Alluviation in the Meurthe and Moselle valleys (Eastern Paris Basin, France): Lithological contribution to the study of the Moselle capture and Pleistocene climatic fluctuations

Stephane Cordier, Dominique Harmand, Benoît Losson, Monique Beiner

Abstract

Geomorphological and lithostratigraphic analysis allow the definition of a record of eleven alluvial stepped units in the Meurthe valley downstream from the Vosges Massif. The deposits are mainly composed of sands derived from Permo-Triassic strata. A similar system of stepped terraces is identified in the Moselle valley near Toul, where the deposits are coarser and contain more crystalline sediments than those of the Meurthe. A distinction is made in these units between the levels deposited before the capture of the Upper Moselle river by the Paleo-Meurthe, which follow the former course towards the Meuse valley, and the post-capture levels, which follow the modern valley Downstream from the present Moselle-Meurthe confluence, the higher deposits (above 25 m relative height) are similar to the Meurthe sediments (Permo-Tnassic origin), as opposed to the youngest deposits (0 to 25 m relative height) which contain crystalline sediments from the Upper Moselle basin. This contrast allows the Moselle capture to be positioned between formations F4 and F3 of the alluvial system downstream from the present confluence. The correlation between these sections of valley underlines the parallelism of the terraces and the weakness of the syn-capture altitudinal gradient between the Upper-Moselle and the Paleo-Meurthe rivers.

In certain parts of the valleys, a contrast is shown between sandy hthofacies from the Permo-Tnassic cover and coarse hthofacies with crystalline elements. The deposition of the sandy series is attributed to full-glacial episodes, while that of the coarse series is correlated with periods of retreat of the Vosgian glaciers, especially during lateglacial episodes.

The consensus of absolute dates of the capture (250-300 000 years B P) allows the incision rate for the Meurthe and the Moselle valleys to be estimated at 0 1 1 mm/y-1 since the capture. This rate is comparable with the rate already obtained for the Moselle valley in Germany.

Résumé

Des études géomorphologiques et lithostratigraphiques permettent d'établir l'existence de onze unités alluviales étagées dans la vallée de la Meurthe à l'aval du Massif vosgien. L'alluvionnement se caractérise par des séries essentiellement sableuses issues des grès et conglomérats du Permo-Trias. Un dispositif alluvial semblable de terrasses etagées est reconnu dans la vallée de la Moselle touloise ; les alluvions mosellanes sont plus grossières et plus riches en éléments cristallins que celles de la Meurthe. Une distinction est effectuée dans ces terrasses entre les niveaux antérieurs à la capture de la Haute Moselle (qui se poursuivent dans la vallée de la Meuse) et les niveaux postérieurs à la capture qui suivent la vallée actuelle.

A l'aval de l'actuelle confluence Moselle-Meurthe, les niveaux situés à plus de 25 m d'altitude relative présentent les caractères des alluvions de la Meurthe (sables siliceux issus du Permo-Tnas) contrairement aux niveaux plus récents (0-25 m d'altitude relative) où les alluvions sont nches en éléments du socle vosgien. Ce contraste permet de situer la capture, à l'aval de la confluence Moselle-Meurthe, entre la mise en place des formations F4 et F3 Des correlations entre les sections de vallées sont alors possibles, qui montrent le parallélisme des terrasses et la faiblesse du gradient hydraulique syn-capture entre la Haute Moselle et la Paléo-Meurthe.

Dans les sections de vallées étudiées, est mis en évidence à l'intérieur d'une même formation alluviale un contraste entre un faciès sableux à matériel surtout issu du Permo-Trias et un faciès plus grossier d'ongine cristalline. La mise en place des séquences sableuses est attribuée aux épisodes pléniglaciaires, celle des faciès grossiers étant relié aux tardiglaciaires.

Une confrontation des résultats obtenus avec les datations de la capture (250-300 ka BP) permet d'avancer un taux d'incision post-capture de 0,11 mm/an dans les vallées de la Meurthe et de la Moselle lorraines. Ce taux peut être comparé à celui enregistré dans la vallée de la Moselle allemande.

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ABSTRACT

Geomorphological and lithostratigraphic analysis allow the definition of a record of eleven alluvial stepped units in the Meurthe valley downstream from the Vosges Massif. The deposits are mainly composed of sands derived from Permo-Triassic strata. A similar system of stepped terraces is identified in the Moselle valley near Toul, where the deposits are coarser and contain more crystalline sediments than those of the Meurthe. A distinction is made in these units between the levels deposited before the capture of the Upper Moselle river by the Paleo-Meurthe, which follow the former course towards the Meuse valley, and the post-capture levels, which follow the modern valley. Downstream from the present Moselle-Meurthe confluence, the higher deposits (above 25 m relative height) are similar to the Meurthe sediments (Permo-Triassic origin), as opposed to the youngest deposits (0 to 25 m relative height) which contain crystalline sediments from the Upper Moselle basin. This contrast allows the Moselle capture to be positioned between formations F4 and F3 of the alluvial system downstream from the present confluence. The correlation between these sections of valley underlines the parallelism of the terraces and the weakness of the syn-capture altitudinal gradient between the Upper-Moselle and the Paleo-Meurthe rivers.

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The consensus of absolute dates of the capture (250-300 000 years B.P.) allows the incision rate for the Meurthe and the Moselle valleys to be estimated at 0.11 mm/y-1 since the capture. This rate is comparable with the rate already obtained for the Moselle valley in Germany.

Key-words: Fluvial terraces, heavy minerals, Meurthe, Upper Moselle capture, glacial cycle.

RÉSUMÉ

L'ALLUVIONNEMENT DANS LES VALLÉES DE LA MEURTHE ET DE LA MOSELLE (est du Bassin parisien, France) : APPORTS DE LA LITHOLOGIE À LA CONNAISSANCE DE LA CAPTURE DE LA MOSELLE ET DES VARIATIONS CLIMATIQUES PLÉISTOCÈNES

Des études géomorphologiques et lithostratigraphiques permettent d'établir l'existence de onze unités alluviales étagées dans la vallée de la Meurthe à l'aval du Massif vosgien. L'alluvionnement se caractérise par des séries essentiellement sableuses issues des grès et conglomérats du Permo-Trias. Un dispositif alluvial semblable de terrasses étagées est reconnu dans la vallée de la Moselle touloise ; les alluvions mosellanes sont plus grossières et plus riches en éléments cristallins que celles de la Meurthe. Une distinction est effectuée dans ces terrasses entre les niveaux antécurs à la capture de la Haute Moselle (qui se poursuivent dans la vallée de la Meuse) et les niveaux postérieurs à la capture qui suivent la vallée actuelle.

A l'aval de l'actuelle confluence Moselle-Meurthe, les niveaux situés à plus de 25 m d'altitude relative présentent les caractères des alluvions de la Meurthe (sables siliceux issus du Permo-Trias) contrairement aux niveaux plus récents (0-25 m d'altitude relative) où les alluvions sont riches en éléments du socle vosgien. Ce contraste permet de situer la capture, à l'aval de la confluence Moselle-Meurthe, entre la mise en place des formations F4 et F3. Des corrélations entre les sections de vallées sont alors possibles, qui montrent le parallélisme des terrasses et la faiblesse du gradient hydraulique syn-capture entre la Haute Moselle et la Paléo-Meurthe.

Dans les sections de vallées étudiées, est mis en évidence à l'intérieur d'une même formation alluviale un contraste entre un faciès sableux à matériel surtout issu du Permo-Trias et un faciès plus grossier d'origine cristalline. La mise en place des séquences sableuses est attribuée aux épisodes pléniglaciaires, celle des faciès grossiers étant relié aux tardiglaciaires.

Une confrontation des résultats obtenus avec les datations de la capture (250-300 ka BP) permet d'avancer un taux d'incision post-capture de 0,11 mm/an dans les vallées de la Meurthe et de la Moselle lorraines. Ce taux peut être comparé à celui enregistré dans la vallée de la Moselle allemande.

Mots-clés : Terrasses fluviatiles, minéraux lourds, Meurthe, capture de la Haute Moselle, cycle glaciaire.

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INTRODUCTION

Situated in the North-East of France, the River Moselle and its major tributary, the River Meurthe, drain the western slope of the Vosges mountains and the eastern Paris basin. Before its capture by the Meurthe during the Middle Pleistocene, the Upper Moselle flowed westward of Toul towards the River Meuse (fig. 1); the drainage network was dominated by two rivers, the Upper Moselle-Meuse and the Paleo-Meurthe (Harmand *et al.*, 1995).

Copious research in the Upper-Moselle-Meuse valley has provided evidence for the capture (Buvignier, 1840; Davis, 1895) and has made it clear that it resulted from complex mechanisms (Harmand *et al.*, 1995; Harmand et Le Roux, 2000): headward erosion in the Paleo-Meurthe basin, bringing about the diversion of a tributary of the Upper-Moselle-Meuse into the Paleo-Meurthe river (Blache, 1943); deposition of an important alluvial accumulation in the vicinity of Toul, favouring the diversion of the Upper Moselle towards the Paleo-Meurthe which was situated at a lower height (Tricart, 1948); possible underground seepage due to the presence of a developed karst (Joly, 1911; Capot-Rey, 1936; Losson, 2000).

Detailed studies in the Upper Moselle (Taous, 1994) and Meuse valleys (Harmand, 1989; Pissart *et al.*, 1997; Harmand *et al.*, 1998) finally allowed terrace correlation between the Vosges massif and Maastricht.

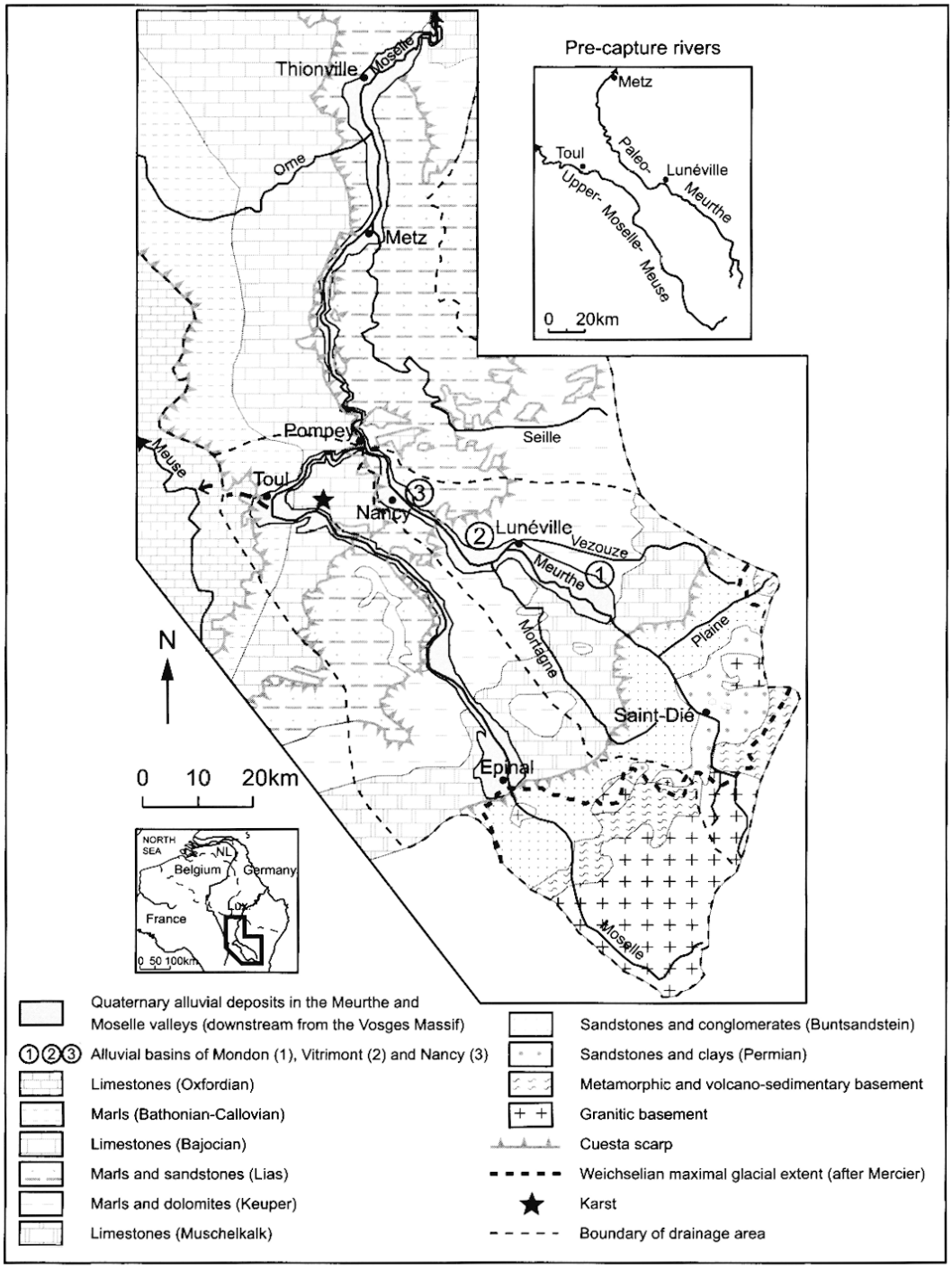

Fig. 1: Morphostructural presentation of the Moselle basin in Lorraine.
Fig. 1 : Présentation morphostructurale du bassin lorrain de la Moselle.

Despite its importance, the Paleo-Meurthe valley has been little researched, either in its upper valley -the Meurthe valley- (Théobald et Gardet, 1935), or downstream from the present confluence between the Moselle and the Meurthe near Pompey (Tricart, 1948). Correlation with the Upper Moselle valley has been difficult, and estimates of the syn-capture altitudinal gradient have remained hypothetical (Harmand *et al.*, 1995; Losson, 2000).

Recent research has thus taken place to define properly the terrace system in the Meurthe and Moselle valleys near Toul, and to characterize the deposits in each section of valley. Comparison of these data then allows evidence of the capture to be observed downstream from Pompey, and thus a paleoclimatic and chronogical reconstruction can be proposed for the first time.

Reconstruction of the terrace system is based on topographical identification of terrace surfaces; however, the topography often obscures the reality of the disposition of terraces : field survey must also be completed by the identification of bedrock surfaces (taking into account several hundred boreholes; Bureau des Recherches Géologiques et Minières and other references), as used in recent research in other valleys (e.g. Antoine, 1994; Hoffmann, 1996).

Characterization of the fluvial deposits is essentially based on lithological analysis (mineralogy of sands, petrography of clasts). These methods are often used in the reconstitution of paleoflows (e.g. Bustamente Santa Cruz, 1973; Larue et Etienne, 2001). These data are complemented in the main sections by a sedimentological approach (sedimentary structures, grain size).

I - THE STEPPED TERRACES OF THE MEURTHE AND THE MOSELLE VALLEY NEAR TOUL

A - THE ALLUVIATION OF THE MEURTHE RIVER IN THE LORRAINE SEDIMENTARY BASIN

1 - The morphostructural context and the alluvial system

Rising in the Vosges Massif, the river Meurthe successively drains the crystalline basement and its Permo-Triassic sandstone and conglomeratic cover (fig. 1). Downstream from the mountains, in the part of the valley studied, the river flows through the Triassic and Jurassic strata (essentially Keuper and Liassic marls) as far as its confluence with the Moselle. Hard rock thresholds (in the Muschelkalk, the Infra-Lias and the Bajocian limestones) delimit three alluvial basins (Mondon, Vitrimont and Nancy) where significant amounts of sediments have been deposited.

Above the alluvial floodplain Me0, ten stepped terrace levels are distinguished, from Me1 the youngest to Me10 the oldest (fig. 2a and b). The lower units (Me0 to Me5) correspond to six alluvial formations (F-Me0 to F-Me5) which are several meters thick (often more than 5 m, except for F-Me1 which is not well developed). These formations are dominated by residual deposits, which overlie the levels Me6 to Me10 (Cordier *et al.*, 2002).

2 - The lithology of fluvial deposits in the Meurthe valley

The study of fluvial deposits is based on the analysis of important sections especially in the Mondon basin. These outcrops are several meters thick and present various facies, justifying multiple samplings. The data are completed by the study of minor sections (one or two samples).

The sections show lithofacies that are essentially sandy or sandy-gravelly. Gravel clasts are present as a minor component. Lithological determinations are thus based both on sands (mineralogy) and clasts (petrography).

-Heavy minerals determinations have been made by Monique Beiner on sandy samples of the floodplain alluvium and from the terrace levels (fig. 3). Heavy minerals in the fraction 40-315 µm were isolated using bromoform (methodology of Parfenoff *et al.*, 1970). Counts, made with a light microscope concern at least 200 grains for each sample.

The determinations show the importance of the Vosges mountains as a sediment source; indeed, the main minerals are tourmaline (mean content 31 %), zircon (24 %) and hornblende (29 %), all originating in the massif. Hornblende (green, green-brown and brown) comes in particular from the basement (Hameurt, 1967). In contrast, tourmaline and zircon (often zoned) are very abundant in the later sandstones and conglomerates (Perriaux, 1961). The predominance of these two minerals (especially downstream from Lunéville, where their global proportion exceeds 60 %), and the lack of garnet (abundant in the crystalline rocks), prove that the sandy deposits of the Meurthe river mainly come from the Permo-Triassic cover.

The mineral composition of the fluvial formations is relatively constant (fig. 3c), although minerals are more diversified in the floodplain alluvium (presence of garnet, titanium oxides and pyroxene). In contrast, the formation F-Me5 is characterized by the absence of hornblende, as a result of weathering (there is only one determination for this formation, however). Finally, the tourmaline-zircon ratio allows the formations F-Me2 to F-Me4 to be distinguished in the Mondon basin: this ratio is in general less than 1.2 for F-Me2, while its mean value is higher: 1.5 for F-Me3 and F-Me4 (greater domination of tourmaline). This variation might be explained by the fact that the deposits originated in the middle Buntsandstein (where tourmaline is abundant), or in other parts of the Buntsandstein (in which zircon is more prevalent; Perriaux, 1961).

-Petrographical analysis of clasts (20-40 mm diameter; with a few exceptions, noted * on fig. 4, counts exceeded a hundred clasts) confirms the mineralogical results: the clasts come mainly from the Permo-Triassic sandstone and conglomeratic cover (quartz, quartzites), and secondarily from the crystalline basement of the Vosges mountains (granites). In the Mondon basin, crystalline clasts are still abundant (sometimes more than 50 %). However, downstream from Lunéville, the ratio suddenly decreases (e.g. compare samples J and Q, fig. 4) and does not exceed 25 % (except for the floodplain alluvium; Havard *et al.*, 1970; Carcaud, 1992).

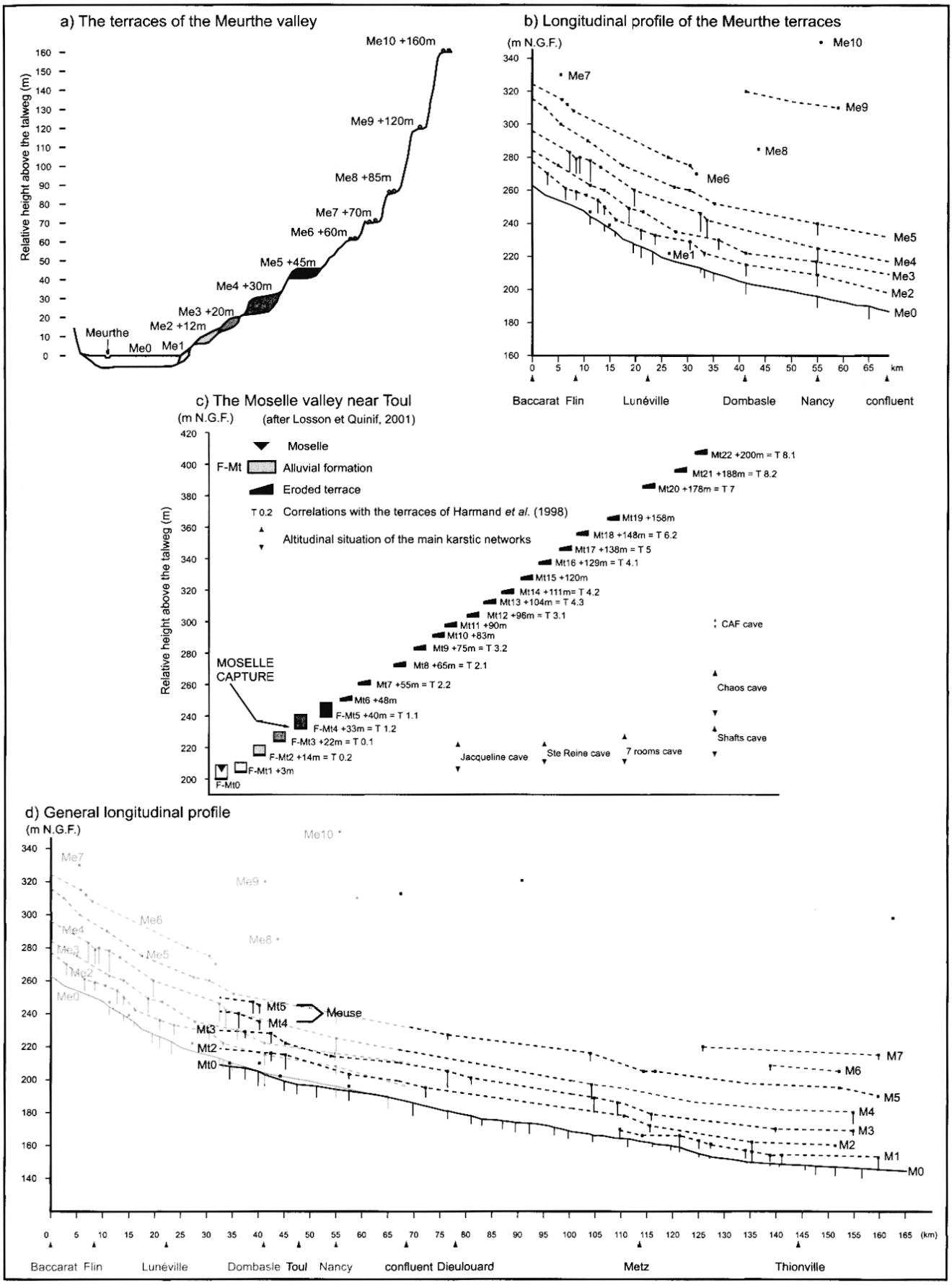

Fig. 2: The terrace system in the Meurthe valley (a) and the Moselle valley near Toul (c) and the longitudinal profiles of the terraces (b and d).
Fig. 2 : Le système de terrasses de la Meurthe (a) et de la Moselle touloise (c). Profils longitudinaux des trois sections de vallée étudiées (b et d).

If we consider the relative age of the fluvial formations, we can see that in general crystalline clasts are more prevalent in the youngest levels (except for the F-Me4 formation in the Mondon basin); this enrichment is due to the weathering of the clasts in the older deposits –field survey thus reveals that the crystalline elements are more weathered in the F-Me4 formation than in the younger ones.

-Lithological analysis in the Meurthe terraces thus proves the importance of the Permo-Triassic strata as a sediment source. This trend, already clear in Mondon basin, becomes more pronounced downstream from Lunéville, where the crystalline deposits are rare. Several explanations can be given for this predominance :

-The main fact is the lithology of the Meurthe catchment : upstream from Lunéville (Mondon basin), 63.9 % of the Vosgian catchment is developed in Permo-Triassic sandstone cover, but only 36.1 % in the crystalline basement (surfaces estimated after Frécaut, 1971). The differential increases downstream from Lunéville, where the Meurthe is joined two main tributaries, the Vezouze and the Mortagne, which drain the sandstone cover (fig. 1); their influence explains the lower percentage of crystalline elements in the Vitrimont and Nancy basins: taking into account the whole catchment (including Vezouze and Mortagne), 75.9 % of the Vosgian basin of the Meurthe is developed in sandstones and conglomerates (24.1 % for the basement).

-Glaciation in the upper catchment (Darmois-Théobald et Menillet, 1973) essentially concealed the basement, limiting the availability of crystalline rocks as fluvial sediment during glacials.

-Finally, the Permian basin of Saint-Dié was during the Pleistocene a "sediment trap" for crystalline material coming from the upper valley (Carcaud, 1992).

Research in the Meurthe catchment has thus allowed (1) the definition of the terrace system, complementing and correcting previous studies (Théobald et Gardet, 1935), and (2) the demonstration of the predominance of Permo-Triassic sediments in the Meurthe deposits.

B - THE ALLUVIAL DEPOSITS OF THE RIVER MOSELLE NEAR TOUL

1 - An important alluvial basin in the Moselle valley (fig. 1)

Like the Meurthe, the Moselle flows downstream from the Triassic and Jurassic outcrops of the Vosges. Near Toul, the valley shows an elbow resulting from the capture of the Upper Moselle by the Paleo-Meurthe. Except where it drains the Bathonian and Callovo-Oxfordian marls, the river is constrained within a narrow valley, developed in Bajocian limestones. In these formations an important karst system developed (fig. 2c), correlated with the paleoflow of the Moselle (infill of galleries by siliceous deposits, Gamez *et al.*, 1995; Gamez et Losson, 1998; Losson, 2000).

In this section (fig. 2c), six alluvial formations (F-Mt0 to F-Mt5) are stepped between 0 and 40 m relative height (Harmand *et al.*, 1995; Pissart *et al.*, 1997; Harmand *et al.*, 1998; Losson et Quinif, 2001). They correspond with the alluvial floodplain Mt0 and the younger terraces (Mt1 to Mt5). Above them, numerous eroded terraces, developed from 40 to more than 200 m relative height, are overlain by residual fluvial deposits (gravels, and more rarely sands).

Recent research in the vicinity of Toul has allowed pre-capture levels (following the former "Val de l'Asne" valley towards the Meuse valley) and post-capture levels (Mt3 to Mt0), which follow the present valley, to be distinguished: taking account of relative heights, these recent units Mt3 to Mt0 may be connected with the corresponding units of the Meurthe valley (Me3 to Me0, fig. 2d).

2 - Lithological results

The fluvial deposits of the Moselle are very different to those of the Meurthe; the sediments in the Moselle valley are coarser, with a larger crystalline component (Dorniol, 1997): mineral determinations made by M. Beiner show the predominance of hornblende (more than 50 %) and garnet from the basement (fig. 3). In contrast, zircon and tourmaline are rare (often less than 20 % except in the oldest levels, where they are relatively abundant because of their resistance to weathering). Lithological numbering also shows important percentages of crystalline clasts (between 30 and 60 %), despite Toul being more than 100 km from the outcrops of basement in the Vosges.

Three important facts can explain this characteristics:

-first, the lithology of the Vosgian basin of the Moselle river, in which granitic outcrops are well developed; estimates suggest that 76.4 % of this basin is developed in basement, but only 23.6 % in the sandstone formations (after Frecaut, 1971).

-Furthermore, there was more extensive glaciations in the Moselle basin (fig. 1): the Weichselian end moraine is thus situated in the Moselle valley 45 km from the present source of the Moselle, in comparison with only 12 km for the Meurthe valley (Seret, 1966; Darmois-Théobald et Menillet, 1973; Seret *et al.*, 1990; J.L.Mercier, personal communication).

-Finally, the mean altitude of the Moselle basin is higher than that of the Meurthe: consequently, the erosive potential and the capacity of the river are more important; the Moselle is also able to carry numerous crystalline elements out of the massif.

Comparison between the Meurthe valley and the Moselle valley near Toul reveals important differences in the composition of their sediments. These differences make it possible to distinguish the pre- and post-capture deposits downstream from the present Moselle-Meurthe confluence.

II - THE PALEO-MEURTHE MOSELLE VALLEY DOWNSTREAM FROM THE CONFLUENCE

Between the Moselle-Meurthe confluence and Metz, the Paleo-Meurthe-Moselle valley is developed in Liassic marls, between the Bajocian cuesta and its outliers (fig. 1). The valley is narrow and contains little in the way of preserved fluvial sediments: alluvial deposits are only observable in a few basins. Downstream from Metz, where the valley moves beyond the cuesta scarp, alluvial formations are thicker and more widely preserved.

a-heavy mineral content of each section (%)

Site	Formation	Number of samples	Tourmaline	Zircon	Garnet	Titanium oxides	Sphene	Metamorphic minerals	Epidote	Hornblende	Pyroxene	Tourmaline/ Zircon
Alluvial formations of the Meurthe												
Basin of Mondon												
A	F-Me4	4	37,54	23,88	1,06	6,56	1,71	3,43	1,71	24,22	0	1,57
B	F-Me4	1	35	17,00	6,00	4,00	2,00	4,00	2,00	32,00	0	2,06
C	F-Me4	2	25,29	15,46	0,77	2,76	1,87	30,81	1,87	23,06	0	1,64
D	F-Me4	6	37,57	21,82	2,95	3,48	3,25	2,14	3,25	28,79	0	1,72
E	F-Me3	5	31,36	17,27	2,22	5,12	0,64	2,23	1,41	39,75	0	1,82
F	F-Me3	1	17,22	36,84	6,22	5,74	0,48	4,76	0,48	28,23	0	0,47
G	F-Me2	1	35,43	29,92	3,15	5,51	3,15	5,51	0	17,32	0	1,18
H	F-Me2	2	28,41	25,67	1,95	8,89	0	1,96	3,03	30,11	0	1,11
I	F-Me2	4	22,02	31,48	4,29	5,91	0	4,62	1,01	30,69	0	0,70
J	F-Me0	3	18,08	22,86	14,03	4,88	3,27	0,86	2,96	31,65	1,41	0,79
Basins of Vitrimont and Nancy												
K	F-Me5	1	26,04	48,44	4,17	15,10	2,60	0	2,60	3,65	0	0,54
L	F-Me3	1	44,79	19,02	3,07	4,29	0	1,84	0	26,99	0	2,35
Alluvial formations of the Moselle near Toul												
M	CF-Mt6	1	71,75	19,05	0,50	4,90	0	3,80	0	0,00	0	-
N	CF-Mt4	1	28,50	26,00	6,50	8,90	0	5,70	4,10	20,30	0	-
O	CF-Mt2	1	20,15	20,15	12,35	4,70	0	3,90	0,80	37,95	0	-
P	F-Mt5	1	16,13	8,39	0	4,52	0	3,23	1,94	65,81	0	-
Q	F-Mt5	1	5,59	22,70	25,00	6,25	0	0,33	2,30	37,83	0	-
R	F-Mt4	1	2,75	10,44	4,40	3,85	0	1,10	0,55	76,92	0	-
S	F-Mt4	1	3,37	30,71	7,87	3,37	0	0,75	3,00	50,94	0	-
T	F-Mt4	1	5,14	14,95	5,14	5,14	0	0	5,61	64,02	0	-
U	F-Mt3	1	4,74	7,11	59,29	2,37	0	0	0,40	26,09	0	-
V	F-Mt3	1	4,62	27,75	4,62	4,62	0	0	4,62	53,76	0	-
W	F-Mt3	1	3,02	5,60	37,50	3,02	1,29	0,86	9,05	39,66	0	-
X	F-Mt2	1	6,64	7,96	15,49	3,54	0,44	1,33	3,98	60,62	0	-
Y	F-Mt2	1	9,06	7,97	10,51	2,54	0	2,90	6,88	60,14	0	-
Z	F-Mt0	1	5,24	0,44	35,81	0,00	0,44	1,31	5,68	51,09	0	-

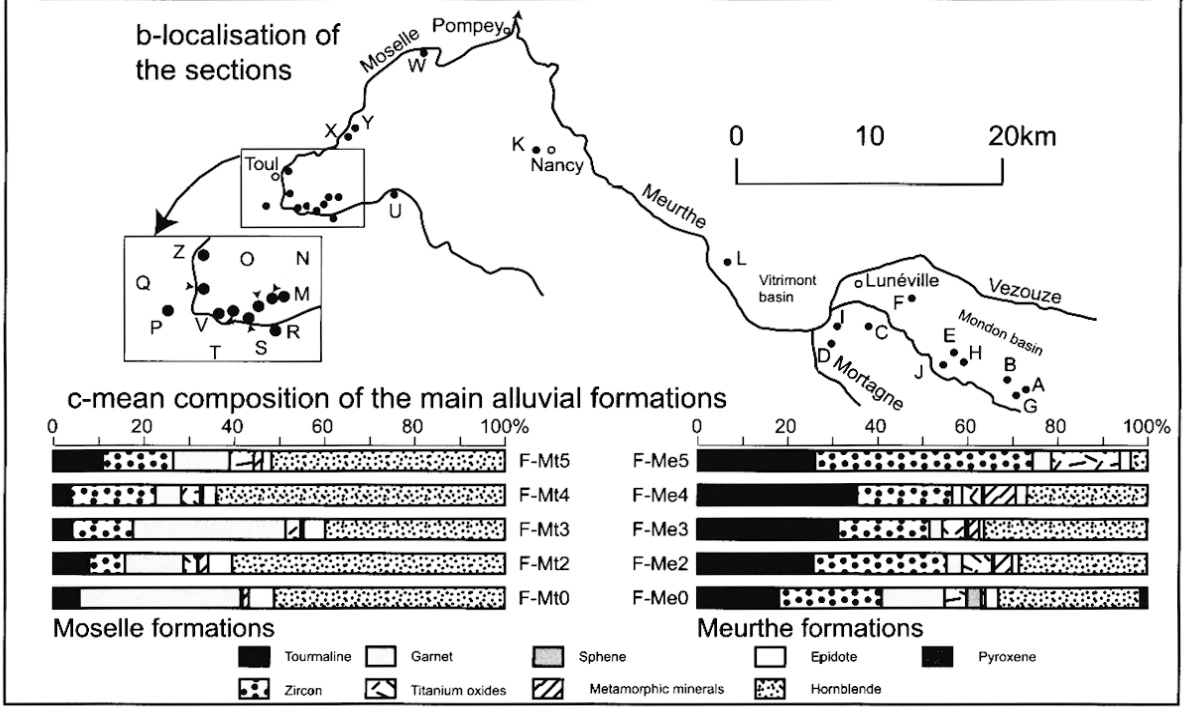

Fig. 3: Mineral spectra of the Meurthe and the Moselle formations.
Fig. 3 : Composition minéralogique des formations alluviales de la Meurthe et de la Moselle.

Using the same criteria as for the other sections of valley, eight fluvial formations (from F-M0 the floodplain to F-M7) are identified downstream from Pompey. They correspond with the floodplain alluvium M0 and the lower terrace levels (M1 to M7), stepped between 0 and 70 m relative height. Above M7, residual deposits can be observed up to 160 m relative height (fig. 2d).

Initial sedimentological analysis (fig. 5) and field surveys show that the formations F-M4 to F-M7 (30-70 m relative height) and the older deposits are mainly composed with sediments that originated in the Permo-Triassic strata :

-the mineralogical composition of the sands shows the predominance of the tourmaline-zircon association (55 to 75 % of the minerals), while minerals from the crystalline basement (hornblende and garnet) are only present in minor proportions (less than 30 %);

Site	Formation	Clasts from the Permo -Trias(%)	Crystalline clasts (%)
Basin of Mondon			
A	F-Me4	59,19	40,81
B*	F-Me4	22,37	77,63
C	F-Me4	30,67	69,33
D*	F-Me4	50,00	50,00
E	F-Me3	52,16	47,84
F	F-Me2	65,55	34,45
G	F-Me2	62,44	37,56
H	F-Me0	33,41	66,59
I	F-Me0	41,74	58,26
J	F-Me0	49,47	50,53
Basins of Vitrimont and Nancy			
K	F-Me5	98,50	1,50
L	F-Me3	85,71	14,29
M	F-Me2	78,46	21,54
N	F-Me2	80,00	20,00
O	F-Me2	80,92	19,08
P	F-Me2	88,71	11,29
Q	F-Me0	70,12	29,88
R	F-Me0	69,24	30,76
S	F-Me0	75,56	24,44

(* = less than one hundred clasts)

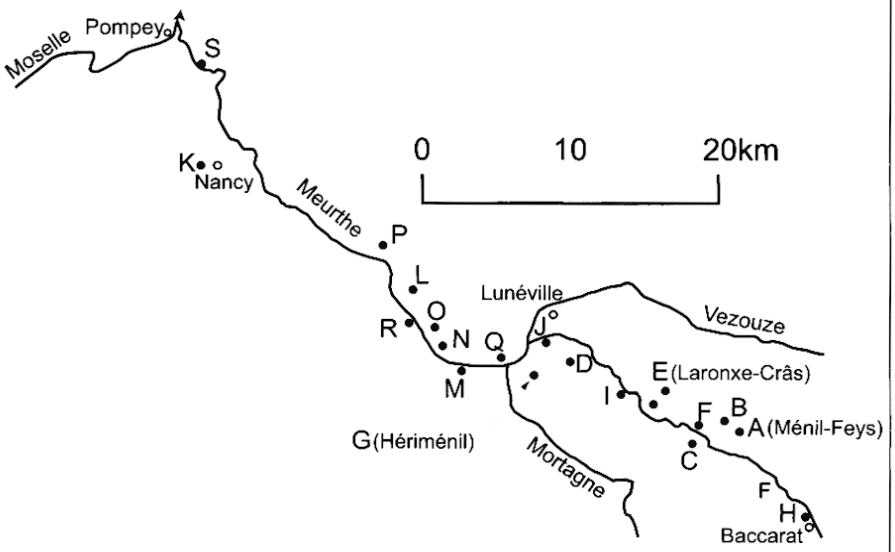

Fig. 4: Petrography of the clasts (20-40 mm) in the Meurthe formations.
Fig. 4 : Pétrographie des galets (20-40 mm) dans les formations alluviales de la Meurthe.

-in the same way, gravel clasts have come only from the sandstone cover (limestones have a proximal origin and are not significant).

These characteristics mainly reflect the lithology of the Meurthe basin; the deposition of these sediments, attributed to the Paleo-Meurthe river, thus occurred before the capture.

In contrast, the lower formations (F-M3 to F-M0, situated below 25 m relative height) often contain numerous sands and gravel clasts originating in the basement:

-the percentage of crystalline minerals (hornblende and garnet) always exceeds 35 % and even 50 % (except for the Saint-Hubert section, see below III). A significant proportion of the tourmaline-zircon association (25 to 45 %) corresponds with the influence of the Meurthe, which remains able to carry sediments from the Vosges after the capture (its influence is all the more important because its Vosgian catchment is as wide as the Moselle catchment). The variations observed in the relative proportion of minerals originating in the sandstone cover and in the crystalline basement thus reflect the relative predominance of one river or the other;

-petrographic determinations for the formations F-M0 to F-M3 confirm this duality: clasts originating in the sandstone and conglomeratic formations (quartz and quartzite) are more abundant because of their resistance to weathering, but crystalline clasts always represent more than 20 % (except downstream from Thionville, where the proportion decreases because of the weathering of the granite clasts).

This petrographical and mineralogical change proves that the capture occurred between the deposition of the F4 and F3 formations of the Paleo-Meurthe-Moselle valley: M3 is the first level deposited after the capture, and corresponds with the Mt3 level defined near Toul.

It is also possible to present a global longitudinal profile for the three sections of valley (fig. 2d). The profile shows the parallelism of the terrace levels, already described in recent research for the other major valley in Lorraine, the Upper Moselle-Meuse valley. This confirms the weakness of general tectonic deformation in the Lorraine sedimentary basin during the Pleistocene (Le Roux et Harmand, 1998), and proves that the altitudinal gradient between the Upper-Moselle-Meuse near Toul and the Paleo-Meurthe near Pompey did not exceed 20 m when the capture occurred.

III - VALLEYS FORMATION IN THE LORRAINE SEDIMENTARY BASIN: INFLUENCE OF GLACIATIONS AND CHRONOLOGICAL RECONSTITUTION

A - ALLUVIATION AND THE GLACIAL CYCLE

Detailed analysis of the main sections (both in the Meurthe valley and downstream from Pompey) allow observation of important variations in the sedimentological structures of the deposits and in their lithological composition; this makes it possible to define typical lithofacies that can be correlated with the Vosgian glaciations.

-In the Meurthe valley: the main sections observed in the Mondon basin (for example, the sections of Laronxe-Crâs, which is correlated with the formation F-Me3, and Ménil-Feys, representative of the formation F-Me4,

fig. 6) always show a lower sandy deposit several meters thick (series A of Laronxe-Crâs, A and B of Ménil-Feys). The overall disposition of the sequences, comparable with recent sections observed in the Loire valley in Burgundy (Straffin *et al.*, 1999; Blum and Törnqvist, 2000), and the observation of crossing channels in the F-Me4 formation (Doeglas, 1962; Marc Durand, personal communication) show that these series were deposited in the Mondon basin by a braided river. This conclusion confirms data from the floodplain (Carcaud, 1992) and the middle terraces of the Moselle downstream from Epinal (Taous, 1994).

The sandy series are overlain by a coarse deposit (series B and C of Laronxe-Crâs, C of Ménil-Feys) with an ero-

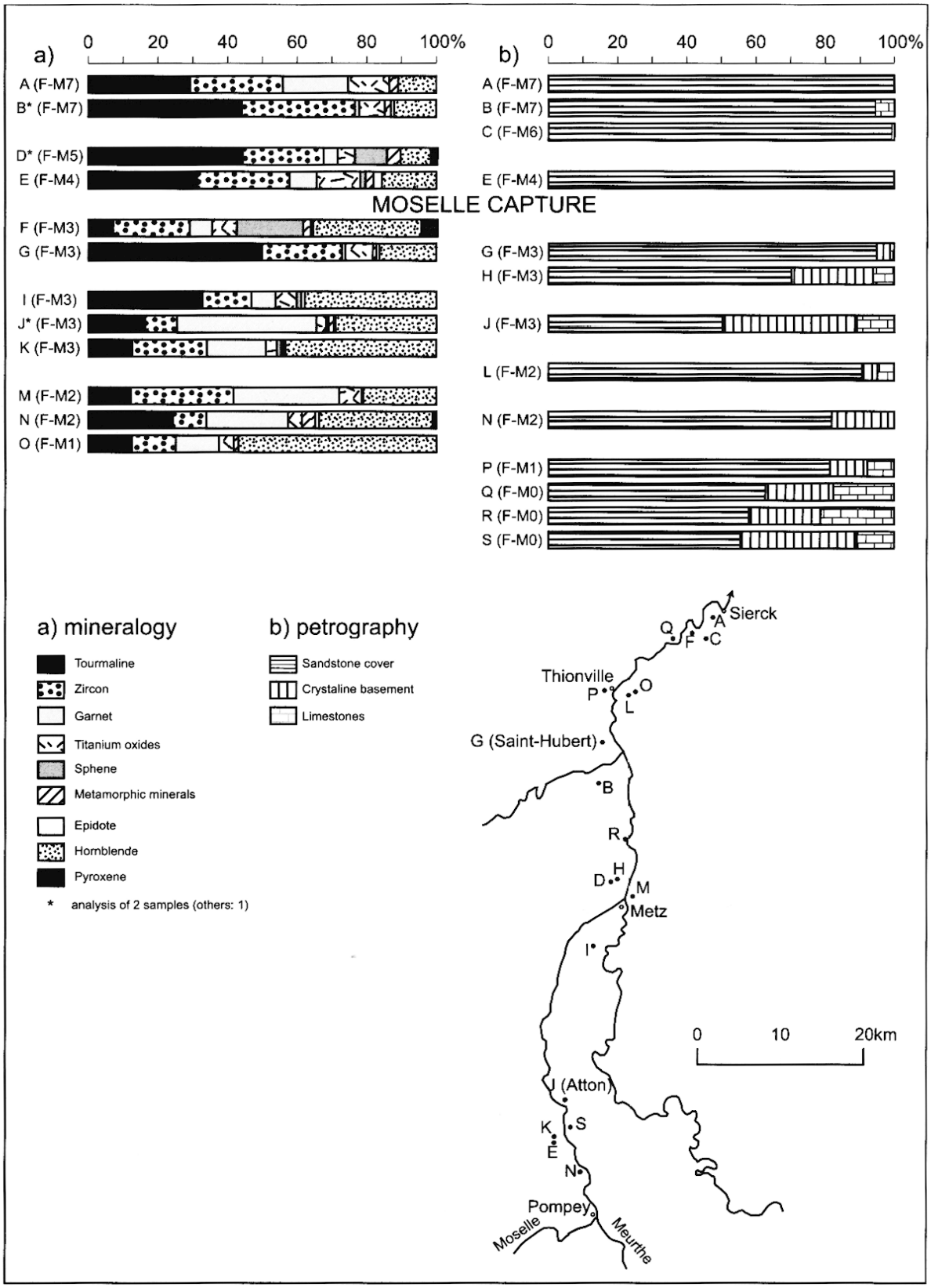

Fig. 5: Lithological composition of alluvial formations downstream from Pompey.
Fig. 5 : Composition lithologique des formations alluviales en aval de Pompey.

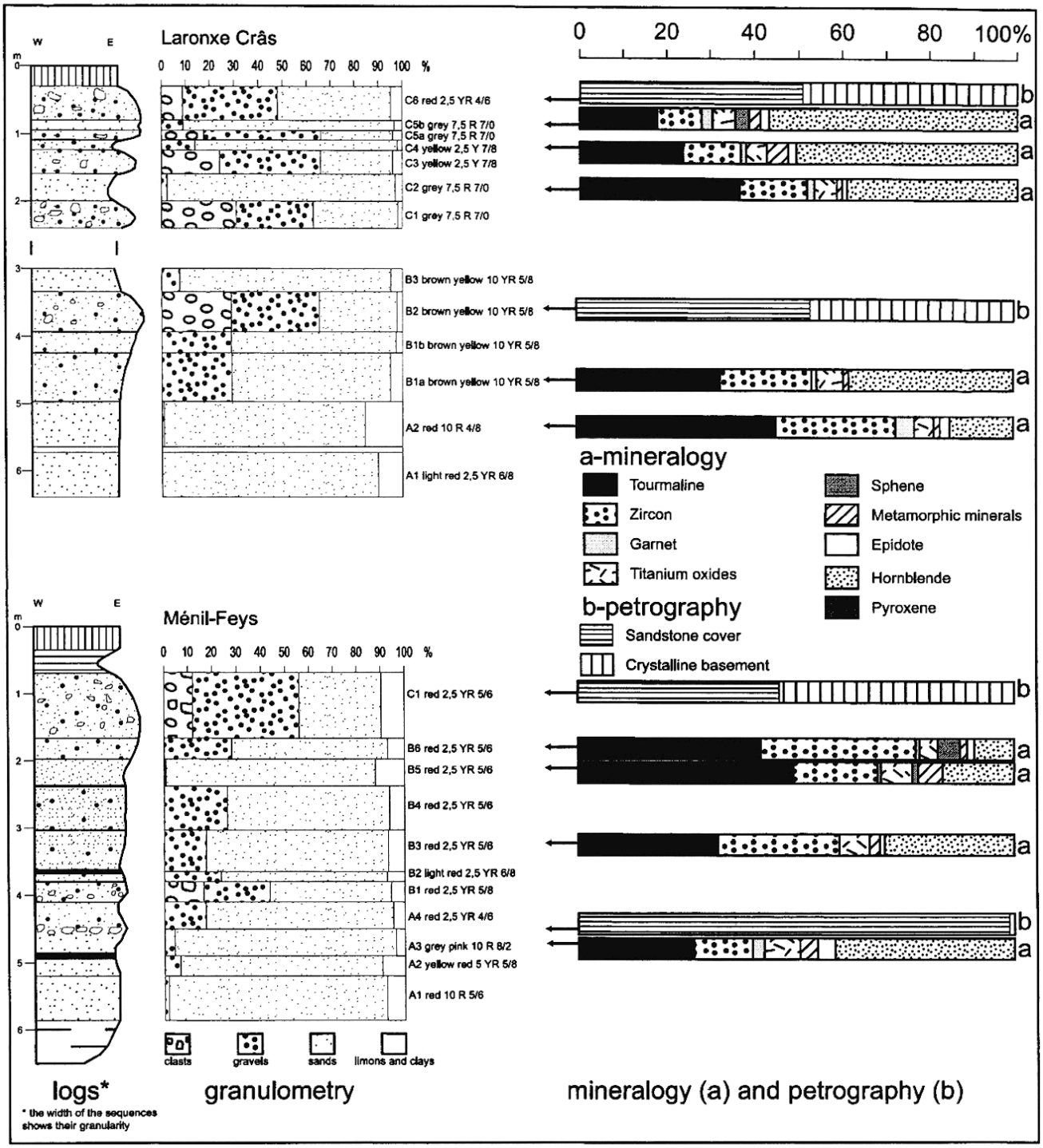

Fig. 6: Sedimentological analysis of the alluvial formations of the Meurthe valley : exposures of Laronxe-Crâs and Ménil-Feys (localisation fig. 4).
Fig. 6 : Synthèse sédimentologique pour les coupes de Laronxe-Crâs et Ménil-Feys.

sive base channelled into the lower sediments. The deposit is overlain by sands and silts that are very weathered and not easily observable in the field (although boreholes reveal that they can be locally several meters thick).

The connection between these characteristics and the lithological composition of the sequences allows a correlation with the glaciations in the Vosges mountains to be proposed: indeed, the lower series contains many sediments originating in the sandstone and conglomeratic cover (tourmaline and zircon, quartz and quartzite clasts, fig. 6). Taking into account the characteristics of the upper Meurthe basin, the deposition of these series is correlated with full-glacial episodes: during these periods, the basement is overlain by ice, and the capacity of the Meurthe river is too weak to allow the transport of abundant crystalline materials out of the massif. The observation of cryoturbation structures in these sandy series (Hérimenil section, fig. 7) confirms this correlation.

In contrast, the upper coarse series contains abundant crystalline elements (hornblende, granites): deposition may thus have occurred during late glacial episodes, when the capacity of the river was maximal, which can

Fig. 7: Contrast between the lower sandy deposits and the upper coarse deposits (section of Hériménil , F-Me2. Localisation on fig. 4). The sandy series presents cryoturbation figures (plications and involutions, on the right of the hammer): this deposit probably occured during the full-glacial periods.
Fig. 7 : Détail de la coupe de Hériménil carrière (Me2) : contraste entre banc grossier sommital et série inférieure sableuse, cette dernière présentant des figures de cryoturbation (plications et involutions) : sa mise en place correspondrait à une phase pléniglaciaire.

explain the frequency of crystalline sands and clasts, as well as the channelling of the underlying deposits.

It is more difficult to assign a relative age to the uppermost sands and silts. They may represent interglacial deposits, preserved after incision by the river to a lower level; the main incision periods must indeed have occurred between interglacial and full-glacial periods, as confirmed by the absence of incision into the Holocene floodplain alluvium (Carcaud, 1992).

This scheme should not be considered as a general model of relationship between incision and climatic cycles in periglacial areas (e.g. in the Thames valley, Bridgland (2000) places incision at the cold to warm transition, after a cold-climate gravel aggradation episode that covers or replaces interglacial floodplain deposits). However the chronology presented for the Mondon basin reinforces results obtained in many other northwest European valleys (Antoine, 1994; Vandenberghe *et al.,* 1994). It seems quite difficult to extend this model in the lower Meurthe valley, because of the lack of data downstream from the Mondon basin.

-Downstream from Pompey, the formation F-M3 presents two main types of lithofacies: at Atton (sample J, fig. 5), the deposits are coarse and contain abundant crystalline clasts and sands. South of Thionville, the F-M3 deposits located close to the axis of the valley still contain crystalline elements, in contrast to the deposits located more laterally: the Saint-Hubert section (sample G, fig. 5) thus presents thick sandy sequences, with sediment predominantly originating in the sandstone cover (lack of granite and hornblende, abundance of tourmaline).

This observation allows the following interpretation to be proposed: during cold periods, sedimentation is dominantly sandy and particularly supplied by the Meurthe river (e.g. Saint-Hubert). During late glacial periods, coarser and crystalline sediments are deposited, mainly by the Moselle river (e.g. Atton).

However, this interpretation remains hypothetical, because of the deficiency of sections. More work is needed to determine the environment of deposition for the post-capture formations downstream from Pompey.

B - THE POST-CAPTURE CHRONOLOGICAL EVOLUTION OF THE MEURTHE AND MOSELLE VALLEYS

In 1985, burned flints were dated by thermoluminescence in the lower Meuse valley near Maastricht (Huxtable and Aitken, 1985). Correlation with the Moselle near Toul show that the Moselle diversion is older than 250 ky B.P. More recently, Losson and Quinif (2001) studied the karst near Toul and dated speleothems (originated in galleries filled with pre-capture deposits in the Shafts and Ste Reine caves, fig. 2c), using the Uranium/Thorium method. The minimum age assigned to the capture by this method is 270-300 ky B.P.

Although these two dates remains hypothetical (due to the uncertainty of their interpretations), they are sufficiently consistent to assign a valid estimation of the age of the capture.

The comparison of this age with the alluvial system makes it possible to estimate the post-capture incision rates, and to assign an age to the youngest terraces:

-the minimum incision rate in the Lorraine sedimentary basin can be estimated at 0.11 $mm.y^{-1}$ since the capture. This rate is close to the mean incision rate for the Moselle valley in the Rhenish Shield during the whole Pleistocene, which is estimated at 0.12 $mm.y^{-1}$ (Negendank, 1983). However the incision in the German valley was not constant during the Pleistocene (Hoffmann, 1996): it is also important to obtain absolute dates for pre-capture levels in the French valleys, and to find the traces of the capture in the Rhenish Shield;

-the chronology for the youngest terraces may be as follow (Westaway, 2001; Cordier *et al.*, 2002): M3 (and its equivalents Mt3 and Me3) dates from OIS 6, M2-Mt2-Me2 from OIS 4, M1-Mt1-Me1 from OIS 2, while the alluvial floodplain sequence dates from the Late-glacial and Holocene (Carcaud, 1992).

CONCLUSION

This study demonstrates the importance of the sedimentary record of the River Meurthe and compares it with

that of the Moselle. Such comparison makes it possible to find evidence of the Upper Moselle capture downstream from Pompey and to show the influence of recent climatic change in the Vosges mountains on the alluviation of the two rivers (both in proximal and median areas).

Correlations with absolute dates for the capture complement the chronological reconstitution by providing an estimate of the incision rate in the Moselle basin and of the age of the post-capture terraces. However these data must still be improved, by obtaining absolute dates in the Paleo-Meurthe valley, and by complementary research in the Moselle valley in Germany.

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