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THE PLEISTOCENE FLUVIAL DEPOSITS OF THE MOSELLE AND MIDDLE RHINE VALLEYS: NEW CORRELATIONS AND COMPARED EVOLUTIONS

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Stéphane CORDIER [1], Manfred FRECHEN [2] & Dominique HARMAND [3]

ABSTRACT

The River Moselle is one of the main tributaries of the Rhine, connecting the Vosges Massif, the Paris Basin and the Rhenish Massif. Research on fluvial archives preserved along the Moselle and Rhine valleys led to the recognition of well-developed fluvial terrace staircases, whose formation is the result of climate and tectonic forcing. The chronostratigraphical framework of these fluvial terraces was recently improved by applying luminescence dating methods, enabling a more reliable correlation of the Middle and Upper Pleistocene terraces for the River Moselle and the Middle Rhine valley (Rhenish Massif). The Moselle fluvial archives were morphologically, sedimentologically and chronologically studied in the Paris Basin and in the southwestern Rhenish Massif (area of Trier, Germany). They include eight middle and lower fluvial terraces, correlating with the middle and upper Pleistocene cold periods. All these fluvial terraces (except that formed during the Weichselian Early and Middle Pleniglacial) can be correlated with the seven youngest fluvial terraces recognized in the Middle Rhine. Minor differences in the elevation of contemporaneous terraces suggest differential uplift rates in both valleys: while the Neuwied tectonic basin (Middle Rhine area) presents a similar fluvial terrace system as the Moselle for the Middle and Upper Pleistocene, the other parts of the Middle Rhine valley showed greater uplift between 600 and 350 ky, coinciding with the development of intensive volcanic activity in the Eifel, which continued until recently.

Key-words: fluvial terraces, neotectonics, Moselle, Rhine, Rhenish Massif, Pleistocene.

RÉSUMÉ

LES ALLUVIONS ANCIENNES DU RHIN MOYEN ET DE LA MOSELLE DANS LE MASSIF SCHISTEUX RHÉNAN : NOUVELLES CORRÉLATIONS ET ÉVOLUTIONS COMPARÉES

La Moselle est l'un des principaux affluents du Rhin, reliant le Massif vosgien, le Bassin parisien et le Massif schisteux Rhénan. Les recherches récentes menées sur les archives fluviales des deux cours d'eau ont abouti à la reconnaissance de terrasses alluviales étagées bien préservées, dont la formation résulte à la fois d'un forçage interne et de l'influence climatique. Le calage chronologique des dépôts a été récemment amélioré par le recours à des datations absolues par luminescence, permettant une meilleure corrélation des terrasses alluviales du Pléistocène moyen et supérieur de la Moselle avec celles du Rhin, en particulier dans le Massif schisteux (Rhin moyen). Huit moyennes et basses terrasses alluviales de la Moselle ont été distinguées sur la base d'analyses morphologiques, sédimentologiques et chronologiques, et rapportées aux périodes froides du Pléistocène moyen et supérieur. Ces terrasses alluviales (sauf celle du début et du milieu Pléniglaciaire weichsélien) peuvent être corrélées avec les sept terrasses alluviales les plus récentes préservées dans le Rhin moyen. Des différences dans l'altitude relative de terrasses alluviales contemporaines indiquent que les phases d'incision peuvent être associées à des vitesses de soulèvement inégales d'une vallée à l'autre. Ainsi, alors que le bassin tectonique de Neuwied présente pour le Pléistocène moyen et supérieur un système de terrasses alluviales comparable à celui de la Moselle dans la région de Trèves, les autres sections de la moyenne vallée du Rhin témoignent d'un soulèvement plus marqué entre 600 et 350 ka, c'est-à-dire au moment où le volcanisme de l'Eifel était actif.

Mots-clés : terrasses alluviales, néotectonique, Moselle, Rhin, Massif schisteux Rhénan, Pléistocène.

1 - INTRODUCTION

The River Rhine is one of the most important hydrographic systems in Northwestern Europe. Its main tributary is the Moselle ("Lothringen Rhine", Schirmer *et al.* 1995), which flows northwards to join the Middle Rhine at Koblenz in the Rhenish Massif (fig.1). The upper parts of the catchments of both rivers (Alps and Vosges Massifs) were covered by glaciers (Alpine glaciation area) during the most extended Middle and Upper Pleistocene glaciations, as well as parts of the Lower Rhine area (Scandinavian glaciation area). Both rivers have experienced major changes in their course and are the result of several captures, especially during the Pliocene and the Pleistocene (Quitzow, 1974; Boenigk, 1995; Harmand *et al.*, 1995). As the morphological and geological contexts of these captures have been different, these diversions constitute reliable chronological tools due to

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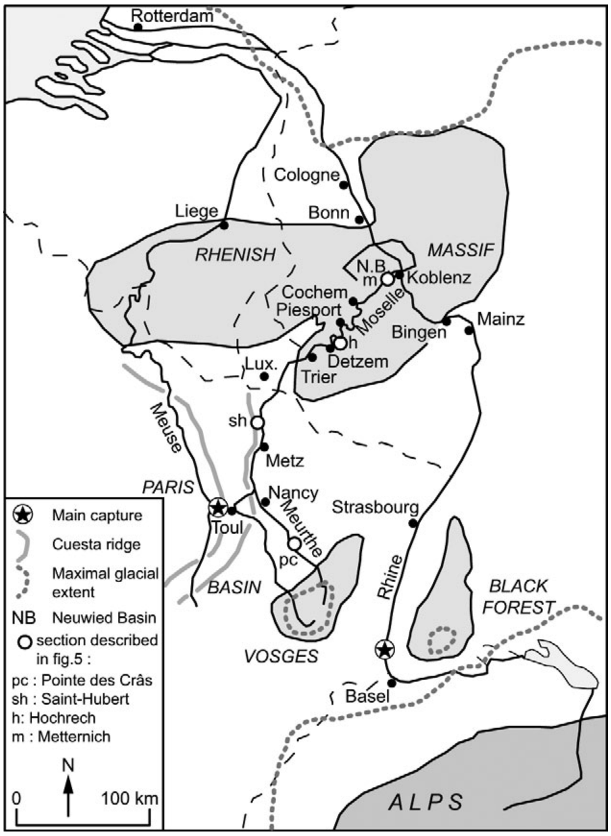

Fig. 1: General map of the Rhine and Moselle catchments.
Fig. 1 : Carte d'ensemble des bassins versants du Rhin et de la Moselle.

the associated changes in petrographical and mineralogical composition of the fluvial sediments (Boenigk, 1976).

The fluvial deposits of the Rhine, the Moselle, and the Meurthe (main tributary of the Moselle) have been extensively investigated during more than a century (e.g., Kaiser, 1903; Jungbluth, 1918; Quitzow, 1974; Brunnacker, 1978; Brunnacker & Boenigk, 1983; Bibus, 1980, 1983a, b, for the Rhine; Borgstätte, 1910; Dietrich, 1910; Wandhoff, 1914; Tricart, 1948; Kremer, 1954; Müller, 1976; Osmani, 1976, 1989; Löhnertz, 1982; Negendank, 1983 for the Meurthe and Moselle). Most of the studies however only focused on a part of the valley. Along the Rhine, the boundaries of studied areas correspond with morphological boundaries (Alpine Rhine upstream from the Lake Constance (Bodensee), High Rhine upstream from Basel, Upper Rhine in the eponymous graben, Middle Rhine in the Rhenish Massif, Lower Rhine downstream from Bonn, fig. 1). Studies along the Moselle valley were often delimited by the national borders between France, Luxemburg and Germany (e.g., Tricart, 1948; de Ridder, 1957). The stratigraphical reconstructions were significantly different in a given area from one author to the other (tab. 1).

More recent research (Cordier *et al.*, 2005, 2006a, b; Boenigk & Frechen, 2006) has developed a pluridisciplinary methodology, including morphological studies, sedimentological analyses, palynology, palaeontology and absolute datings. This has led to an improvement in knowledge of the fluvial terrace stratigraphy, especially for the time period of the Middle and Upper Pleistocene, and to propose longitudinal correlations into each fluvial system (fig. 2 & 3).

This paper also aims to compare the Pleistocene evolution of both systems, updating the first attempts of correlation realized during the 1980s (Bibus, 1983a, b). Since detailed results are provided in recent papers (Cordier *et al.*, 2005, 2006a, b, for the Moselle; Boenigk & Frechen, 2006, for the Rhine), only the main results concerning the fluvial terrace systems will be presented here.

2 - REGIONAL SETTING AND METHODOLOGY

2.1 - PRESENTATION OF THE STUDY AREA

The Moselle and Meurthe both rise within the Hercynian Massif of the Vosges. Their upper catch-

	TRIER-COCHEM				COCHEM-KOBLENZ			TRIER-KOBLENZ	MIDDLE RHINE			
TERRACE SYSTEMS	KREMER (1954)	MÜLLER (1976)	LÖHNERTZ (1982)	NEGEN-DANK (1983)	OSMANI (1976)	BIBUS (1983b)	NEGEN-DANK (1983a)	HOFFMANN (1996)	QUITZOW (1974)	BRUNN-ACKER (1980)	BIBUS (1983a)	SCHIRMER (1995)
UPPER TERRACES	HöT L	HöT L	t1-2	tMM1/2 L	äHT L	M1	tUM1/2 L	HöT			tR1-2-3	LPT L
MAIN TERRACES	OHT C MHT E UHT H	HT L	t3 t4 t5-6	tMM3 L tMM4 L tMM5 C	OHT L MHT UHT	M2 M3/4 M5	tUM1 L tUM2 tUM3-4 tUM5 C	äHT jHT UjHT	ÄHT L JHT UJHT C	HT 1/2 L HT 3 C HT 4	tR4 tR5 tR6	äHT L JHT C UJHT
MIDDLE TERRACES	OMT S	OMT E	t7	tMM6 E	OMT E	M6	tUM6 E	OMT	OMT1 OMT2 MMT E	MT I MT II MT III E	tR7	MT 1 C MT 2 MT 3 E
	UMT S	UMT S	t8	tMM7 S	UMT S	M7 S	tUM7 S	UMT	UMT S	MT IV S	tR8 S tR9	MT 4 S MT 5
LOWER TERRACES	NT W	NT W		tMM8 W tMM9	NT W	M8 W M9	tUM8 W tUM9	NT	ÄNT W JNT	ONT W YNT	tR10 W tR11 tR12	NT 1 W NT 2 NT 3

Ages assumed by the authors : L = Lower Pleistocene (Pre-Cromerian); C= Cromerian; E = Elsterian; H = Holsteinian; S= Saalian and Eemian; W = Weichselian and Holocene.

Tab. 1: The Moselle and Middle Rhine terrace staircase according to several authors.
Tab. 1 : Les terrasses alluviales de la Moselle et du Rhin moyen selon divers auteurs.

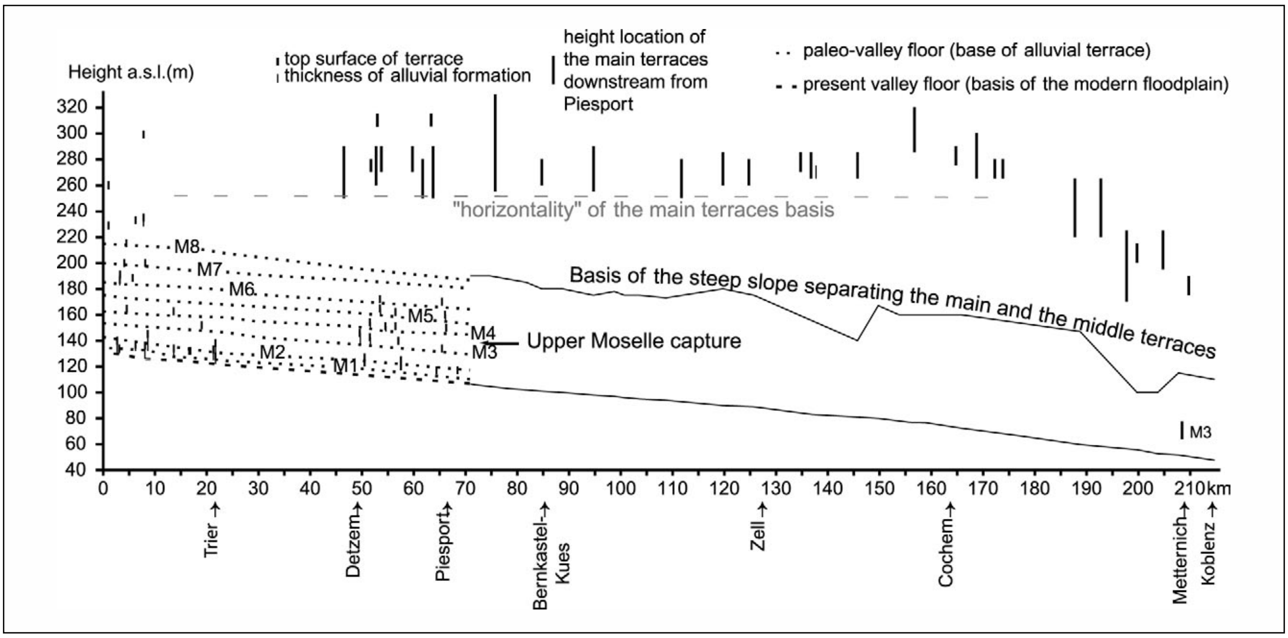

Fig. 2: Idealized sketch of the Moselle terraces between the Meurthe confluence and Koblenz.
Fig. 2 : Profil schématique des terrasses alluviales de la Moselle entre la confluence de la Meurthe et Coblence.

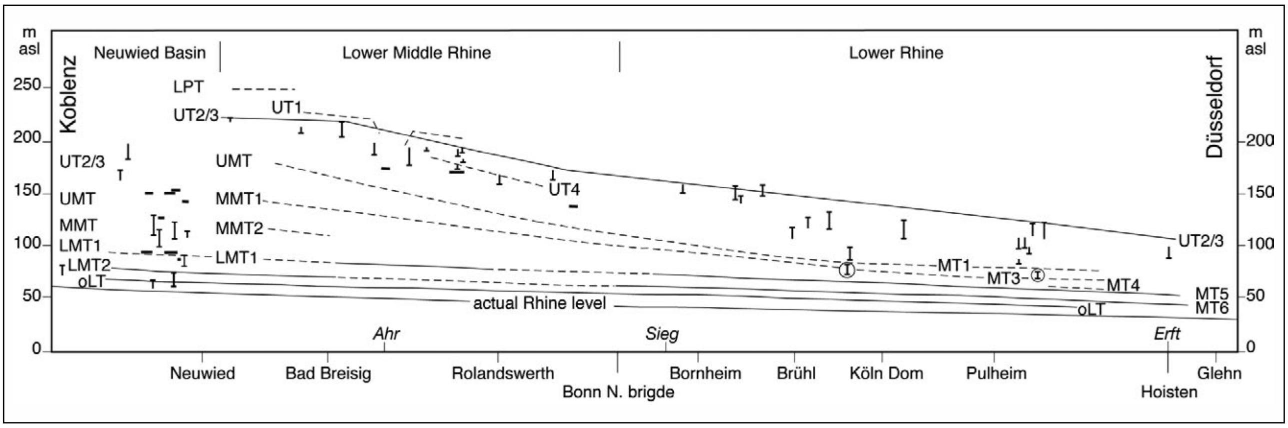

Fig. 3: Idealized sketch of the Middle and Lower Rhine terraces between Koblenz and Düsseldorf (modified after Boenigk & Frechen, 2006).
Fig. 3 : Profil schématique des terrasses alluviales du Rhin moyen et inférieur de Coblence à Düsseldorf (d'après Boenigk & Frechen, 2006, modifié).

ments were covered by glaciers during Pleistocene cold periods (Seret, 1966; Flageollet, 1988, 2002). The location of glacial deposits, however, indicates that the extension of the ice was more important in the Upper Moselle catchment (Nordon, 1931; Flageollet, 1988): the terminal moraine of the last Weichselian Pleniglacial is preserved at about 40 km downstream from the river source, while that of the Meurthe valley is preversed at only 12 km from the present source (Nordon, 1928; Darmois-Théobald & Ménillet, 1973). The second major difference concerns the lithology of the catchments: 75 % of the Upper Moselle catchment is developed in crystalline rocks (Hameurt, 1967), while the Upper Meurthe catchment is essentially developed in Permian and Triassic sandstones and conglomerates (Perriaux, 1961; Cordier, 2004; Cordier *et al.*, 2004).

Downstream from the Vosges Massif, the confluence of both rivers is located in the Paris basin (fig. 1), where important amounts of fluvial sediments have been preserved in the marly depressions separating the successive cuesta ridges. Further downstream, the Moselle river flows through the Rhenish Massif. Its course is characterized by broad meanders, especially between Trier and Cochem.

The confluence of the Moselle and the "Middle Rhine" is located at Koblenz. The Middle Rhine valley is situated between Bingen and Bonn, corresponding with the crossing of the Rhenish Massif (fig. 1). Deeply incised gorges have been formed through the Devonian schists and quartzites.

Field studies have demonstrated that major differential tectonic movements occured in the Rhenish Massif, in a context of general uplift of the massif since the Tertiary (Meyer *et al.*, 1983). In particular, the Neuwied Basin ("Middle Rhine basin", Schirmer *et al.*, 1995), located in the Rhine-Moselle confluence area, corresponds with an area of relative subsidence (Frechen, 1996), as its uplift is slower than that of the neighbouring massifs (Eifel, Siebengebirge).

2.2 - DEFINITION OF FLUVIAL TERRACE AND METHODOLOGY

The study focuses on the Moselle and Rhine stepped fluvial terraces, which are here defined both as river landform and fluvial sediments (Cordier, 2004), corresponding with:

– a top-surface ("terrace" sensu stricto). This surface has often been modified due to subsequent erosion or slope/aeolian deposition and is consequently not reliable to correlate one terrace with another one.

– a basal surface separating the fluvial sediments and the geological basement (bedrock). This surface is allocated to the maximal incision level reached by the river prior to sedimentation and presents a weak sensitivity to reworking (only dissolution processes in limestones);

– fluvial sediments (corresponding with fluvial formations) preserved between these surfaces. Their aggradation occured between two phases of main fluvial incision. In the study area, these sediments systematically show typical fluvial stratification features (as cross-bedded stratifications) and include distal material (from the Vosges massif for the Moselle or the Alps for the Rhine).

The fluvial formations of the Moselle and the Middle Rhine have been investigated using morphological, sedimentological and chronological approaches:

– morphological studies led to definition of the their geometry : expansion, thickness, and relative height. The last of these was often defined in previous studies as the difference in height between the top surface and the present floodplain. Taking into account the erosion of the top surfaces (see above), the relative height here corresponds (as commonly in recent studies) with the difference in height between the bedrock of a fluvial formation and the bedrock of the present floodplain. The relative height should, however, only represent a first discrimination: fluvial dynamics (especially when the river is migrating) can actually generate significant differences in the height of the base of a given fluvial terrace.

The morphological location of the fluvial terraces was also commonly used by German authors, who distinguished "lower terraces" (close to the present floodplain), "middle terraces" (separated from the latter ones by a rather sharp slope, and generally preserved on convex banks of the meanders), and "upper ("main" and "high") terraces", morphologically preserved as "plateau terraces". Although these terms have sometimes been used in a stratigraphical sense (Kremer, 1954), it is important to mention that the morphological position of a given fluvial terrace can change along the valley, as observed for example for the terrace M3 which is sometimes separated from the terrace M2 by a steep slope, sometimes by a gentle one. Consequently these terms will here only be used descriptively. This paper will thus mainly focus on the "middle and lower terraces", which are the younger fluvial terraces with a maximal relative height of about 100 m.

– sedimentological analyses have included both coarse deposits (pebble counting) and sand (heavy mineral determination), in order to provide a qualitative characterization of the fluvial deposits. Sharp contrasts in the sediment composition from one fluvial formation to another can then be used as evidence for previous captures, while less pronounced differences makes it possible to distinguish between terrace groups ("upper", "middle", "lower" terraces).

– chronological data have been obtained using relative (palynology, palaeontology) and absolute dating methods ($^{40}Ar/^{39}Ar$, $^{40}K/^{40}Ar$ and luminescence in the Rhine valley; luminescence, radiocarbon and uranium series dating in the Meurthe and Moselle valleys). They have served to improve knowledge of the fluvial terrace chronostratigraphy, especially for the youngest ones, as well as correlation between the Rhine and the Moselle terrace systems.

3 - THE PLEISTOCENE FLUVIAL TERRACES ALONG THE MOSELLE VALLEY

3.1 - THE "MIDDLE AND LOWER FLUVIAL TERRACES"

Recent research (Cordier, 2004; Cordier *et al.*, 2005) has enabled distinction along the Moselle valley of eight fluvial terraces below 90 m relative height (from M8 the oldest to M1, fig. 4). They have been recognized not only in the Paris Basin but also in the Rhenish Massif (Detzem-Piesport basin, corresponding with the broad meanders of Detzem-Leiwen, Trittenheim and Piesport), where previous research only distinguished three "middle and lower" fluvial terraces (Kremer, 1954; Müller, 1976; Löhnertz, 1982). These eight fluvial terraces are regularly stepped between +80 and +3 m relative height, with a mean difference in height of 10 m between successive bedrock-terrace contact surfaces. The bedrock surfaces beneath the fluvial formations are located at constant relative height between the Moselle-Meurthe confluence and Piesport. Downstream from Piesport, a high slope, whose base is located at more or less 90 m above the present riverbed, separates this younger fluvial formations from the older ones ("main and high terraces"). This makes it possible to extrapolate the longitudinal profile of the "middle and lower terraces" from Piesport until the Rhine confluence (fig. 2).

The thickness of the associated sediment sequences is highly variable, ranging from 1-2 m for the oldest formations (owing to weathering and erosion), to about 5-8 m for the youngest.

In the Paris basin, the Moselle and Meurthe fluvial formations have a more or less similar disposition from one formation to the other (Cordier *et al.*, 2006a), and three units can typically be recognized (fig.5):

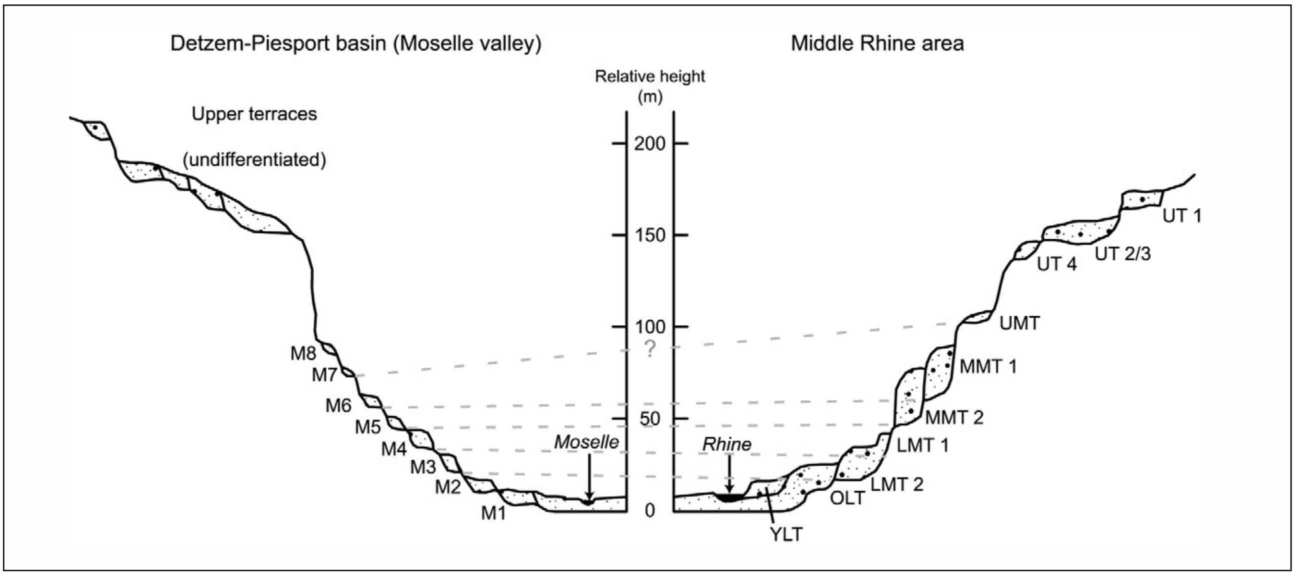

Fig. 4: Schematic cross-profile showing the fluvial terrace staircase of the Moselle and Rhine valleys in the Rhenish Massif. The relative heights are defined from the lowest bedrock (base of the modern floodplain for the Moselle, base of OLT for the Rhine). The dotted lines join the contemporaneous fluvial terraces.

Fig. 4 : Profil transversal schématique montrant la disposition des terrasses alluviales de la Moselle et du Rhin dans le Massif schisteux. Les altitudes relatives sont définies à partir du niveau d'incision maximal (base des alluvions modernes pour la Moselle, base des alluvions de la basse terrasse supérieure pour le Rhin). Les lignes pointillées relient les terrasses alluviales contemporaines.

– a coarse unit, generally preserved at the base of the formation except near the Vosges Massif (e.g. section of Pointe des Crâs, fig. 5) where it overlies sands;

– a sandy unit, well developed in the Meurthe formations and at the margins of the Moselle valley downstream from the Meurthe-Moselle confluence (e.g. section of Saint-Hubert, located at the vicinity of the western slope of the valley);

– a silty to loamy unit, preserved at the top of the formation.

The sediments are significantly coarser in the Rhenish Massif, due to an increase in the proportion of proximal deposits. The fluvial sequence typically shows a contrast between lower coarse sediments (including more or less thick sandy beds, sections of Hochrech and Koblenz-Metternich, fig. 5) and upper fine deposits. The longitudinal correlations however indicate the persistence of climate control on fluvial dynamics.

The qualitative sediment composition also differs between the Paris Basin and the Rhenish Massif: upstream from Trier, the main sediments source is the Vosges Massif. The latter sediments consist mainly of quartz, quartzite and granite clasts, associated with a heavy mineral spectrum, in which tourmaline, zircon, hornblende and garnet are predominant (Cordier *et al.*, 2004).

Downstream from Trier, the amount of sediments originating from the Rhenish Massif (schists, quartz, volcanic minerals from the Eifel) strongly increases (Kremer, 1954; Müller & Negendank, 1974; Löhnertz, 1982).

Despite this evolution, a major contrast has been recognized along the Moselle valley, from the Meurthe confluence to the Rhenish Massif : the pebbles of the oldest fluvial formations (from M8 to M4) are mainly composed of quartz and quartzite, the heavy mineral spectra being dominated by tourmaline and zircon (typical from the sandstone and conglomeratic outcrops of the Vosges Massif, Perriaux, 1961); the three youngest fluvial terraces (from M3 to M1) include a significant proportion of crystalline clasts (granites) and sands (hornblende and garnet) originating from the Vosges Hercynian basement. This difference reflects a lithological contrast between the Upper Meurthe catchment, mostly developed in sandstones and conglomerates, and the Upper Moselle catchment, where crystalline rocks are predominant. This sedimentological division has also to be attributed to the Upper Moselle capture (realised at the expense of the Meuse basin), which occured at the end of the sedimentation of M4 (Cordier *et al.*, 2005). The M4 formation and all older ones were formed by the Palaeo-Meurthe, while the youngest include sediments originating from both the Upper Meurthe and the Upper Moselle catchments. This interpretation is in good agreement with morphological studies in the area of Toul, where four post-capture fluvial formations have been recently recognized (Losson, 2003).

3.2 - THE "UPPER" FLUVIAL TERRACES

In contrast to the "middle and lower terraces", the preservation of the older river terraces is highly variable: in the Paris Basin, the only remains consist of residual clasts, preserved at the top of the main cuesta ridges and along the German-Luxembourgian border (Cordier, 2004). In contrast, river terraces situated at more than 100 m relative height are well developed in the Rhenish Massif: they are associated with broad surfaces and the thickness of the fluvial sediments is often more than 10 m.

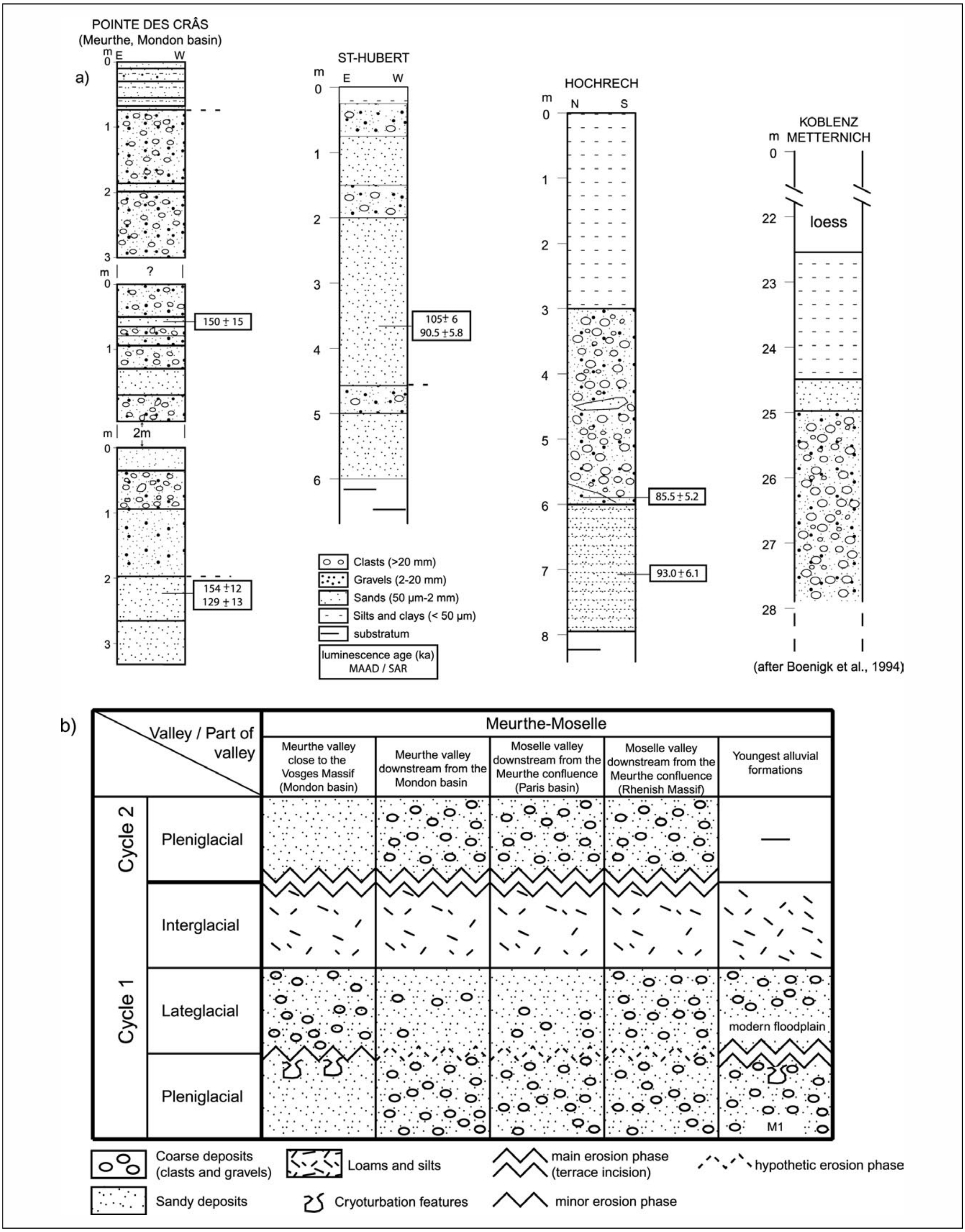

Fig. 5: The fluvial sequences along the Meurthe and Moselle valleys.
a) description of some profiles from the Meurthe valley to Koblenz related to the first post-capture fluvial terrace M3 (location : see fig.1). The choice of these profiles is due to the presence of thick sandy beds/units, enabling luminescence analyses. The dating results here presented corresponds either with IRSL analyses of feldspar (Pointe des Crâs, Saint-Hubert) or with OSL analyses of quartz grains (Hochrech).
b) relations between fluvial terraces formation and Pleistocene climate change in the Meurthe and Moselle valley (modified after Cordier *et al*., 2006a).
Fig. 5 : Les séquences alluviales de la Meurthe et de la Moselle.
a) présentation de profils correspondant à la terrasse alluviale M3, pour les vallées de la Meurthe et de la Moselle jusqu'au Rhin (localisation des sites : cf. fig.1). Le choix de présenter ces profils a été déterminé par la présence de lits/unités sableux épais, permettant l'échantillonnage et la réalisation de datations par luminescence. Les résultats sont présentés ici. Ils ont été obtenus soit par la datation IRSL de felsdpaths (coupes de Pointe des Crâs et de Saint-Hubert) soit par la datation OSL de quartz (coupe de Hochrech).
b) schéma montrant les relations entre la genèse des terrasses alluviales de la Meurthe et de la Moselle et les cycles climatiques pléistocènes (d'après Cordier et al*., 2006a, modifié).*

The number of these "upper terraces" is however still under discussion, ranging from 2 to 4 and even 5. The reconstruction of a longitudinal profile is difficult, even if there is general agreement to assume "horizontality" of their longitudinal profile: between Trier and Cochem, the "upper terraces" are obviously situated at constant absolute heights (see fig. 2). Several reconstitutions have been proposed: Löhnertz (1982, 2003) compared the fluvial evolution with that of the present main Siberian rivers (very gentle longitudinal gradients associated with coarse sedimentation). On the contrary, Hoffmann (1996) assumed the presence of numerous faults leading to such "horizontality". These assumptions however remain questionable (especially due to the lack of a reliable stratigraphy) and further research is needed to explain this morphological feature.

The sedimentology of the formations of the "upper terraces" is more or less similar to that of the pre-capture "middle terraces". The sediments have a predominance of quartz (the more so as the sediments are older, since less durable materials have been diminished by weathering), quartzites and schists associated with tourmaline and zircon in the heavy-mineral spectra (Beiner *et al.*, this volume).

4 - THE PLEISTOCENE FLUVIAL TERRACES ALONG THE MIDDLE RHINE VALLEY

Recent research in the Middle Rhine has led to the recognition of five "upper terraces" and seven "middle and lower terraces" (Boenigk & Frechen, 2006). The distinction between these two groups is based on the same morphological criteria as already presented for the Moselle valley.

4.1 - THE "MIDDLE AND LOWER TERRACES"

The "middle and lower terraces" have small and narrow remnants located in the entrenched valley. They are subdivided into five stepped "middle terraces" and two inset "lower terraces" (fig. 4).

The morphological location of a given fluvial terrace may be different from one area to another, owing to tectonic activity, and so the relative height of each river terrace is significantly variable. The lowest values of relative heights are observed in the northwestern part of the Rhenish Massif (area of Bonn, separating the Middle and the Lower Rhine), and most of all in the Neuwied Basin. The river terraces reach their maximal relative height just downstream from the Neuwied Basin.

The relative heights of the "upper and middle middle terraces" range between +80 and +120 m (Upper Middle terrace), +60 and +80 m (Middle Middle terrace 1) and +40 and +60 m (Middle Middle terrace 2), respectively (fig. 3 & 4). The youngest levels are situated at more constant relative heights: +30 m (Lower Middle terrace 1) and +20 m (Lower Middle terrace 2), respectively. The morphology of the "lower terraces" (Older Lower Terrace OLT and Younger Lower terrace YLT) does not show major changes through the Middle Rhine valley (fig. 4).

The thickness of the fluvial formations is important, sometimes exceeding 10 m (e.g. for the MMT and LMT). The grain-size of the sediments is very similar to that of the Moselle in the Rhenish Massif, including coarse deposits with interbedded sands and a silty cover (Brunnacker, 1978). The sediments are characterized by the presence of a significant proportion of clasts and sands from the Eifel volcanic area (Meyer, 1994; Boenigk, 1995). The heavy-mineral spectra are also dominated by apatite (Upper Middle terrace), or basaltic augite (Middle and Lower Middle terraces, Lower terraces).

4.2 - THE "UPPER TERRACES"

In the Middle Rhine valley, the "upper terraces" (*sensu lato*) correspond morphologically with extended surfaces and thick fluvial formations (up to 20 m) like along the Moselle valley. Five fluvial terraces have been recognized (Boenigk & Frechen, 2006, fig. 4), one "Lower Pleistocene Terrace" (LPT) and four "Upper terraces" (from UT 1 the oldest to UT4). Their relative heights range from +200 m for the older (LPT) to +120 m for the younger (UT4). However these values are approximate, owing to tectonic activity and deformations along the valley.

The sediment composition of the "upper terraces" differs from that of the younger ones: they are characterized by a predominance of quartz clasts, and heavy minerals such as epidote, garnet and green hornblende. Volcanic minerals are not present, except in the sediments of the youngest terrace UT3/4 (*sensu* Boenigk & Frechen, 2006), as a minor component of the heavy mineral spectra.

5 - THE PLEISTOCENE CHRONOSTRATIGRAPHY OF THE FLUVIAL TERRACES

5.1 - THE MOSELLE VALLEY

Research in the Moselle and Meurthe valleys made it possible to propose a chronostratigraphical framework for the time since the Upper-Moselle capture (based on the terminology used in by Veldkamp & Van den Berg, 1993 or Antoine *et al.*, 1998):

– a first age estimate for the capture was derived from the thermoluminescence dating of burned flints found in sediments from the Lower Meuse in the Netherlands : the age estimate (ca 250 ka, Huxtable & Aitken, 1985) makes it possible to allocate the last pre-capture M4 formation (+30 m relative height) to MIS 8 (fig.6). This result was confirmed by more recent uranium series dating results on speleothems (sampled in a cave near Toul, a few kilometres upstream from the present Moselle-Meurthe confluence, where pre-capture

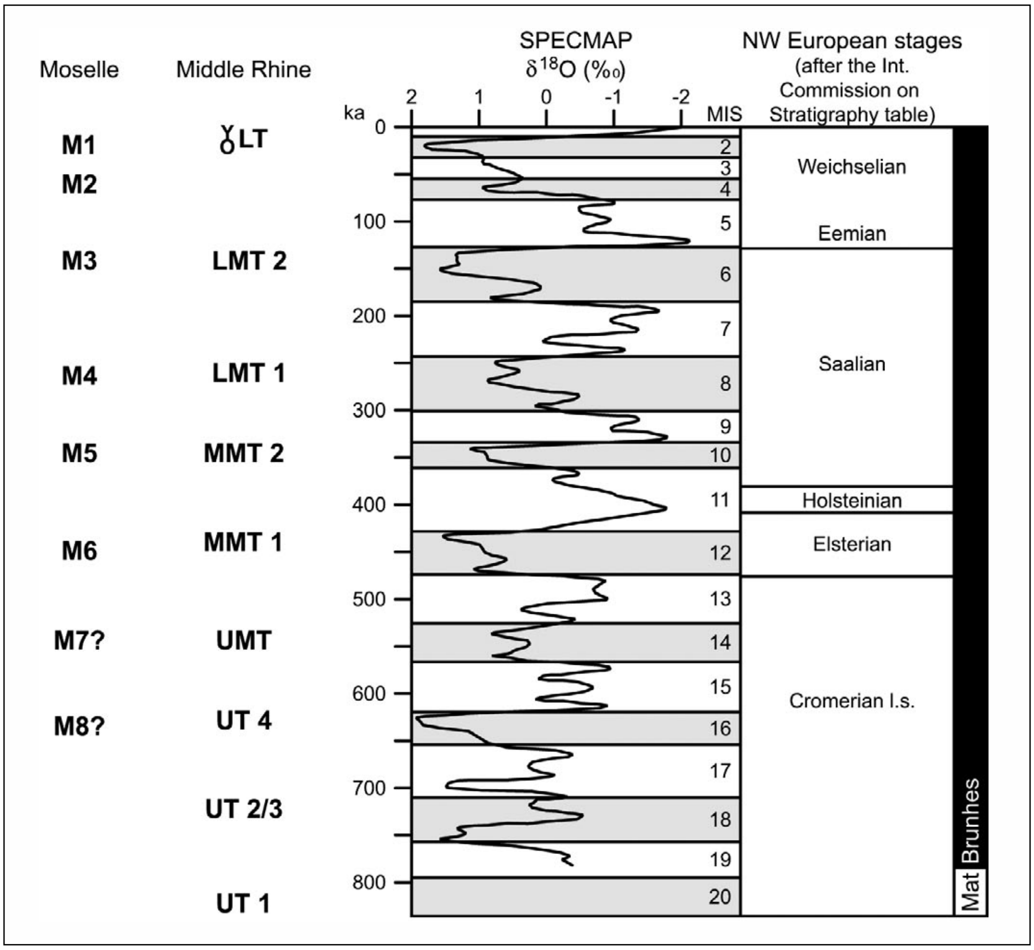

Fig. 6: Stratigraphy of the Moselle and Middle Rhine Pleistocene fluvial terraces.
Fig. 6 : Stratigraphie des terrasses alluviales pleistocènes de la Moselle et du Rhin moyen.

deposits have been trapped, fig. 1, Losson *et al.*, 2001; Losson, 2003), which provided an age estimates at ca 250-270 ka.

– the first post-capture fluvial formation M3 (+20 m) was studied in both the Moselle and Meurthe valleys:

• samples were taken in the Meurthe valley upstream from Lunéville, from units A and B, for IRSL dating. The results yielded ages generally ranging from 170 to 130 ka (for detailed results and description of the stratigraphy see Cordier *et al.*, 2005, 2006a): This led to correlation of this formation with the last cold period of the Saalian glaciation (MIS 6, Veldkamp & Van den Berg, 1993). These dates are furthermore in good agreement with palaeontological observations (remains of *Mammuthus primigenius* in the gravel body of this formation in several sections of the Meurthe and Moselle valleys, see Cordier, 2004).

• in the Rhenish Massif (Detzem-Piesport basin and downstream) where samples were taken for OSL dating from sandy intercalations into the coarse deposits. The OSL age estimates yielded deposition ages correlating to the Early Weichselian (corresponding with MIS 5 the error margin of the dates prevents, however, further precise correlation with substages of MIS 5).

Although the OSL age estimates are younger for the M3 formation in the Rhenish Massif, these results are in good agreement with those from the Meurthe valley. As expected during sedimentological analyses (see above §3.1) and previously proposed (Cordier *et al.*, 2006a), each fluvial terrace of the Meurthe-Moselle formed during one glacial-interglacial cycle, with coarse to sandy sedimentation under cold or cool conditions and silty sedimentation probably occuring under temperate conditions, the main incision phase (responsible for the staircase creation) being linked to the transition between as warm stage and a cold stage (see also fig.5). The coarse sediment deposition of formation M3 thus mainly corresponds with the end of the Saalian (MIS 6) close to the Vosges Massif, while it may have continued in the Rhenish Massif until the end of the Early Weichselian. This observation must be related to the fact that the Moselle and its tributaries flow in the Rhenish Massif through Devonian rocks (schists, quartz, quartzite) and can readily transport coarse sediments.

– the deposits of the fluvial formation M2 (+10 m) were dated by luminescence in the Meurthe valley. This yielded age estimates correlating with the Weichselian Lower and Middle Pleniglacial (MIS 4 and 3, fig. 6). This result is in good agreement with the interpretation of evidence from the Trier area by Zolitschka and Löhr (1999), who suggested a similar age for the “older lower terrace” NT1, corresponding with M2.

– the youngest fluvial formation M1 (+3-5 m) has been dated in the Luxemburgian Moselle valley (section of Remerschen), using both radiocarbon (see Naton *et al.*, this volume), IRSL (on feldspars) and OSL (on quartz) methods. While the OSL dating on quartz indicates a maximum age estimate ranging between 32.2 ± 2.4 and 39.3 ± 3.9 ka, the IRSL dates on feldspars (using both MAAD and SAR methods) indicate that the sedimentation occured during MIS 2 (ages ranging between 21.3 ± 1.5 ka and 17 ± 1.4 ka). This result is in excellent agreement with the presence of cryoturbation features in the sediments of M1 at Remerschen and along the Moselle valley (Coûteaux, 1970) and could fit with the radiocarbon dates from the contact between fluvial and slope deposits (30.770 ± 300 BP; see Nation et al., this volume, for discussion). As a consequence this fluvial formation correlates very probably with the Weichselian Upper Pleniglacial (fig. 6).

– Radiocarbon dating in the Paris basin (Carcaud, 1992) and palynological analysis in the vicinity of Trier (Zolitschka & Löhr, 1999) provide evidence that the modern floodplain should have been formed during the Lateglacial and Holocene periods. Further datings are however needed to confirm these preliminary results.

– These multidisciplinary results confirm that there is a direct link between climate change and fluvial dynamics formations along the Moselle valley. So far the luminescence chronology is in good agreement with the chronostratigraphic interpretations. Each main gravel body corresponds with a cold period (Weichselian Upper Pleniglacial for M1, Weichselian Lower Pleniglacial for M2, Saalian for M3 and M4) and can be allocated to a cold stage (MIS 2 for M1, MIS 4 for M2, MIS 6 for M3, MIS 8 for M4). Taking into account this parallelism, the older fluvial formations (from M5 to M8) may be allocated to MIS 10, 12, 14 and 16, respectively (fig. 6). The oldest one M8 (+85 m relative height) would thus have been formed during the first part of the Middle Pleistocene (around 650 ka).

The deposition age of the "upper terraces" sediments preserved along the Moselle valley remains unknown. There has been general agreement from recent research (Hoffmann, 1996; Löhnertz, 2003) for allocation of the "young upper terrace" to about 780 ky. This age is however mostly based on an extrapolation of the age of the assumed contemporaneous fluvial terrace in the Lower Rhine (Klostermann, 1992), and is consequently questionable: since the correlation of the "high terraces" remains unsure, not only between the Rhine and the Moselle valleys, but also along the Moselle valley itself, this chronology should still not be considered as reliable, and further research including absolute dating is needed to resolve this question.

5.2 - THE MIDDLE RHINE VALLEY

The chronostratigraphy of the Middle Rhine fluvial formations has been facilitated by the presence of both volcanic deposits intercalated in the sediments (enabling absolute dating by $^{40}Ar/^{39}Ar$) and loess/palaeosoil sequences covering the fluvial deposits, especially in the well-known sections of Ariendorf, Kärlich and Koblenz-Metternich (Boenigk & Frechen, 1998, 2001). This has provided the following proposed chronological framework for the "middle and lower terraces" (fig. 6):

– the presence of brown hornblende in significant proportion in sediments from the Upper Middle terrace (UMT) enables correlation of the fluvial deposits with the aeolian sediments of unit G from the Kärlich section (Boenigk & Frechen, 2006). As unit H was dated to about 450 ky using $^{40}Ar/^{39}Ar$ from interbedded pumice tephras, the deposits of fluvial terrace UMT probably correlates with MIS 14.

– the volcanic deposits from the Ariendorf section overlying the Middle Middle Terraces (MMT1 and MMT2) were dated to about 451 and 418 ky by the $^{40}Ar/^{39}Ar$ method, and so the terraces MMT1 and MMT2 can probably be correlated with MIS 12 and 11.

– the two Lower Middle terraces (LMT) are correlated with MIS 8 and 6, from their loess-palaeosol cover (e.g. section of Koblenz-Metternich, where the Eemian-Weichselian sequence is preserved at the top of the Lower Middle terrace sediments, Boenigk & Frechen, 2001).

– Finally, the presence of tephra originating from the last cataclysmic eruption in the East Eifel Volcanic Field (Laacher See eruption) at the top of the "oldest lower terrace" and in the sediments of the "younger lower terrace" enables allocation of these fluvial deposits to MIS 2 and 1, respectively.

The chronological framework is less precise for the "upper terraces", except for the oldest Upper Terrace (UT1), which should be allocated to MIS 20 (800 ky) on the base of the reverse magnetisation of its sediments. As a consequence, the "younger upper terraces" UT2 and UT3/4 correlate very probably with MIS 18 and 16, respectively (fig. 6).

Despite some remaining uncertainty in the chronological framework, the results underline the correlation already described in the Moselle valley between the Pleistocene cold stages and the fluvial terraces aggradation.

6 - COMPARISON OF THE FLUVIAL TERRACE MORPHOLOGY AND CHRONOSTRATIGRAPHY IN THE MOSELLE AND MIDDLE RHINE VALLEYS

The above-mentioned results make it possible to compare the fluvial evolution in both valleys, especially for the Middle and Upper Pleistocene time period. As the chronology is more reliable for the young fluvial deposits, the comparison will be presented from the present to the oldest times.

6.1 - FROM THE WEICHSELIAN UPPER PLENIGLACIAL TO THE HOLOCENE (MIS 2-1): DEVELOPMENT OF THE VALLEY BOTTOM (LOWER TERRACE AND MODERN FLOODPLAIN)

In the study area, the valley bottom is characterized by three major phases of aggradation from the oldest to the youngest (fig. 4): the first, always preserved as a lower fluvial terrace (M1, OLT), corresponds, as shown before, with the Weichselian Late Pleniglacial (MIS 2). The second correlates to the Lateglacial, and consists of coarse sedimentation (lower sediments of the modern floodplain of the Moselle, YLT). The youngest aggradation period is associated with fine-grained sediments, deposited during the Holocene (top of the modern floodplain of the Moselle, Holocene deposits of the Rhine).

The fluvial evolution seems to have been similar for the past 30 ky in both valleys. Indeed, these results are similar to those from other northwestern European river valleys (Mol *et al*., 2000).

6.2 - THE WEICHSELIAN LOWER AND MIDDLE PLENIGLACIAL (MIS 4 AND 3): A HIATUS IN THE RHINE TERRACE SYSTEM?

In contrast with the Middle Rhine, where the "older lower terrace" (OLT) seems to be directly dominated by the "middle terraces" system, an additional "lower fluvial terrace" has been found in the Moselle valley as well as in that of its tributary the Meurthe (fig. 4). It is located 5 m above the Upper Pleniglacial formation (M1), and 10 m above the present floodplain. OSL age estimates and the presence of cryoturbation features indicate that this fluvial terrace was formed during MIS 4 and 3. The M2-M1 incision would thus have occured at the MIS 3-2 transition.

The presence of this fluvial terrace in the Moselle (and Meurthe) valley, whereas it is missing in the Middle Rhine area, might be explained by a cold oscillation in the Vosges Massif, (generating a supplementary sedimentary cycle in the Moselle basin). This assumption is however questionable since this aggradation period is confirmed for sediments from the southernmost Upper Rhine Graben. Fluvial sediments from a section in the north of Basel yielded IRSL age estimates ranging from 55-60 to 25 ky (Frechen *et al*., in prep.). It is also very likely that contemporaneous sediments are present in the Middle Rhine Valley, where they might be preserved as part of the Older Lower terrace or Lower Middle terrace sediments.

6.3 - THE SAALIAN

The period between 380 and 130 ky ("Saalian" according to Reille *et al*., 2000 and the International Commission of Stratigraphy) seems to be characterized by the more or less similar evolution of both valleys (fig. 4): the three main cold periods (MIS 6, 8 and 10) are associated with three main aggradational periods leading to the formation of three fluvial terraces (M3, M4 and M5 in the Moselle valley, LMT2, LMT1 and MMT2 in the Middle Rhine valley). They are located at quite similar relative elevations, +20 m, +30 m and +45-50 m, respectively.

This result is fundamental because it shows that the Moselle and Rhine areas have experienced comparable incision cycles during this period. The calculated incision rates give a mean value of 0.12 mm/yr (fig. 7), which is slightly smaller than the recently proposed value for the Middle Rhine valley by Westaway (2001), using

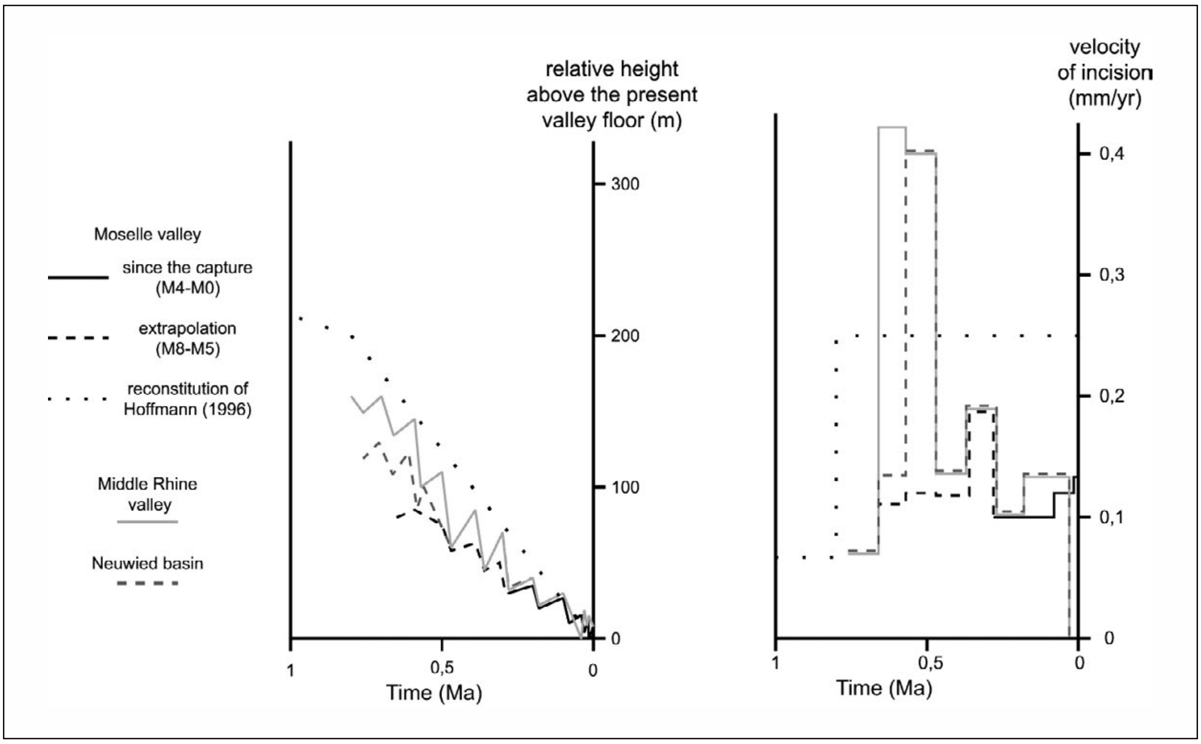

Fig. 7: Compared incisions and aggradations in the Moselle and Rhine valley since 1 Ma.
Fig. 7 : Creusements et alluvionnements comparés de la Moselle et du Rhin depuis 1 Ma.

previous chronological interpretations to assume an incision rhythm ranging from 0.11 mm/yr in the area of Bonn to 0.16 mm /yr in the Neuwied Basin.

Such a similarity indicates that there has been no significant relative tectonic movements during the past 400 ky, neither in the Western Rhenish Massif nor between the Rhenish Massif and the Paris Basin.

6.4 - THE MIDDLE PART OF THE MIDDLE PLEISTOCENE (MIS 12-14)

In contrast to more recent periods, the reconstruction of the evolution of both valleys shows major differences (fig. 4): despite the period between 600 and 400 ky being associated with the formation of two fluvial terraces (M6 and M7 along the Moselle valley, MMT1 and UMT along the Middle Rhine valley), their relative heights significantly differ from one valley to the other or, to be more precise, between the Moselle valley-Neuwied Basin block and the Middle Rhine valley upstream and downstream from the Neuwied Basin. The fluvial terraces M6 and M7 are located at similar relative heights to the contemporaneous fluvial terraces MMT1 and UMT in the Neuwied Basin (+60 and +70-80 m, respectively), while MMT1 and UMT are respectively preserved at ± 80 m and more than +110 m in the rest of the Middle Rhine valley (except at the border to the Lower Rhine where the relative height significantly decrease).

This contrast shows that the Rhenish Massif experienced greater uplift in the Middle Rhine valley area (except the Neuwied Basin) than that recognized along the Moselle valley in the Paris basin and the southern Eifel-Hunsrück (fig. 7). The acceleration of such uplift, related to the Eifel plume, is confirmed by the volcanic activity described between 600 and 400 ky in the Eifel (Schmincke *et al.*, 1983; Bogaard & Schmincke, 1990; Boenigk, 1995). However, it is important to underline that the main volcanic activity continued between 400 and 13 ky, while the Rhenish Massif experienced weak uplift.

These results confirm the morphological correlations proposed for the area between Piesport and Koblenz concerning the “Middle and Lower terrace systems”. Furthermore, it would seem that there was no updoming in the area of Cochem (the so-called “Cochemer Gewölbe”) at least during the last 600 ky. The previous results of Hoffmann (1996) and Meyer and Stets (1998), suggesting that the Moselle valley experienced greater uplift between Trier and Cochem than in the southern Neuwied Basin, are under question.

6.5 - EARLIER PARTS OF THE RECORD

The correlation between the Moselle and Rhine fluvial terraces remains uncertain for MIS 16 (and for earlier periods, fig.4): the contemporaneous deposits correspond with the oldest “middle terrace” of the Moselle (M8, +85 m relative height), but with the “youngest upper terrace” of the Rhine (UT4, +110-140 m relative height). However, taking into account the fact that the allocation of these two fluvial terraces to MIS 16 is based only on extrapolation, it would be premature to draw conclusions about these difference and problems.

6.6 - DISCUSSION

This study focusing on the Moselle and the Middle Rhine fluvial terraces demonstrates that these fluvial systems have experienced almost identical evolution during the Middle and Upper Pleistocene, and especially during the past 600 ky. Aggradation and erosion episodes seem to have been relatively synchronous, except for MIS 4 (formation of the fluvial terrace M2 in the Moselle valley, while no contemporaneous fluvial sediments have up to now been recognized along the Middle Rhine valley). The intensivity of erosion (incision values) is very similar for the past 400 ky. In contrast, a higher incision rate is evident for the first part of the Middle Pleistocene in most of the Middle Rhine valley, compared to that recorded in the Neuwied Basin and the Moselle valley. This differential uplift is probably related to the volcanic activity in the Eifel.

7 - IMPLICATIONS: RECONSTRUCTION OF THE PLEISTOCENE TECTONIC EVOLUTION OF THE RHENISH MASSIF

The above-mentioned results focused on the “middle and lower terrace” system. However, they make it possible to propose a reconstruction of the tectonic evolution of the western Rhenish Massif during the whole Pleistocene, including the periods of formation of the “upper terraces”. This reconstruction is illustrated in fig.7, which indicates the variation in time for:

– the relative height of the Moselle and Rhine at particular times (with distinction between erosion and aggradation periods) ;

– the rate of incision, which is only a minimum value (since a part of the incision can be linked to climatic or fluvial dynamics parameters) and an averaged value since it is defined excluding the aggradation periods (as presented in Van Balen *et al.*, 2000, or Westaway, 2001). Despite these simplifications, this parameter is useful to reveal the main periods of incision in relation to the uplift of the Rhenish Massif.

Four periods could be distinguished:

– the end of the Pliocene and the lower Pleistocene (until about 700 ky before present): this period is characterized by a slow uplift of the Rhenish Massif (fig. 7) and correlates with the formation of the plateau valley (“Plateautal”) and the “upper terraces” (as evidenced by their morphological location). This result may be confirmed by sedimentological studies, which clearly indicate the rarity of volcanic deposits in the fluvial terrace sediments, suggesting a period of low volcanic and tectonic activity for the Rhenish Massif ;

– between ca 700 and 600 ky: the “main upper terrace” (UT2/3) formed about 700 ky ago. The morphology of the valleys then shows evidence of a significantly increased uplift rate after the formation of UT2/3 (fig. 7): the younger fluvial terraces are located below the plateau valley (e.g. fluvial terrace UT4 of the Middle Rhine), and in the so-called entrenched valley ("Engtal"), like the oldest "middle terrace" of the Moselle;

– between 600 and 400 ky: the strong uplift continued after 600 ky along the Middle Rhine valley (fig. 7), where this period is associated with the formation of the two oldest "middle terraces" (UMT and MMT1). This uplift, already described in previous studies (Illies et al., 1979), could be linked with the period of high magmatic and volcanic activity that occured between 600 and 350 ky (Illies *et al*., 1979; Meyer, 1994). The incision rate of the Rhine can be estimated as about ca 0.25-0.40 mm/yr. In contrast, the Neuwied Basin and the Moselle valley (both in the Paris basin and in the Rhenish Massif) are characterized by a lower incision rate which can be estimated as about 0.1-0.2 mm/yr;

– since 400 ky: the whole area shows similar evolution, reflecting slow uplift (± 0.11 mm/yr, fig. 7) of the whole western Rhenish Massif and the eastern Paris basin.

– This evolution can be compared with that of the Meuse valley through the Rhenish Massif (Van Balen *et al*., 2000), which also shows a decrease in incision rate since 600 ka. Incision rates are, however, consistently lower in the Meuse valley (maximum values of 0.1 mm/yr between 600 and 450 ka, 0.06 mm/yr between 450 and 250 ka and 0.025 mm/yr since 250 ka). The comparison for the recent period (which is better documented in the Rhine and Moselle areas than the older times) is furthermore difficult, due to the capture by the Palaeo-Meurthe river of the Upper Moselle (previous Meuse headwaters), leading to a decrease in the discharge of the Meuse (Van Balen *et al*., 2000).

8 - CONCLUSIONS

This study provides a synthesis of river terrace correlation and Pleistocene evolution of the Middle Rhine and Moselle, based on a new chronological framework. This clearly shows the link between the two areas, since each fluvial terrace of the Moselle (except the lower fluvial terrace M2) corresponds with a Middle Rhine river terrace. The comparison of the relative height of the contemporaneous bedrocks furthermore demonstrates for the first time that the fluvial terrace system in the Moselle valley is more or less similar to that preserved in the subsiding Neuwied Basin. In contrast, the higher relative height of the Middle Rhine fluvial terraces (outside the Neuwied Basin) shows that this area experienced greater uplift between about 600 and 400 ky.

These results call into question the previous chronostratigraphy of the Moselle "upper terraces". More research (especially absolute dating) is required on the chronostratigraphic position of the Moselle fluvial terraces (especially between Piesport and Koblenz) and of those of the Moselle tributaries (Saar…), in order to show possible local differences in the uplift rates in the Moselle basin over the last 600 ka.

It is also important to improve the comparison and correlation between the Rhine and its main tributary, by studying the relationships between climate change and fluvial evolution. The main incision periods correspond with the warm-to-cold transitions in the Moselle valley, while their location in the climatic cycles remains more approximative in the Rhine valley (allocation to cold stages?).

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