New evidences on the Moselle stratigraphy between the Muerthe confluence (Paris Basin) and Koblenz (Rhenish...

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New evidences on the Moselle terrace stratigraphy between the Meurthe confluence (Paris Basin) and Koblenz (Rhenish Massif)

by

STÉPHANE CORDIER, DOMINIQUE HARMAND, MANFRED FRECHEN, and MONIQUE BEINER

with 7 figures and 2 tables

Summary. The Moselle valley runs through three countries (France, Germany and Luxembourg). While its Pleistocene history was a constant matter of interest since a hundred years, most of the research only took into consideration little parts of the valley, and shed light either on the climate control on the valley evolution in the Paris Basin, or on the tectonics control in the Rhenish Massif. No reliable correlation was possible so far. This paper aims to propose a first overview of the middle and lower Moselle valley (i. e. between the Meurthe confluence and the Rhine confluence). Ongoing research in this area has allowed the distinction of eight middle and lower terraces (located at less than 100 m above the present river bed), due to geomorphological studies and lithological analyses (e. g. identification of a mineralogical and petrographical break corresponding with the Upper Moselle capture). This resulted in the realization of a longitudinal profile. The chronostratigraphical frame recently provided by absolute datings (especially in the Meurthe valley) led to the following results:

- the middle and lower terrace system formed during the Middle and Lower Pleistocene;
- the Moselle valley evolution is climatically controlled, each terrace formation corresponding with a cold stage;
- this fluvial response to climate change coincides with a slow uplift (0,12 mm/yr) along the Moselle valley, both in the Paris Basin and the Rhenish Massif, without differential movement of one tectonic unit against the other. Therefore, the idea of a strong continuous uplift of the Rhenish Massif since 800 ky must be reconsidered.

No similar correlation could be evidenced for the high terraces, which are only well-preserved in the Rhenish Massif where they correspond with the so-called main terraces. Furthermore, the stratigraphy of these main terraces remains hypothetical, for both the number of alluvial units and their longitudinal profile between Trier and Koblenz. On the same way, the chronological frame of the middle and lower terraces calls into question the previously assumed age for the middle main terrace (ca 800 ky). The hypothesis for the valley evolution at the Lower Pleistocene/Middle Pleistocene transition is finally discussed.

Zusammenfassung. *Revision der Stratigraphie der Moselterrassen zwischen der Meurthemündung im Pariser Becken und Koblenz im Rheinischen Schiefergebirge.* – Das Moseltal verläuft geographisch durch die drei Länder Frankreich, Deutschland und Luxemburg. In zahlreichen Arbeiten wurde versucht, die Fluss- und Talgeschichte zu rekonstruieren. Diese Studien beschäftigten sich jedoch oft nur mit einem Teilbereich des Flusslaufes und konzen-

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trierten sich entweder auf den Einfluss der Klimawechsel (Arbeiten im Pariser Becken) oder der Tektonik (Arbeiten im Schiefergebirge). Eine länderübergreifende Korrelation unter Berücksichtigung eines multidisziplinären Ansatzes fehlt bisher. Das Ziel dieser Arbeit ist ein terrassenstratigraphischer Überblick über das „Mittel-" und „Niedermoseltal", d. h. zwischen der Meurthemündung und Koblenz. Morphologische und sedimentologische Untersuchungen ermöglichen es, acht Mittel- und Niederterrassen unterhalb von 100 m relativer Höhe über dem heutigen Flussbett zu unterscheiden und ein Terrassenlängsprofil zu rekonstruieren. Infolge des Vergleichs mit absoluten Datierungen der Meurthe-Terrassen ergibt sich Folgendes:

- Das Alter der Mittel- und Niederterrassen korreliert mit dem Mittel- und Jungpleistozän.
- Während dieser Zeit ist die Mosel-Terrassenentwicklung von kalt-warmzeitlichen Klimawechseln beeinflusst, d. h. jede Hauptakkumulationsphase korreliert mit einer Kaltzeit.
- Synchron erfolgt eine geringe Hebung von 0,12 mm/yr des Pariser Beckens und des Schiefergebirges, jedoch ohne nachweisbare relative Hebung einzelner Regionen. Eine starke regelmäßige Hebung des Schiefergebirges muß also bezweifelt werden.

Da die älteren Terrassen nur im Schiefergebirge gut erhalten sind („Hauptterrassen"), ist es schwierig, ein verlässliches Längsprofil zu erstellen. Problematisch sind ebenfalls Gliederung und Längsprofil der Hauptterrassen zwischen Trier und Koblenz. Die Mittel- und Niederterrassen-Stratigraphie steht außerdem im Widerspruch zu dem oft zitierten Alter der „mittleren Hauptterrasse" von ca. 0.8 Mio. a. Die Flussgeschichte der Mosel wird für die Grenze Unterpleistozän/Mittelpleistozän diskutiert.

Résumé. *Révision de la stratigraphie des terrasses alluviales de la Moselle entre la confluence de la Meurthe (Bassin parisien) et Coblence (Massif schisteux).* – La vallée de la Moselle s'inscrit à travers trois pays (la France, l'Allemagne et le Luxembourg). De nombreuses études ont été réalisées, concernant son évolution pléistocène. La plupart d'entre elles ne portaient cependant que sur des petites sections de vallées, en privilégiant tantôt l'origine climatique des terrasses (dans le Bassin parisien), tantôt l'influence de la tectonique (cas des recherches dans le Massif schisteux). La réalisation de corrélations d'ensemble s'avérait ainsi délicate. L'objectif du présent article est de proposer une première étude d'ensemble le long de la moyenne et de la basse vallée de la Moselle, entre la confluence de la Meurthe et la jonction avec le Rhin. Les recherches menées dans ce secteur ont de fait débouché sur la reconnaissance de huit moyennes et basses terrasses alluviales à moins de 100 m d'altitude relative. Cette reconnaissance, basée à la fois sur une approche morphologique, et sur des études minéralogiques et pétrographiques, aboutit à la réalisation d'un profil longitudinal d'ensemble. La prise en considération des repères chronologiques (relatifs et absolus) obtenus notamment dans la vallée de la Meurthe permet d'établir les résultats suivants:

- les moyennes et basses terrasses ont été mises en place au cours du Pléistocène moyen et supérieur;
- l'évolution de la Moselle durant cette période est déterminée par les fluctuations climatiques, chaque phase d'aggradation majeure étant corrélée à un stade isotopique froid;
- cette évolution s'inscrit dans le cadre d'un soulèvement général lent (0,12 mm/an) affectant à la fois le Bassin parisien et le Massif schisteux, sans mouvement différentiel entre ces deux blocs tectoniques. L'hypothèse d'un soulèvement rapide du Massif schisteux depuis 800 ka doit donc être reconsidérée.

Aucune corrélation similaire ne peut en revanche être établie pour les hautes terrasses, celles-ci n'étant bien conservées que dans le Massif schisteux où elles constituent les «terrasses principales». La stratigraphie de ces terrasses demeure en outre incertaine, aussi bien pour le nombre des terrasses principales que pour l'allure de leur profil longitudinal entre Trèves et Coblence. De même, la chronologie proposée pour les moyennes et basses terrasses incite à remettre en cause l'âge généralement avancé pour la terrasse principale moyenne (environ 800 ka). Plusieurs hypothèses peuvent ainsi être proposées pour l'évolution de la vallée de la Moselle à la transition Pléistocène moyen/Pléistocène supérieur.

1 *Introduction*

Research on the evolution of European fluvial systems and their response to climate and tectonic control has been carried out since more than a century. The terraces of the Meuse valley were recently correlated between France, Belgium and the Netherlands (PISSART et al. 1997, HARMAND et al. 1998). A similar project has never been carried out along the Moselle river. The Moselle valley has been intensively studied, especially downstream from the Meurthe confluence in France (THÉOBALD 1932, THÉOBALD & GARDET 1935, TRICART 1948, FISCHER 1965, CORBONNOIS 1981), along the German-Luxembourgian border (FERRANT 1933a, b, DE RIDDER 1957, FISCHER 1962, LIEDTKE 1963), and in Germany (BORGSTÄTTE 1910, DIETRICH 1910, WANDHOFF 1914, KREMER 1954, MÜLLER 1976, OSMANI 1976, 1989, LÖHNERTZ 1982, NEGENDANK 1983a, b, HOFFMANN 1996).

Morphological research, often combined with sedimentological analyses, allowed each author to define a local terrace system in the distinct parts of the valley. Despite these approaches, the Pleistocene history of the River Moselle has remained hypothetical, for several reasons:

- Most of the studies focused on a relatively short part of the valley, resulting in various local and regional interpretations of the terrace system. Furthermore, these attempts of correlation were not reliable, owing to major differences in the number and the altitudes of the assumed terraces. No consistent longitudinal profile crossing the national borders has ever been realized along the Moselle valley. The attempt of FISCHER (1962, 1965) only considered the most developed terraces between the Vosges Massif and the confluence with the River Saar, without sedimentological evidence, while the correlation of NEGENDANK (1978) consists of a juxtaposition of the results in each part of the valley.
- No real distinction was made in these parts of the Moselle valley between the terraces formed before the Upper Moselle capture (i. e. while the Upper Moselle joined the Meuse) and the post-capture terraces.
- The national borders are not only scientific, but also geological boundaries, since the valley crosses three tectonic units: the Vosges Massif in France, the eastern Paris Basin mainly developed in France and Luxembourg, and the Rhenish Massif in Germany. This morphostructural context and the presence of Pleistocene glacial deposits in the Vosges Massif led the French authors to focus on the relations between the climate change and the river style in the Paris Basin: THÉOBALD & GARDET (1935) tried to correlate terraces, both with the sea-level changes and with the Alpine glaciations of PENCK & BRÜCKNER (PENCK 1910). TRICART (1948) recognized four alluvial units, which he also correlated with the four alpine glaciations. A similar approach was developed by FERRANT (1933a, b) in the Luxembourgian Moselle valley. However, the subsequent research in the Luxembourgian part of the valley, as well as the research in Germany, considered climate change only as a chronostratigraphical evidence. German authors actually mainly focused on the tectonic control of the valley evolution in the Rhenish Massif; the studies of NEGENDANK (1978, 1983), LÖHNERTZ (1982), BIBUS (1983) or HOFFMANN (1996) shed light on the space- and timescales of tectonic deformations and uplift.

As a consequence, the datings of the terraces were only relative, based either on the Alpine or on the Nordic chronology; no independant age control was available

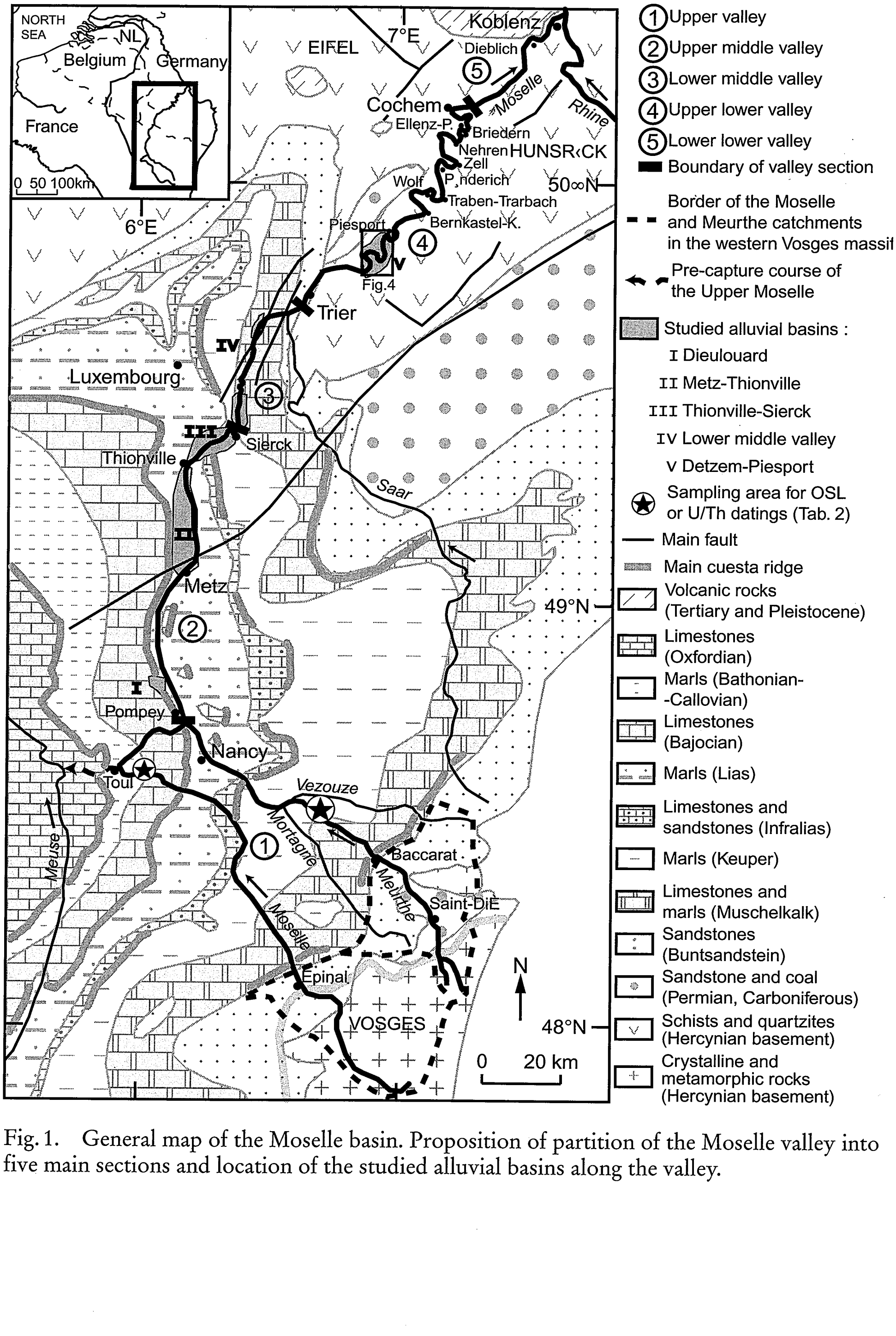


Fig. 1. General map of the Moselle basin. Proposition of partition of the Moselle valley into five main sections and location of the studied alluvial basins along the valley.

for the alluvial terraces, both in the Paris Basin and the Rhenish Massif, and the terraces' stratigraphies were often schematical.

The aim of this study is to define properly the Moselle terrace system including the stratigraphical location of the Upper Moselle capture, to revise its chronological frame, and to relate the Moselle terrace system with the palaeoclimate and tectonic activity.

2 *Study area and methods*

The studied part of the valley corresponds with the middle and lower Moselle valley, located between the Meurthe confluence and the Rhine confluence. The River Meurthe is actually a major tributary of the River Moselle because it corresponds with the pre-capture river, flowing through the Paris Basin and the Rhenish Massif while the Upper Moselle courses westwards. Both rivers rise within the Vosges Massif, where they successively drain the crystalline basement, (mainly developed in the Upper Moselle basin; fig. 1), and the Permo-Triassic sandstones and conglomerates (mainly developed in the Upper Meurthe basin).

Downstream from the Vosges mountains, both rivers flow through the Lorraine cuesta ridges until their confluence at Pompey. The river Moselle then crosses the German-Luxembourgian border in the Siercker threshold, which corresponds with small Devonian quartzite outcrops ("Taunus quartzite"). This threshold actually separates the "upper middle valley" (Pompey-Sierck) and the "lower middle valley" (so-called „Obermosel" of the German authors), located between Sierck and Trier. In this latter area, the river Moselle flows through the Luxembourgian Gulf, which develops in the same rocks as the northern Lorraine (essentially limestones and marls). However the regularity of the cuesta ridges is here transected by several major faults (fig. 1).

Downstream from Trier, the "lower Moselle valley" (middle and lower valley of the German authors) develops through the Devonian schists of the Rhenish Massif until the Rhine confluence at Koblenz. The Moselle course within this high plateau can be characterized by a succession of entrenched meanders, the most important ones being located in the surroundings of Bernkastel-Kues.

Alluvial basins with well-preserved terraces have been investigated both in the marly depressions of the eastern Paris Basin and in the Rhenish Massif (fig. 1). While most of the previous research in the area under study only considered the top surface of the terraces, in this paper the morphological study of the terrace system is based additionally on the relative height of the terrace basis above the present floodplain bedrock, which is estimated on the basis of several hundred boreholes (especially in the Thionville-Sierck basin), as demonstrated in numerous other European river valleys (Harmand 1989, Antoine 1989, 1993, Juvigné & Renard 1992, Chaussé 2003, Chaussé et al. 2004, Despriée et al. 2003, 2004). It is supplemented by sedimentological investigations including mineralogy, petrography and grain-size, and, for the youngest units, by OSL and radiocarbon dating.

As this research on the Moselle valley evidenced a prevailing dichotomy between the middle and lower terraces located at less than 100 m relative height, and the upper terraces, located at more than 100 m relative height, the paper will deal with these two systems separately, before proposing a general chronostratigraphical discussion.

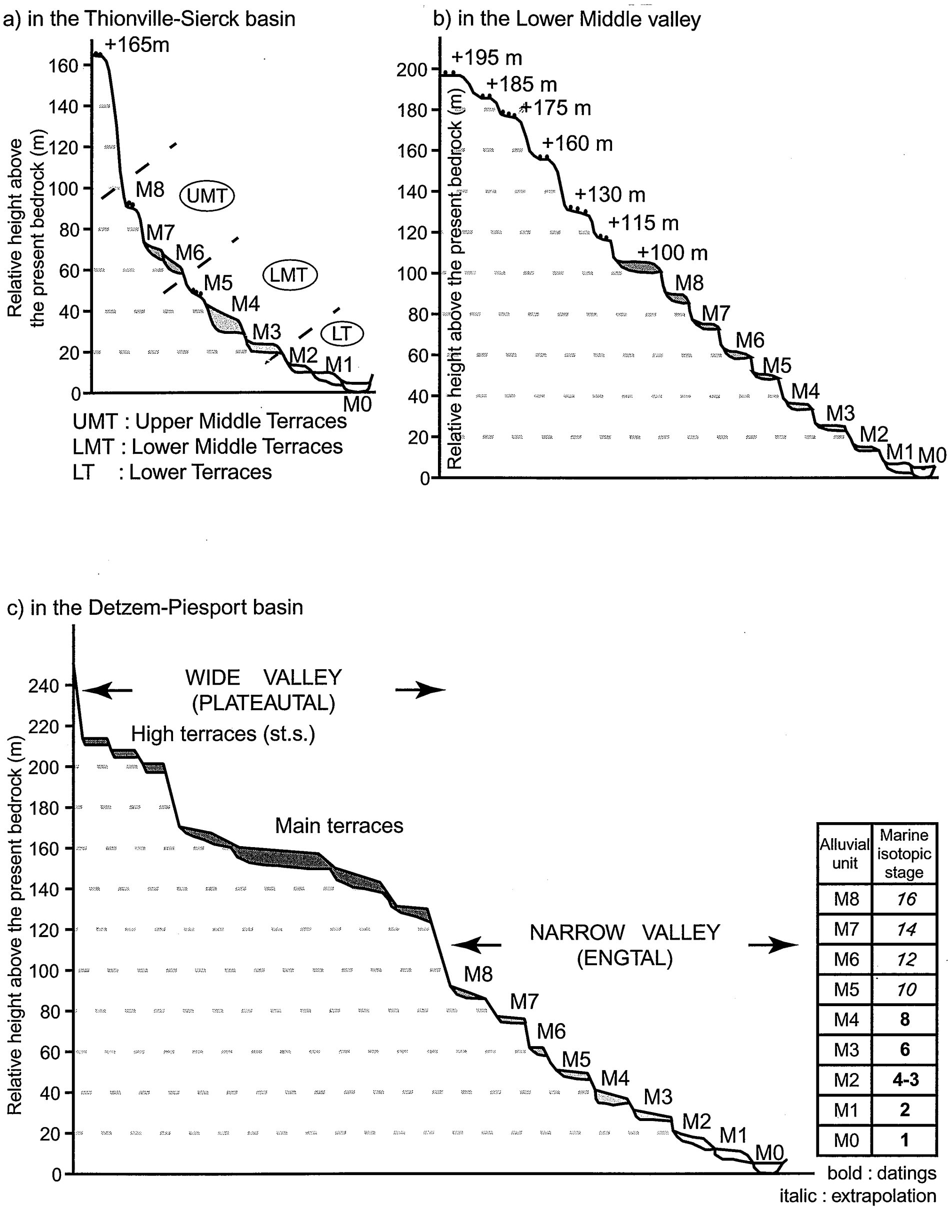


Fig. 2. Schematic cross-profiles of the Moselle valley a) in the Thionville-Sierck basin b) along the german-luxembourgian border c) in the Detzem-Piesport basin. Note the constancy of the relative height of the middle and lower terraces M8-M1 through the Paris basin (a and b) and the Rhenish Massif (c).

3 *The middle and lower terrace system*

3.1 *In France*

In France, the terraces of the upper middle valley (Pompey-Sierck) have been investigated in three alluvial basins, corresponding to depressions mostly developed in the Keuper and the Liassic marls (fig. 1): Dieulouard, Metz-Thionville and Thionville-Sierck. In the basin of Thionville-Sierck, a collaboration with the French Geological Survey (BRGM; MÜLLER et al., in prep.) made it possible to realize 120 boreholes into the alluvial units in order to define precisely the morphology of their bedrocks.

The middle and lower terrace system consists of eight stepped terraces (from M8 the oldest to M1 the youngest), whose basis is situated at a constant height above the bedrock of the present floodplain M0 (fig. 2a). The youngest units (from M4 to M1) and the floodplain are well preserved, and have broad flat surfaces with alluvial sediment sheets up to 8 m thick. Broad terraces can be associated with the units M7, M6 and M5, especially in the Thionville-Sierck basin; however, their alluvial formations are weathered and the thickness of the deposits is often less than 3–4 m. The upper middle terrace M8 is finally mainly evidenced by residual deposits in the Thionville-Sierck basin.

Despite of major differences in the mapping of the alluvial units, this result is in good agreement with the results proposed by THÉOBALD & GARDET (1935) suggesting a similar terrace system for the middle and upper terraces (fig. 3).

3.2 *Along the German-Luxembourgian border*

Owing to the absence of wide marly depressions in the lower middle valley between Sierck and Trier, the alluvial terraces are not well preserved. The terraces often show gentle slopes towards the River Moselle and the sediment remains are often only residual. The only major exception concerns the lower alluvial terrace (M1), which corresponds with "broad surfaces" in the Wintrange basin between Schengen and Remich, and in the Wasserbilliger basin between the Syr and Sauer confluences. In the latter area, boreholes provided evidence that the thickness of the alluvial formation can exceed 12 m.

Intensive field work and the realization of complementary boreholes in collaboration with the BRGM and the National Museum for History and Art of Luxembourg, made it possible to define eight middle and lower terraces separated by steep slopes.They are located at the same relative height as those of the upper middle valley (fig. 2b). This terrace system is relatively similar to that proposed by FERRANT (1933a, b) whereas it strongly differs from that of DE RIDDER (1957) and LIEDTKE (1963), which suggested two middle terraces and one lower terrace only (fig. 3).

3.3 *In the Rhenish Massif*

The terrace morphology changes downstream from Trier, in the lower valley. The distinction between the middle and lower terrace systems, as well as the high terrace system appears very clearly in the valley morphology.

The middle and lower terraces are indeed well preserved along the convex bank of the Moselle meanders, the so-called "entrenched valley" („Engtal", *sensu* HOFF-

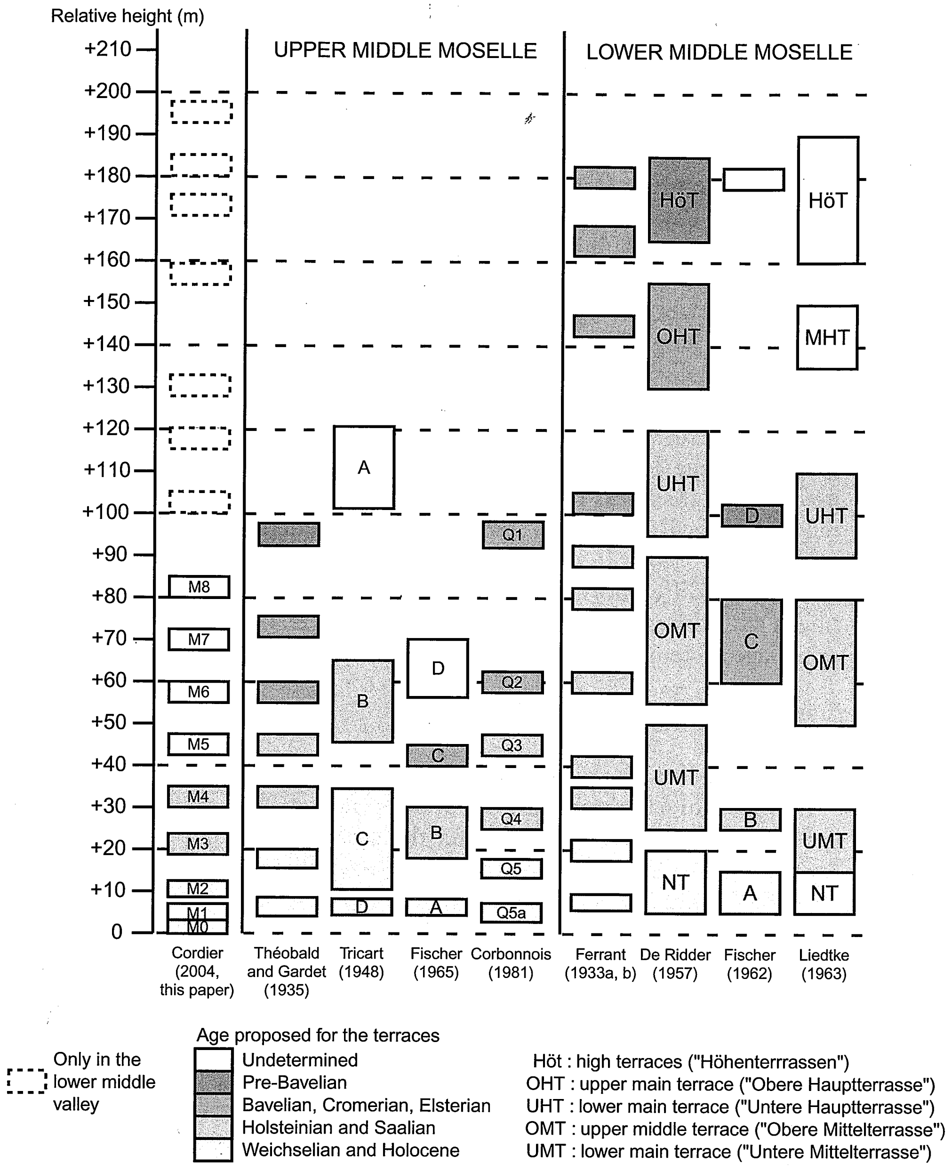
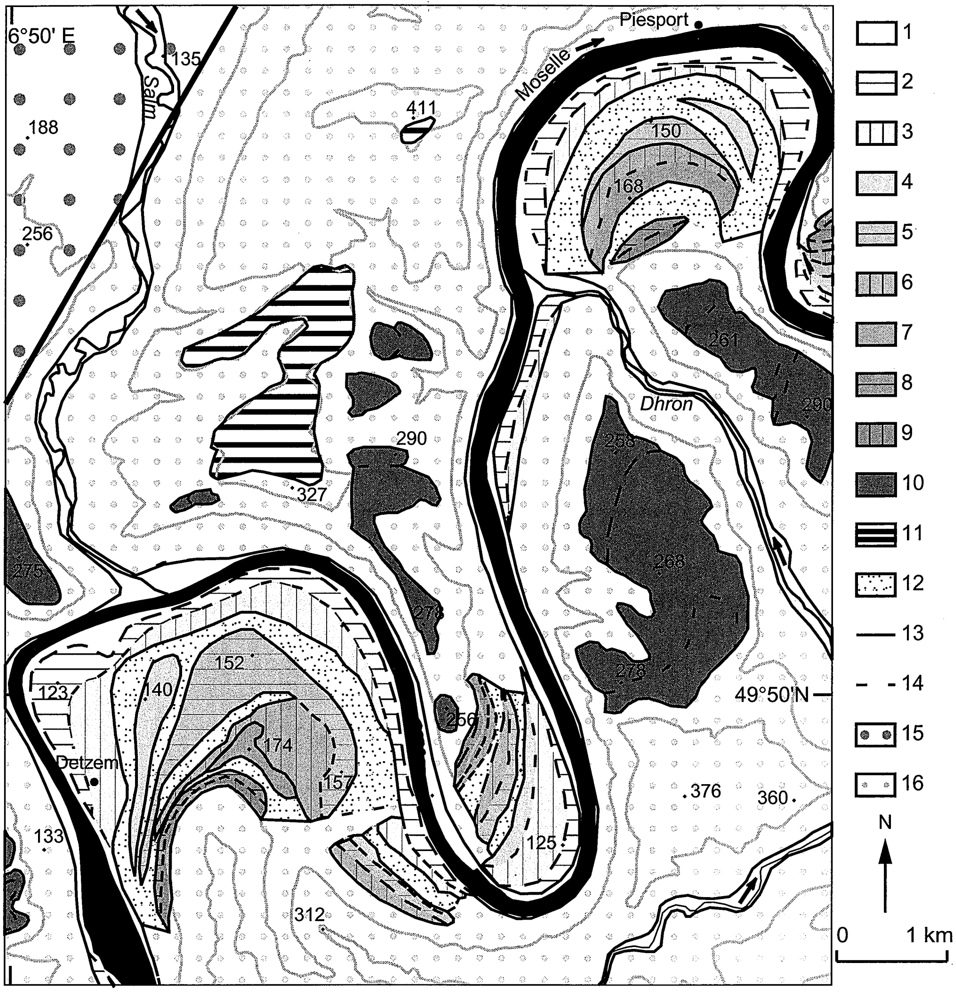


Fig. 3. Chronostratigraphy of the Moselle terraces in the middle valley, according to several authors. The thick alluvial terraces (e. g. UMT, OMT ...) recognized in some previous studies (e. g. DE RIDDER 1957, LIEDTKE 1963) actually corresponds with "terraces systems", each one including two or three terraces.

Table 1 Chronostratigraphy of the Moselle terraces in the lower valley, according to several authors. Despite a general agreement concerning the distinction between high, main, middle and lower terraces system, the number of terraces in the upper systems (high and main terraces system) is not unquestionable so far.

			UPPER LOWER VALLEY (Trier-Cochem)					LOWER LOWER VALLEY (Cochem-Koblenz)			WHOLE LOWER VALLEY			
TERRACE SYSTEMS			CORDIER (2004)	KREMER (1954)	MÜLLER (1976)	LÖHNERTZ (1982)	NEGENDANK (1983a,b)	OSMANI (1976)	BIBUS (1983)	NEGENDANK (1983a)	HOFFMANN (1996)	Relative height in Trier	Relative height in Cochem	Relative height in Koblenz
"PLATEAUTAL"	high terraces		Htes T	HöT	HöT	t1 - t2	^{t}MM1/2	ÄHT	^{t}M1		HöT	180-205m	220-250m	—
	upper	main terraces	TPS	OHT	HT	t3	^{t}MM3	OHT	^{t}M2	^{t}UM1	äHT	165-175m	200-215m	—
	middle		TPMs TPMi	MHT		t4	^{t}MM4	MHT	^{t}M3,4	^{t}UM2	jHT (several levels)	130-150m	180-200m	135-180m
	lower		TPI	UHT		t5 - t6	^{t}MM5	UHT	^{t}M5,6	^{t}UM3 ^{t}UM4.5?	UjHT (several levels)	110-125m	—	110-120m
"ENGTAL"	upper	middle terraces	M8 M7 M6 M5 M4 M3	OMT	OMT	t7	^{t}MM6	OMT	^{t}M7	^{t}UM6	OMT	70-90m	70-85m	80-90m
	lower			UMT	UMT	t8	^{t}MM7	UMT	^{t}M8	^{t}UM7	UMT	30-55m	35-65m	25-60m
	lower terraces		M2 M1	NT	NT		^{t}MM8 ^{t}MM9	NT		^{t}UM8 ^{t}UM9	NT	0-15m	0-10m	0-20m

Age proposed for the terraces
- Undetermined
- Pre-bavelian
- Bavelian, Cromerian and Elsterian
- Holsteinian and Saalian
- Weichselian and Holocene



1, present floodplain of the River Moselle (M0) and its main tributaries; 2, alluvial terrace M1; 3, alluvial terrace M2; 4, alluvial terrace M3; 5, alluvial terrace M4; 6, alluvial terrace M5; 7, alluvial terrace M6; 8, alluvial terrace M7; 9, alluvial terrace M8; 10, main terraces; 11, high terraces; 12, slope deposits; 13, steep slope between two terraces; 14, gentle slope between two terraces; 15, Permian sandstones; 16, Devonian schists and quartzites

Fig. 4. The alluvial terraces in the Detzem-Piesport basin. While the main and high terraces are located on both parts of the valley, evidencing a former valley course, the youngest terraces are only preserved in the convex banks of the present Moselle meanders.

MANN 1996). Previous investigations recognized three terrace levels only: the lower, lower middle and upper middle terraces, *sensu* KREMER (1954), MÜLLER (1976) and OSMANI (1976) (tab. 1). ZÖLLER (1985) however recognized two lower middle terraces in an old meander of the Moselle in the present lower Saar valley („Konzer Tälchen“). On the same way, NEGENDANK (1983a, b) locally suggested a subdivision between two lower terraces, especially downstream from Bernkastel-Kues. The subdivision was mainly based on the differences in elevation of the fluvial deposits. More recently, ZOLITSCHKA & LÖHR (1999) established a clear morphological subdivision between two lower terraces (NT1 and NT2) near Trier, whose basis are located at 7–8 m and 3 m above the present floodplain bedrock, respectively.

Our research in the lower Moselle valley mainly focused on the Detzem-Piesport basin. This basin is situated 30 km downstream from Trier, and includes the two well developed meanders of Detzem and Piesport, and the famous spur of Trittenheim („Trittenheimer Sporn“). The presence of numerous quarries in this small part of the valley allowed an excellent reconstruction of the morphology of the alluvial units. It first evidences the fact that the morphology of a terrace may vary from one meander to the other: terrace M3 thus clearly corresponds with a middle terrace in the Detzem-Leiwen and Piesport meander, where it dominates the youngest terraces by a steep slope (fig. 4). On the contrary it corresponds with the “upper lower terrace” in the spur of Trittenheim, as the steep slope is situated between M4 and M3. This observation should admonish to be cautious while using the classical terminology of “middle” and “lower” terraces.

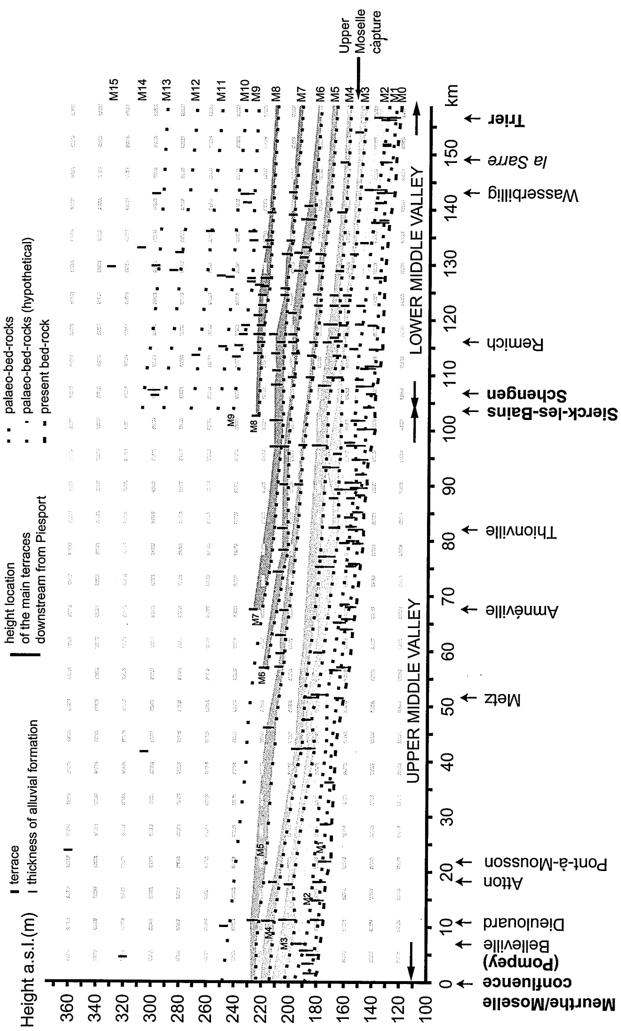
Most of all, six “middle” terraces (from M8 to M3) were distinguished in the Detzem-Piesport basin between 90 and 25 m relative height (fig. 2c and 4). While the upper units M8 and M7 are often weathered and eroded, the remaining units are well visible in the landscape, as evidenced by the presence of flat surfaces separated by steep slopes. The mean thickness of these alluvial deposits is often close to 4 m.

It is difficult to define the middle and lower terraces downstream from Piesport because of:

- the smaller size of the meanders, e. g. meanders of Wolf, Nehren, Briedern, Ellenz-Poltersdorf (for location, see map of fig. 1);
- the presence of upper terraces'sediments in their convex bank, e. g. meanders of Bernkastel-Kues, Traben-Trarbach, Pünderich, Zell, Cochem and Dieblich;
- the presence of thick slope deposits, e. g. in the meander of Pünderich (KREMER 1954);
- the lack of sections, preventing from a good recognition of the bedrock topography.

The geomorphology of the meanders, however, makes it possible to extrapolate the terrace system, as defined in the Detzem-Piesport basin. The bottom of the major slope, which clearly separates the middle terraces from the higher levels, is quite systematically situated at about 90 m relative height corresponding with the upper limit of M8 (fig. 5).

Taking into account the results already obtained in Trier, the whole middle and lower terrace system also consists of eight stepped alluvial units.The altitudes are comparable with those of the middle and lower terraces, as described upstream from Trier (CORDIER et al. 2005).



Height a.s.l.(m)
terrace
thickness of alluvial formation
height location of the main terraces downstream from Piesport
palaeo-bed-rocks
palaeo-bed-rocks (hypothetical)
present bed-rock
M15
M14
M13
M12
M11
M10
M9
M8
M7
M6
M5
M4
M3
M2
M1
M0
Upper Moselle capture
UPPER MIDDLE VALLEY
LOWER MIDDLE VALLEY
km
Meurthe/Moselle confluence (Pompey)
Belleville
Dieulouard
Atton
Pont-à-Mousson
Metz
Amnéville
Thionville
Sierck-les-Bains
Schengen
Remich
Wasserbillig
la Sarre
Trier

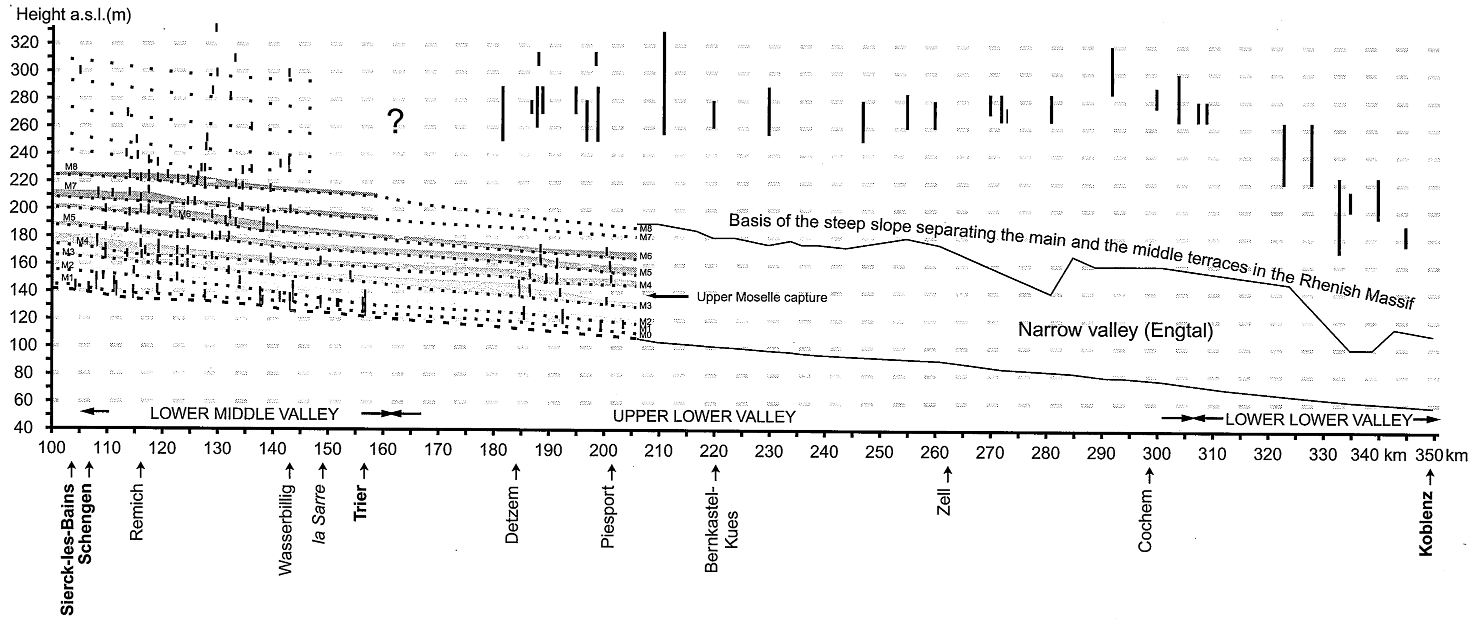


Fig. 5. Longitudinal profile of the Moselle terraces, evidencing the parallelism of the middle and lower terraces between the Meurthe confluence and Piesport. This parallelism can be extrapolated until Koblenz, as the basis of the steep slope delimiting the narrow valley is situated at a constant relative height (about 90 m).

4 *Longitudinal correlation and stratigraphy of the middle and lower terraces*

The constant relative height of the middle and lower terraces (from M8 to M1) between Pompey and Piesport makes it possible to realize a longitudinal profile (fig. 5), which can also be extrapolated until Koblenz, according to the constant elevation of the basis of the slope between the middle and the upper terraces.

4.1 *The location of the Upper Moselle capture in a terrace system: sedimentological evidence for the morphological correlation*

This morphological correlation is confirmed by sedimentological analysis: a major lithological contrast exists between the upper alluvial units (M8 to M4) and the younger ones (M3 to M0):
- the upper units are mainly composed of quartz and quartzite pebbles, sand-sized tourmaline and zircon heavy minerals, except downstream from Trier, where the sediments are combined with schists and quartzites from the Rhenish Massif (fig. 6). These sediments are typical Vosgian sandstones and conglomerates (Perriaux 1961), evidencing the influence of the Permo-Triassic stratas;
- a high percentage of granite pebbles and sand-sized hornblende and garnet, which correlate with the crystalline basement of the Vosges massif (Hameurt 1967) is typical for the younger terraces M3 to M1 and the present floodplain M0.

This contrast has been evidenced near the present Meurthe-Moselle confluence (upper middle valley) and in the Rhenish Massif, where a clear difference appears between the mineralogical composition of the alluvial units M6-M5-M4 and that of M3 in the Detzem-Piesport basin. The mineralogical composition of this latter formation is characterized by a high proportion of garnet (fig. 6), and secondarily of hornblende, which originated mostly in the Vosges Massif ("green" and "vosgian" hornblende), and secondarily in the Eifel volcanism (Meyer 1994, W. Boenigk, pers. comm.). An evidence for a petrographical "break" was more difficult to find in the Rhenish Massif, due to the weathering of the Vosgian granite pebbles during their transport. The pebble countings of Kremer (1954) and Löhnertz (1982) also revealed that the proportion of granite is always too weak to allow a clear distinction between the alluvial units, even in the younger alluvial formations of the lower Moselle. In this study petrographical analyses also focused on the gravels (between 315 and 20 mm in diameter). This approach yielded excellent results, indicating a significant contrast in the gravel composition between the units M4 and M3 (fig. 6).

This duality is similar to that recently recognized between the Meurthe and the Upper Moselle formations (Cordier et al. 2004):
- the Meurthe formations are actually characterized by the predominance of sediments originating in the sandstones and conglomerates. This composition mainly reflects the lithology of its upper basin, located up to 75 % in the Permo-Triassic strata (Cordier et al. 2002).
- the mineralogy and the petrography of the Upper Moselle sediments have been well studied (Taous 1994, Fischer 1965, Negendank 1978, Harmand et al. 1995, Losson 2003, 2004). These results evidence that most of the sediments derive from the crystalline basement of the Vosges Massif (granite, hornblende and garnet). Like in the Meurthe basin, this result has to be linked to the lithology of the Upper Moselle basin, where the crystalline outcrops represent about 75 % of the bedrock.

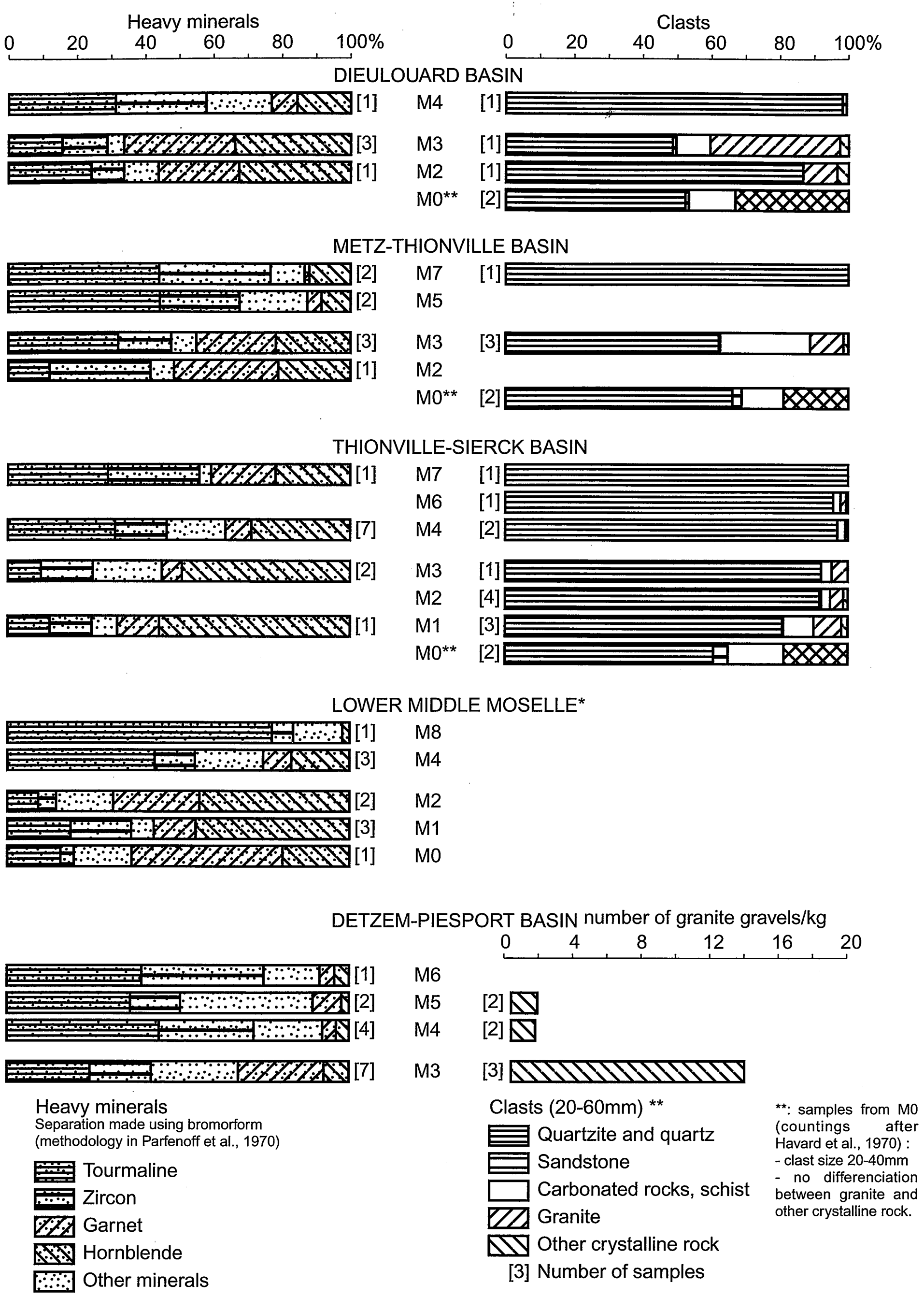


Fig. 6. Lithological composition of the Moselle alluvial terraces (after CORDIER 2004 and CORDIER et al. 2005a). The youngest alluvial formations (from M3 to M0) contain a significant proportion of crystalline sediments (granite, garnet and hornblende), evidencing they correspond with post-capture terraces, formed after the Upper Moselle valley joined the Meurthe.

Taking into consideration the recent evolution of the regional hydrographic network, the increase of crystalline sediments in the younger units must be allocated to the Upper Moselle capture: the upper middle terraces (and with greater reason the upper terraces) also formed while the Upper Moselle joined the Meuse, and only the lower units M3 to M0 formed since the capture (Cordier et al. 2005). This result is in excellent agreement with more recent research in the Upper Moselle valley, which allowed to recognize four post-capture alluvial units upstream from Pompey (Losson 2003).

The capture occurred betwen the formation of the units M4 and M3. The constant relative height of these two units between Pompey and Piesport provides complementary evidences for the geometrical correlations of the middle and lower terraces in this area.

4.2 *The chronostratigraphy of the middle and lower terraces*

The location of the Upper Moselle capture in the terrace system also yields a chronological interpretation of terrace M4: the capture has actually been dated, first in the lower Meuse valley by means of thermoluminescence of burnt flints (Huxtable & Aitken 1985), which provided an age of about 250 ky (tab. 2). This age was supported both by absolute datings (ESR on molluscs) and relative datings (pedostratigraphy, biostratigraphy, Meuse terraces stratigraphy; Van Kolfschoten et al. 1993). Furthermore, the uranium-series dating of speleothems, sampled in a gallery which contains siliceous pre-capture deposits allocated to M4, recently confirmed this result by providing an age of about 270 ky (Losson & Quinif 2001, Losson 2003, 2004). There is also a general agreement to date the capture to about 250–270 ka (Van Balen et al. 2000), and to correlate the pre-capture unit M4 with MIS 8.

The age estimates for the post-capture terraces M3 and M2 has been determined by OSL dating of fluvial sands from the Meurthe valley (tab. 2), which can be correlated with the terrace system of the Moselle (Cordier et al. 2004; 2005). The unit M3 correlate with MIS 6, as evidenced by the results for the samples 323 to 326 (Only the IRSL age of sample 323, using MAAD method, suggests that the sedimentation continues until MIS 5.1, but more analyses are needed to explain the important discrepancy between the MAAD and SAR ages for this sample). On the same way the unit M2 has to be linked to MIS 4 and 3 (even if the MAAD age obtained for sample 319 suggests a slightly older age for this sample, possibly reflecting an incomplete light exposure). The unit M1 is allocated to MIS 2, as evidenced by a radiocarbon dating on a juniperus charcoal sampled in the alluvial sands in the luxembourgian valley, which provided an age of 30,770 ± 300 years BP (Cordier et al. 2004). The present floodplain M0 finally has a Lateglacial to Holocene age (Carcaud 1992, Zolitschka & Löhr 1999).

This chronostratigraphical frame indicates that the terrace formation mainly occurs during Pleistocene cold stages (MIS 8, 6, 4 and 2 for units M4, M3, M2 and M1, respectively). If this hypothesis is applied for the older units, it is possible to correlate the upper middle terraces M5, M6, M7 and M8 with MIS 10, 12, 14 and 16, respectively. This correlation is in good agreement with the relative height of these terraces. It furthermore evidences that the middle and lower terrace system of the Moselle valley formed during the last 650 ky.

4.3 *The longitudinal profile and its tectonics incidences*

The longitudinal profile of the middle and lower terrace system along the Moselle valley (fig. 5) is characterized by the absence of significant deformation through the Paris Basin and the Rhenish Massif. This result is in agreement with THÉOBALD & GARDET (1935) and KREMER (1954), which evidence the parallelism of the terraces. On the contrary, it calls into question the previous research in the lower middle valley between Sierck and Trier indicating either a middle terrace deformation into a domal shape (DE RIDDER 1957) or a constant elevation (FISCHER 1962).

This result is of fundamental importance because it clearly demonstrates the lack of different uplift rates along the Moselle valley in the Rhenish Massif and the Paris

Table 2 Dating results obtained on samples carried out from the Meurthe and Moselle valleys (after several authors).

OSL DATINGS IN THE MEURTHE VALLEY (after Cordier, 2004)

Alluvial terrace	Lab-ID. LUM	Cosmic [μGy/a]	Water [%]	Dose rate [Gy/ka]	Palaeodose [Gy]-MAAD	Palaeodose [Gy]-SAR	IRSL age [ka]-MAAD	IRSL age [ka]-SAR
M2	317	140 ± 14	20 ± 5	3.58 ± 0.25	252.4 ± 4.8		70.5 ± 5.2	
	318	140 ± 14	20 ± 5	4.49 ± 0.33	313.2 ± 2.8	261.8 ± 5.7	69.8 ± 5.2	56.4 ± 4.5
	319	140 ± 14	20 ± 5	4.29 ± 0.30	369.0 ± 4.2	303.6 ± 8.0	86.1 ± 6.0	70.8 ± 5.2
	322	140 ± 14	20 ± 5	3.80 ± 0.26	187.7 ± 2.5	154.2 ± 14.9	49.5 ± 3.5	40.6 ± 4.8
M3	323	140 ± 14	20 ± 5	3.42 ± 0.25	305.6 ± 3.8	449.8 ± 35.3	89.4 ± 6.6	132 ± 14
	324	140 ± 14	20 ± 5	3.38 ± 0.27	520.6 ± 4.1	437.4 ± 29.4	154 ± 12	129 ± 13
	326	140 ± 14	20 ± 5	3.51 ± 0.29	526.3 ± 29.2		150 ± 15	
	320	140 ± 14	20 ± 5	2.43 ± 0.22	395.4 ± 3.1		163 ± 15	

U/Th DATING OF SPELEOTHEMS FROM THE UPPER-MOSELLE VALLEY NEAR TOUL (after Losson, 2003)

Alluvial terrace	Lab. sample	[U] ppm	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	$[^{234}U/^{238}U]$ t=0	Age [ka]
M4	Pui-GIO-2	0,253 ± 0,004	1,243 ± 0,020	0,969 ± 0,042	19 ± 3	1,518	269,8 +64/-41

RADIOCARBON DATING OF A JUNIPERUS CHARCOAL FROM THE LUXEMBOURGIAN MOSELLE VALLEY (source : National Museum for History and Art of Luxembourg)

Alluvial terrace	Lab. sample	Measured radiocarbon age	$^{13}C/^{12}C$ ratio	Conventional radiocarbon age
M1	beta-182248	30790 ± 300 BP	26.1‰	30770 ± 300 BP

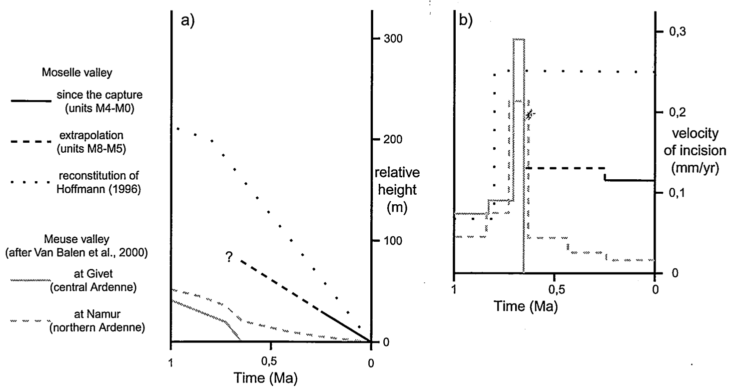


Fig. 7. Incision in the Moselle valley since 1 Ma and comparison with the Meuse valley. The assumed incision rhythm, estimated using the chronostratigraphical results, is significantly below than the one assumed by HOFFMANN (1996). On the contrary it confirms that the incision along the Moselle valley exceeds the one observed in the Meuse valley, not only since the Upper-Moselle capture but also since 700 ky.

Basin at least since the Upper Moselle capture (Middle Saalian), and even since the aggradation of M8, allocated to MIS 16. The Moselle valley evolution during the middle and upper Pleistocene gives evidence for a moderate uplift of these two tectonic units. The maximal uplift rate, deduced from the velocity of incision, is estimated to 0.115 mm/year since the upper Moselle capture, and to 0.125 mm/year since the formation of terrace M8, without significant acceleration during this period (fig. 7).

This result is comparable with the value proposed by WESTAWAY (2001) for the area of Koblenz, with an estimated uplift rate of 0.15 mm/year. The mechanism of uplift assumed by this author (inflow of lower crust under the Rhenish Massif, in response to a lateral pressure gradient) seems however inconsistent with the longitudinal profile of the middle and lower terraces, which evidences a similar evolution of the Rhenish Massif and the Paris Basin.

The uplift rate proposed here considerably differs from the one obtained by HOFFMANN (1996) for the Moselle valley, and extended by MEYER & STETS (1998) for the rivers of the Rhenish Massif. These authors assume a constant strong uplift of the massif, from 800 ky ago until today, and estimate the uplift rate during the Middle and Upper Pleistocene at ca 0.25 mm/yr. Our results also differ from the reconstructions of VAN BALEN et al. (2000) for the Meuse valley in the western Rhenish Massif (Ardenne hills) who assumed highly variable incision velocities (fig. 7). While the difference concerning the last 250 ky clearly results in the Upper Moselle capture, uncertainties remain for the pre-capture evolution.

This uplift is contemporaneous with Pleistocene climate change. The chronostratigraphical frame of the middle and lower terraces makes it possible to link the fluvial evolution with the major climate fluctuations, as in numerous other main European valleys (BRIDGLAND 2000, BOENIGK & FRECHEN, in press). The succession of glacial and interglacial stages generates modifications in the fluvial style of the Moselle, and mainly a succession of:

- aggradation phases correlated with cold periods (coarse sediments) as evidenced by cryoturbation features and cold faunal remains in the sediments (Coûteaux 1970, Cordier 2004, Cordier et al. 2005, 2006);
- erosion of these sediments at the cold-to-warm transitions, as observed in numerous exposures;
- silty sedimentation during warm periods;
- main incision phases at the warm-to-cold transitions, favoured by increasing precipitations under continental conditions (Antoine 1994).

5 *The upper terrace system*

While the middle and lower terrace are preserved in the whole study area, the occurence of the upper terraces (located at more than 100 m relative height) is extremely variable. These terraces are actually only evidenced in France by residual deposits preserved at the top of the Bajocian cuesta ridge and in the Siercker treshold (fig. 2a). The important weathering (disappearing of the stratifications, lack of sandy to silty sediments), and the absence of flat surfaces prevent from correlating these remains. In the lower middle valley between Sierck and Trier, the presence of Muschelkalk limestone outcrops favoured the morphological conservation of the upper units; six upper terraces were recognized, although they often correspond with residual deposits (fig. 2b).

However, the upper terrace system is well developed in the Rhenish Massif, where it corresponds to the "plateau valley" („Plateautal"), located at more than 130 m above the Moselle (fig. 2c); it is composed by the high and main terraces of the German authors („Höhenterrassen" and „Hauptterrassen"). While the high terraces mainly consist of residual deposits, the main terraces are the best preserved archives of the lower Moselle valley. They are associated with broad surfaces slightly tilting towards the river Moselle, and the thickness of sediments often exceeds 10 m. Despite these characteristics, the main terrace system remains hypothetical because of the lack of data concerning the morphology of their basal surface. The number of main terraces is also highly variable according to different authors, ranging from one (Müller 1976) to three (Kremer 1954, Osmani 1976, Negendank 1983) or more (Bibus 1983, Hoffmann 1996). Our research in the Detzem-Piesport basin allowed to recognize four terraces, but the stratigraphy remains hypothetical due to the lack of data concerning the altitude of the bedrocks.

6 *Discussion*

The main terraces of the Moselle valley correspond to important fluvial archives in the Rhenish Massif. Although they have been intensively studied, two major questions remain. The first concerns their longitudinal profile and its interpretation: previous publications suggested that the main terraces are located at a constant absolute elevation („Horizontalkonstanz", Löhnertz 1982, 2003) between Trier and the area of Cochem, then their relative altitude abruptly decreases until the Rhine confluence (fig. 5 and tab. 1). If the absence of fluvial archives between 230–240 m a. s. l. and the top of the M8 terrace in the upper lower valley support the idea of a present horizontality of the main terrace profiles, the interpretation of this profile remains unsure, as the authors develop either the theory of an updoming centred in the area of Cochem (Negendank 1978, 1983a, b) or that of a primary weak slope (Löhnertz 2003), or finally consider it as the result of the deformation of several blocks (Hoffmann 1996, Meyer & Stets 1998). It seems difficult to answer this question, because the main terrace system itself remains hypothetical.

No reliable correlation has ever been made between the upper lower valley (between Trier and Cochem) and the lower lower valley (between Cochem and Koblenz): sedimentological results only enable to distinguish between the main and the middle terrace systems, due to a higher proportion of quartz gravels in the main terraces (50 % versus 35 %; Osmani 1976, 1989).

The most important question concerns the age of the main terraces. Recent research in the Moselle valley (Hoffmann 1996, Meyer & Stets 1998, Löhnertz 2003) assumed that the "middle main terrace" formed during the early Middle Pleistocene (about 780 ky BP). This interpretation is based both on sedimentological studies and an absolute dating: mineralogical analyses first evidenced the presence of volcanic minerals (volcanic hornblende, pyroxen) in the main terraces sediments (Hoffmann 1996, Boenigk, pers. comm.), which are attributed to the early volcanism of the Eastern Eifel, allocated to around 750 ky ago (Westaway 2001). On the same way, palaeomagnetical determinations realized in the middle main terrace deposits of the lower Rhine valley near the Dutch border (Klostermann 1992) led to recognize the Matuyama-Brunhes boundary in these sediments. Despite the fact that these results are in good agreement, the ages may be underestimated: investigations in the Western Eifel actually demonstrated that volcanism started there in the latest Pliocene. On the same way, the palaomagnetical approach seems unreliable for the Moselle valley, since a reliable correlation between the Rhine valley and the Moselle valley in the Rhenish Massif is lacking.

Taking into consideration the morphology of the terrace system, the assumed age for the middle main terrace seems also inconsistent with the age allocated to the upper middle terrace M8, implying a very strong dome-shaped uplift ranging from 50 m in area of Trier to 110 m in the area of Cochem during a short period of time (about 150 ky, between 780–800 and 650 ky BP). The incision rate during this period is estimated to about 0.5 mm/yr; if such an acceleration of incision is conceivable (R. Van Balen, pers. comm), and not uncompatible with the recent research concerning the uplift of the Rhenish Massif (Garcia-Castellanos et al. 2000), this rate seems more typical of young uplifted mountains than of a part of a Variscan orogenic belt. Moreover, no tectonical deformations were described in the alluvial deposits of the main terraces along the Moselle valley. This observation also implies the main terrace stratigraphy and chronology to be reconsidered in order to obtain a consistent model with that of the middle and lower terraces.

7 *Conclusion*

The terrace system of the middle and lower Moselle valley, between the Meurthe confluence and the Rhine confluence, consists of high terraces and of eight stepped middle and lower terraces (from M8 to M1). While the high terraces are well preserved only in the Rhenish Massif (main terraces), the middle and lower units are preserved in the whole studied area. As their bases are located at constant relative heights, a longitudinal profile can be realized. It is confirmed by sedimentological analysis, which evidences a mineralogical and petrographical contrast between the formations of the older terraces (M8 to M4) deposited before the Upper Moselle capture, and the younger sediments (terraces M3 to M1) deposited since that capture. OSL and radiocarbon datings provided an independant age control for the lower terraces (M4 to M1). This chronostratigraphical frame led to correlate each terrace formation with a glacial-interglacial cycle, evidencing the climate control on the Moselle valley evolution. Extrapolating these results, an age estimate is proposed for the upper middle terraces (M8 to M5). Terrace M8 is also allocated to MIS 16, about 650 ky ago. The parallelism of the middle and lower terraces through the Paris Basin and the Rhenish Massif is interpretated as reflecting the absence of differential tectonic movements between these two units since the beginning of the Middle Pleistocene. As a consequence, this result calls the former stratigraphy of the main terraces (allocated to the Matuyama-Brunhes boundary) into question. Only the realization of new datings will make it possible to reconstruct the formation of the main and middle terraces of the Moselle valley, and to provide a consistent model of the valley evolution during the Pleistocene.

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