pré Droué section of the Upper Moselle valley (coarse deposits associated with longitudinal bars; Taous, 1994), and in the Sarre valley (basal pebbles of ice-raft origin; Zöller, 1985; Harmand, 2007; Harmand and Durand, 2010). This is consistent with the evidence for deposition in braided channels (see above), which are typically associated with cold conditions in Western Europe (e.g. Mol et al., 2000; Busschers et al., 2007). It is also likely that the capture events occured at the ends of cold periods. This is especially the case for the Upper-Moselle capture, which is recorded in the Maastricht-Belvédère section below a palaeosol assigned to a Saalian interstadial (Vandenberghe, 1995).

Detailed study in the Meurthe valley downstream from the Vosges Massif (and especially of terrace Me4 sediments) allowed a more precise correlation between sediment deposition and the climate cycle as defined by isotope analyses of deep-sea and ice cores (Lisiecki and Raymo, 2005). Two thick sandy units were recognised and related to braided channels active during a pleniglacial phase. The low proportion of crystalline sediments is explained by their trapping in the glaciated area, but also by the morphostructural framework: downstream from the glaciated area, the Meurthe actually flows first through the Saint-Dié basin, then through the sandstone gorges formed in the area of Raon-l'Etape, enabling high amount of crystalline sediments to be trapped in the Saint-Dié basin. The top of the upper sandy unit was eroded before the deposition of coarser deposits (see above 3.2). This erosional transition and the significant component of crystalline sediments originating from the upper Meurthe catchment made it possible to correlate this unit with the melting of the Meurthe glacier at the cold-to warm transition (Cordier et al., 2006a, b). It seems, however, difficult to propose a regional correlation between terrace formation and Pleistocene climate changes. In particular, the sedimentation at the Pré Droué section is influenced by its proglacial location: the two main stratigraphical units observed in this gravel-pit correspond with two distinct sedimentations periods. The lower unit including a significant crystalline component originating from the upper catchment, but also sediments produced by the erosion of the regoliths developed on Triassic sandstones. In contrast the upper unit is mainly composed of angular crystalline sediments. They are associated either with a progression of the glacier front, or with the erosion of a previously deposited moraine (Taous, 1994; Harmand and Durand, 2010). Due to the error range, the ESR age estimates obtained from this gravel-pit (see above) do not allow a more precise correlation with climate.

A correlation between the terraces and the four glaciations recognised in the Vosges Massif (Flageollet, 2002 ; Harmand and Durand, 2010) is, however, plausible. The last glaciation (Würm) is associated with the Noirgueux end moraine, located ca 20 km upstream from Epinal (Flageollet, 1988; Seret et al., 1990). Due to the lack of an absolute chronology, the correlation between the Noirgueux system and Upper Moselle terrace UM 1 or 2, recognised downstream from Epinal, remains uncertain. In contrast, ESR dating of the Pré Droué section is consistent with the correlation, proposed by Flageollet (1988), with the penultimate glaciation ('Riss'). Finally, the fluvial sediments associated with the two embedded fans of Epinal-Châtel (terraces UM 9 and 11) correlate older glaciations attributed to the Mindel by Flageollet (1988). Following this, a significant gap separates the two old glaciations (ice caps covering the Vosges Massif and associated with terraces UM9 and 11) and the last two glaciations (valley glaciers contemporaneous with the Pré-Droué and Noirgueux systems and younger than 250 ka). The lack of glacial landforms associated with terraces UM8 to UM4 suggests either that they have been eroded by the subsequent glaciations, or that the climatic conditions did not allow a real glacier to cover the Vosges Massif.

The formation of terrace (e.g. succession of periods of sedimentations with possible reworking/partial erosion of the sediments, and of incision periods leading the the formation of a new valley floor below the previous one) should hence be firmly allocated to climate forcing. Sedimentological and geochronological evidences indicate that most of the fluvial deposition took place during and at the end of the Pleistocene cold periods. The periods of erosion are allocated to the climate warm-to-cold or cold-to-warm transitions. As shown by Cordier et al. (2006a), this evolution is comparable with the recognised in many other fluvial systems, especially in Northwestern Europe. However, the reconstructions for the study area also suggest that the response of the different rivers to a given climate change may differ. Similarly the response in a given area may be different from one Pleistocene climate cycle to another. This is well illustrated by the comparison between the Meurthe fluvial terrace Me4 (which exposes sediments related to various environmental conditions) and the younger levels (Me1-M1 and Me0-M0) in which the Pleniglacial and Late-Glacial to interglacial sediments are separated. It should especially relate to the crossing (or absence of crossing) of geomorphic threshold (Schumm, 1979).

Conclusions

This paper provides a regional overview of the terrace systems of the main rivers originating from the NW part of the Vosges Massif (Moselle, Meuse, Meurthe and Sarre). Recent research allowed a extensive mapping of the terraces, and the development of a chronological framework based on the OSL and ESR dating methods. Numerical ages are actually fundamental to confirm the correlations between the valleys, as these were first based on morphological evidences and on the occurrence of several captures. They also confirm that major depositional events take place during the cold periods associated with the presence of glaciers in the Vosges Massif. The capture events are likely to occur at the end of cold periods. However, the comparison between the different valleys shows that their evolution may differ strongly, in particular in terms of incision rates. The occurrence of several capture events and palaeomeander downcutting phases should therefore be considered not only as the consequence of the distinct evolution of neighbouring valleys but also as a trigger for post-capture fluvial evolution (e.g. in the Meuse valley). Further dating is, however, required to improve knowledge of valley evolution and regional correlations.

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