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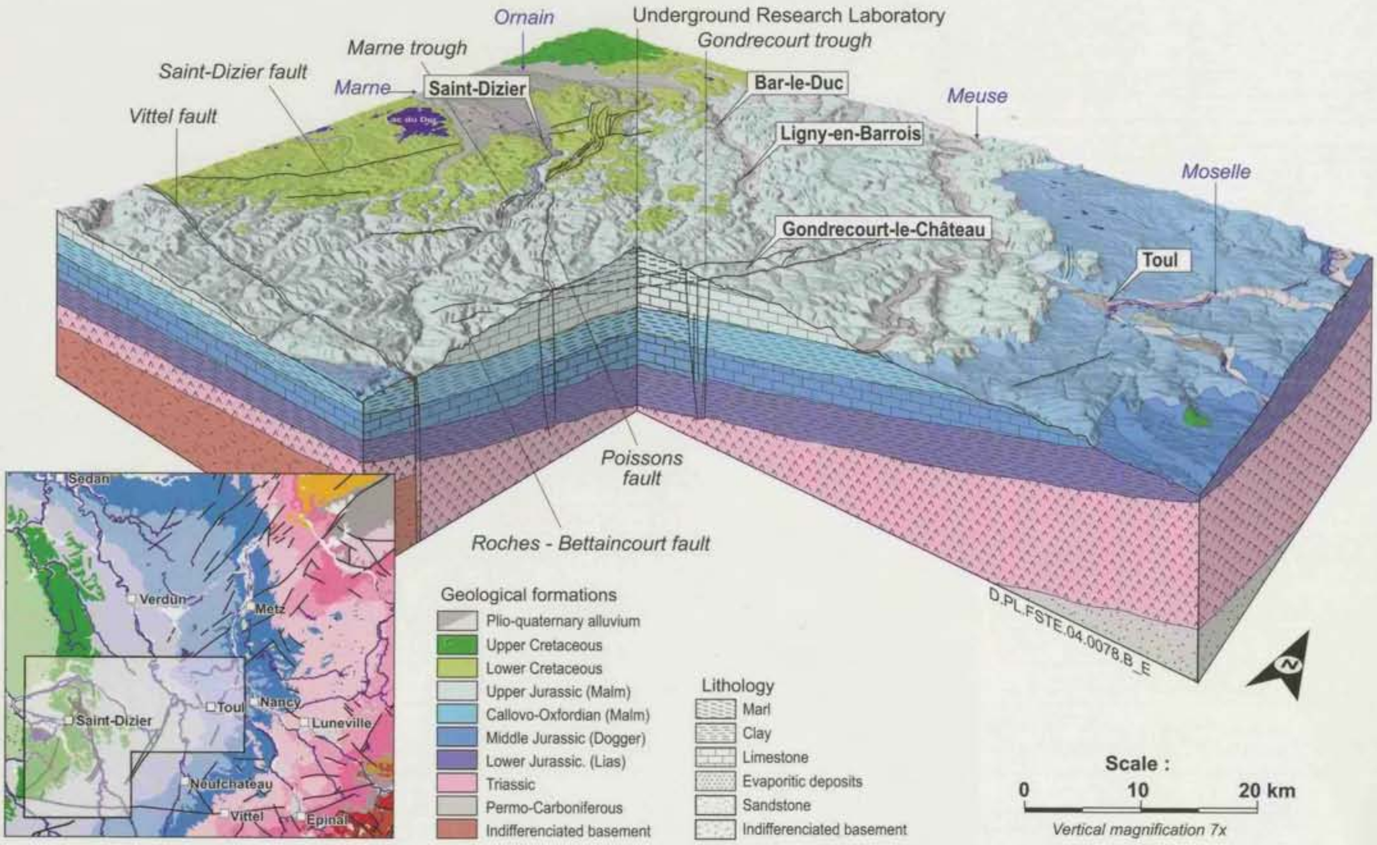
A multi-disciplinary approach to the eastern Jurassic border of the Paris Basin (Meuse / Haute-Marne)



Guest-Editor : Patrick Lebon

Mémoires de la Société Géologique de France
nouvelle série, n° 178, 156 p.

ANDRA
Agence nationale
pour la gestion des déchets radioactifs

Mém. Soc. géol. France, n.s., 2007, n° 178, pp. 135-155

Morphologic evolution of eastern Paris Basin: "ancient surfaces" and Quaternary incisions

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Key words. – Paris Basin, Paleosurfaces, Terraces, Karst, ESR, Erosion modelling

Abstract. – The investigations on the site of the Meuse/Haute-Marne underground laboratory to evaluate its geological stability have largely contributed to revise the geomorphologic evolution of the Paris Basin by the study of the "ancient" paleoweathering surfaces and the processes controlling erosion during the Quaternary. Field work (mapping, sampling) associated to dating methods (paleomagnetism on alterites, ESR on alluvial terraces and U/Th TIMS on speleothems) and combined with numerical modelisation, have been essential in all studies. They permit to unravel some debates such as the characterization of several paleosurfaces that were attributed to the Tertiary for all of them, to identify several sets of fluvial erosion forms in areas where they were supposed to be none of them, to understand the role of the karsts in the surficial erosion. The main results can be summarized as follow: 1) the "top surface" is in fact composed of several, well identified, paleoweathering surfaces that were shaped at various periods: early Cretaceous and lower Tertiary; 2) the evolution of the Quaternary landscape is driven by the river incisions and the cuesta retreat, karsts play a significant role but not determining; 3) modelling shows that a tectonic uplift has to be taken into account to simulate the incision. These results are important for the Geoprospective analysis: ancient surfaces bring valuable information about long term regional geodynamic evolution, continental weathering and its impact on the geological formation characteristics, while the river incision give quantitative elements on the landscape recent evolution that permit to estimate the plausible evolutions of the site during the next one million years.

Evolution géomorphologique de l'est du Bassin parisien: surfaces anciennes et incisions quaternaires

Mots clés. – Bassin de Paris, Paléosurfaces, Terrasses, Karst, ESR, Modélisation de l'érosion

Résumé. – Les investigations sur l'emplacement du laboratoire souterrain de Meuse/Haute-Marne pour évaluer sa stabilité géologique ont en grande partie contribué à réviser l'évolution géomorphologique du bassin de Paris par l'étude des paléosurfaces d'altération et des processus commandant l'érosion pendant le Quaternaire. Les travaux sur le terrain (cartographie, échantillonnage) associés aux méthodes de datations (paleomagnétisme sur des altérites, l'ESR sur les terrasses alluviales et l'U/Th TIMS sur des spéléothèmes) et combinés avec la modélisation numérique, ont été essentiels dans toutes les études. Ils ont permis de clore certains débats par la caractérisation de plusieurs paléosurfaces qui étaient jusque-là attribuées au Tertiaire, par l'identification d'ensembles de formes d'érosion fluviale dans des secteurs où elles n'avaient jamais été identifiées, par la compréhension du rôle des karsts dans l'érosion de surface. Les résultats principaux peuvent être récapitulés comme suit : 1) « la surface supérieure » se compose en fait de plusieurs surfaces d'altération, bien identifiées, qui ont été formées à diverses périodes : Crétacé inférieur et début du Tertiaire ; 2) l'évolution du paysage quaternaire est conduite par les incisions des cours d'eau et le recul des cuestas, tandis que les karsts jouent un rôle significatif mais pas déterminant ; 3) la modélisation montre qu'un soulèvement tectonique doit être pris en considération pour simuler l'incision. Ces résultats sont essentiels pour l'analyse de Géoprospective: les paléosurfaces apportent une information importante sur l'évolution géodynamique régionale à long terme, l'altération continentale et son impact sur les caractéristiques géologiques de la formation, alors que l'incision par les cours d'eau donne les éléments quantitatifs sur l'évolution récente du paysage qui permettent d'estimer des évolutions plausibles du site pendant le million d'années à venir.

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INTRODUCTION

In France, investigations on the feasibility of a repository for long-lived radioactive waste in a deep geological formation are carried out according to a regulatory framework [DSIN, 1991, Basic Safety Rule, RFS III.2.f.]. These are prescribing that the long-term geological evolution has to be taken into account to assess the dynamics of radionuclide transfers over the very long timescales involved.

To assume the very long term stability of a geological repository, until one million years, the purpose is: (1) to know the past evolution of the host formation in order to understand the current state and the 3-D distribution of the characteristics of the different layers of the subsoil, and (2) to estimate the changes that might occur in the future over the lifetime of the repository and their impact on the characteristics of the host geological formation in relation to radionuclide transfer to the biosphere. The studies performed include tectonic, climatic changes with the associated effects, such as permafrost periodic development (inducing modifications both for deep water circulations and surface conditions). Their impact on the long-term geomorphologic evolution, landscape and biosphere changes during climatic cycles are also considered (conditioning radionuclide transfers to the biosphere system). This paper focuses only on the geomorphologic evolution.

The Meuse/Haute-Marne underground laboratory site is located in the southeastern part of the Paris Basin, characterised by a limited and slow geodynamical evolution, away from seismic active zones and the ice sheets that developed in northern Europe and in mountain regions during glacial climatic periods. Geographically speaking, this region is characterised by outcrops of Jurassic formations where clay and limestone layers alternate, thus allowing the development of contrasted reliefs: valleys cut through a cuesta landscape, submitted to permafrost during cold climatic periods. Within this context, the research work promoted by Andra has concentrated on two main axes. The first one has been devoted to the Neogene evolution of the landscape, focussing on the identification and dating of the paleosurfaces of the Paris Basin as they represent key element for the long term geodynamical evolution of this sedimentary basin surrounded by several hercynian basement outcrops (Massif Armoricain, Massif Central, Vosges and Ardenne). The second one has concentrated on the Quaternary evolution of the morphology and hydraulic systems. Indeed, Quaternary is marked by climatic cycles of amplitudes that were unknown during the last 30 Ma, leading to surface conditions that vary very rapidly. Surface studies on the slope retreat, river incision and karst evolution have been performed in order to bring elements for a forecast modelling of plausible geomorphologic evolution taking into account the erosion rates as a function of the climatic changes, the geodynamic context.

Many research teams have been involved in these projects. Within the context of this publication, choices had to be made because an extensive presentation could not be envisaged. Therefore, we would like, first to thank all the teams that have brought their contribution to the results that are presented in the following. The choice has been made to focus on the paleosurface identification and the evolution of the hydraulic system. Other themes, such as direct climatic impacts, like soils and vegetation, although considered to obtain an integrated model of geosphere evolution, are not presented in the following.

The first theme has been selected because the results that have been obtained during these last years bring an entirely revised picture of the so called "siderolithic", a large part of it being now attributed to the Mesozoic, "infra-Cretaceous surface". The second theme relates to the karsts and fluvial evolution that correspond to a specific aspect of the Quaternary marked by a major change in the landscape evolution in response to a renewal of erosion.

THE CONCEPT OF THE TOP SURFACE – "SURFACE SOMMITALE"

The concept of a top surface (or envelope of the topography) in the Paris Basin emerged at the end of the 19th century, when the authors noticed that the highest points of the topography were part of a homogeneous virtual surface, far simpler than the present topography and independent of the structural context and the hydrography. This surface would be the rests of a peneplain, final landform of a fluvial erosion cycle according to Davis [1889, 1909], in which the rivers embanked due to a renewal of the erosion.

Defined in the centre of the basin in 1888 [de La Noe and de Margerie], this notion is enlarged by Briquet [1908, 1933] who assigns a single peneplain to the whole basin and its borders. Nowadays the ideas evolved [Dewolf and Pomerol, 1997] and it is proved that the "*surface fondamentale*" or "*haute surface*" in the centre, corresponding to the most part of the basin, is acyclic and was continuously reshaped from late Cretaceous to present [Klein, 1975].

Nevertheless, the geological records of the ancient continents are scarce and often blurred by the successive evolutions. Their dating has for long been the hindrance to correlate continental paleosurfaces with marine deposits in the basins. Progresses in dating paleoweatherings have fully renewed our knowledge of the continental paleogeography of the Paris Basin.

Two main ancient periods of continental evolution are recognized in the Paris Basin: on one hand the Early Cretaceous with the Wealden formations, and on the other hand the Tertiary, especially with the so called "Siderolithic", namely the Clay-with-flints and the ferruginous sands and clays resting on the Jurassic and Cretaceous aureoles.

THE "ANCIENT" PALEOSURFACES OF THE PARIS BASIN

The early Cretaceous paleosurface

Early Cretaceous ages obtained on several paleoweathering profiles, previously ascribed to the Tertiary, deeply renewed the knowledge of this major continental period in the Paris Basin, correlative to the bauxite deposits in southern France.

The "Siderolithic" of the surrounding crystalline massifs

The red formations at the edge of the Cher Graben (near Montluçon), those of the Limagnes (Lembron) and of several smaller grabens in the centre of the Massif Central are classical "Siderolithic" sites [Deschamps, 1973]. The most typical facies are red hardpans, related to leached ferruginous paleosoils, marking out "glacis" anchored on paleoreliefs, which have secondly been silicified by impregnation of the clayey materials by opal [Thiry, 1999]. Paleomagnetism dating indicate that: 1) in the Cher Graben, the upper part of the profiles gives ages around 120 to 130 Ma and their lower part ages around 50 Ma [Théveniaut, 2003; Quesnel *et al.*, 2003], 2) the paleosoils in the Lembron area may date back to 140 Ma [Thiry *et al.*, 2004], and 3) the preliminary results obtained on paleosoils of the Naussac Graben indicate an age of 160 Ma [Ricordel, 2007]. These datings point out that during Early Cretaceous the Massif Central was devoid of any sedimentary cover in the studied sites.

No direct data is available about the Armorican Massif cover during early Cretaceous. Indirect indications are supplied by the importance of the detritic deposits of the peripheral Albian-Cenomanian transgression that show that the basement was cropping out during the transgression [Juignet, 1971; Louail, 1984]. In Brittany, kaolinitic profiles located on benches higher than the Paleogene surface and devoid of any silicification may be related to the lower Cretaceous paleosurface [Wyns, 1991]. On the southern edge of the Armorican Massif, the thickness of the preserved saprolite usually reaches 10 to 15 m, or less, depending on the extent of the subsequent truncations [Steinberg, 1967]. On the northeastern edge, paleoweatherings also occur upon the basement and the Jurassic marls and limestones [Thiry *et al.*, 2006].

The kaolinitic weathering profiles of the Ardenne area are usually not covered. Dating of the profile of Transinne developed on the Devonian schists and sandstones [Yans, 2003], gives ages contained between 125 and 135 Ma in the upper part of the profile and between 88 and 94 Ma towards the base of the profile. The spreading out of the dating is consistent with the downward progression of the weathering. In the Sarre area, dating of goethite from a profile developed on volcanics suggest an age comprised between 120 and 142 Ma [Lippolt *et al.*, 1998].

The Jurassic aureoles in the Paris Basin

In the Paris Basin the lower Cretaceous deposition area was reduced to a NW-SE gutter, extending from the Bray to Burgundy. On both sides of the gutter, the Jurassic formations were cropping out and submitted to weathering (fig. 1).

In the northeastern part of the gutter, corresponding to the continental realm of the Wealden deposits, the weathering is less outstanding. In Normandy and Maine, the Cretaceous strata lay unconformably on the various Jurassic aureoles, indicating tectonic strains between the Upper Jurassic emersion and the Albian-Cenomanian transgression [Rioult *et al.*, 1966]. Southeastwards, on the edge of the Armorican Massif, paleokarsts filled with pisolithic iron ore were described on the Jurassic limestone beneath the transgressive Albian and Cenomanian deposits. In the Maine, a detrital formation containing gibbsite together with kaolinite has been described between the Bajocian and the Cenomanian and interpreted as reworked from bauxitic profiles [Estéoule *et al.*, 1969].

In the southeastern part of the gutter, paleoweathering is the thickest and the best preserved beneath the Cretaceous transgression. In the Aube, re-consideration of the facies ascribed to the Wealden allowed to show that these are in fact paleoweathering profiles developed upon marine Hauterivian deposits and sealed by the Aptian transgression [Ferry *et al.*, 2001]. In Lorraine, the "Fer Fort" (iron ore) deposits from the "Borne de Fer" butte relate to an *in situ* ferricrete, developed at the expense of the Bajocian limestones and marls. These ferruginous formations were ascribed to the Siderolithic *sensu lato* and usually to the Eocene. Paleomagnetism dating give ages between 120 and 130 Ma [Théveniaut *et al.*, 2007]. In Nivernais, Clay-with-Jurassic-flints containing pisolithic iron ores have been preserved. Red Clay-with-Jurassic-flints bearing gibbsite are true in situ paleoprofiles over the Callovian-Oxfordian limestone and are ante-upper-Cretaceous transgression [Thiry *et al.*, 2005]. These Siderolithic iron deposits are correlative with the bauxite deposits in southern France.

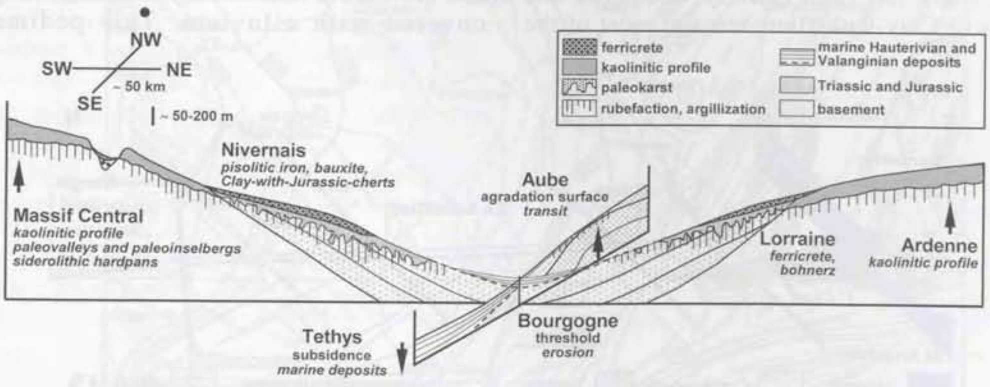


FIG. 1. – Structural sketch of the Wealden gutter and its edges during the Barremian. The fluvio-deltaic complex accumulated in a wide flood plain behind the Burgundy threshold. Paleoweathering is as intense and mature as far from the gutter axis [after Thiry *et al.*, 2006].
FIG. 1. – *Schéma structural de la gouttière wealdienne et de ses bordures au cours du Barrémien. Les complexes fluvio-deltaïques s'accumulaient dans une large plaine d'inondation située derrière le seuil de Bourgogne. L'altération reste intense et mature même loin de l'axe de la gouttière [d'après Thiry* et al., 2006].

The Wealden gutter and its tributaries

In the Paris Basin and in the English Channel, the Jurassic/Cretaceous boundary indicates a break in the deposition systems, paleogeography and subsidence [Maniez *et al.*, 1980; Guillocheau *et al.*, 2000]. The marine realm was thrown back to the southeast and a relictual Purbekian lagoon only remained in the centre of the basin. Then a strongly regressive context settled down with successive continentalisation episodes according to Cretaceous sea fluctuations. A fluviatile complex of Wealden facies built a clastic body, which rises thickness between 50 and 200 m. The flood plain was supplied by the Armorican Massif southwards and the Brabant and Ardenne northwards.

On the gutter sides the weathering intensity, the profile thickness and their maturation depend directly on the emersion duration, i.e. on the distance from the gutter axis and the elevation. Thus, in Aube and in Champagne, paleoweathering confined to rubefaction and argillization of the Lower Cretaceous formations with short emersion. On the other hand, further on the edges of the gutter and on the crystalline basement are located the thickest and most mature weathering profiles.

The Lower Tertiary regolith

The major regression at the end of the Cretaceous left behind a wide glacis made of sands, limestones and chalks. Incision of these deposits followed the lowering of the base level and promoted their weathering. In Paris Basin, a widespread regolith with extensive weathering of the chalk, but also of the Jurassic limestone platforms and even the surrounding basement areas, developed under warm and humid climatic conditions.

On the western and southern edge of the Paris Basin, the high average amount of insoluble material in the Chalk-with-flints led to the development of a cryptokarstic attack of the chalk and development of a thick Clay-with-flints cover [Klein, 1970]. Even if the weathering processes lasted all along the Cainozoic, the main part of the Clay-with-flints was already formed before the late Eocene. Biostratigrahic dating of the residual flints allow to show that these profiles, up to 40-50 m of thickness, are *in situ* profiles and thus have not undergone any reworking along the Cainozoic [Quesnel, 1997]. On the southeastern edge of the basin, chalk has been entirely weathered and only sparse patches of Clay-with-flints remain, most of the residual material was later even been reworked in widespread flint conglomerate or silicified [Thiry *et al.*, 2005]. A thick regolith developed also probably in the eastern part of the basin where weathering affected the sandy-clayey formations of Early Cretaceous, Liassic and Triassic ages. There are no remaining testimonies; the whole area has been stripped off to its weathering cover due to Neogene and Quaternary uplift.

At the beginning of the Tertiary, the landscapes of the Paris Basin and neighbouring basement areas were varied. On the one hand, wide plains with a limestone substratum were covered by a thick weathering blanket characterized by hydromorphic soils, mainly formed of Clay-with-flints with disordered kaolinite and kaolinite/smectite mixed layers. On the other hand, plateaus and paleoreliefs corresponding to the weathered crystalline basements were covered by kaolinic paleosoils, *pro parte* inherited from former periods, mainly made up of well-ordered kaolinite. These thick weathering blankets were the source of materials that fed the so-called siderolithic discharge at the beginning of the Tertiary [Blanc-Valleron and Thiry, 1997].

The "siderolithic" discharge and the silcrete armour

The first Alpine tectonic movements were perceptible during the early Tertiary, and the warm and humid climate of the Cretaceous time became drier. The instability of the relief, together with the climatic change, induced rhexistasy: the alterites were eroded, inducing the onset of the most important detrital discharge of the whole Tertiary. This "siderolithic" discharge was not synchronous everywhere, but protracted, at least from Palaeocene to Middle Eocene. It forms the basal detrital sequence in the Tertiary basins and is made up of sandy, clayey, kaolinitic and Fe-rich formations. This discharge gave the kaolinitic deposits of the Argiles Plastiques Formation in the centre of the basin.

The western edge of the Paris Basin (Normandy) was apparently very little affected by this discharge as the *in situ* Clay-with-flints profiles remain and do not support any consistent detrital cover. In return, the southern and the southeastern edges of the basin support widespread flint pebble conglomerates and related sandy and clayey formations generally assigned to the Lower Eocene. Soil erosion and correlative sedimentary discharge shaped a wide glacis covered with alluvium. This pediment intersected

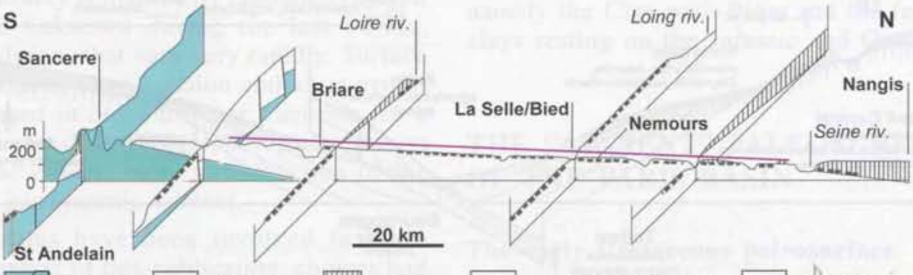


FIG. 2. – Geological section along the Loire-Loing corridor showing Eocene paleosurface shaped by the "siderolithic" discharge and armoured by the pedogenic silcretes developed during middle to upper Eocene (section location on fig. 3).
FIG. 2. – *Coupe géologique suivant le corridor Loire-Loing montrant le remodelage de la paléosurface éocène par la décharge sidérolithique et son armature par les silcrètes pédogéniques développées pendant l'Éocène supérieur (localisation de la coupe fig. 3).*

Cretaceous and Jurassic formations around the Tertiary basin and it even extended on the crystalline basement. In the basinal area, sediments were deposited both in aggraded flood plains and in lacustrine or lagoonal environments [Blanc-Valleron and Thiry, 1997].

The glacis, which is made by the "siderolithic" discharge, underwent different weathering processes under drier climates during Middle and Upper Eocene. Indeed, the upper part of the "siderolithic" discharge is often capped by silcretes. Their micro-morphological organization indicates a pedogenetic origin [Thiry, 1999]. The silcretes crop out in a scattered fashion or remain only as residual testimonies all around the Tertiary basin [Thiry, 1981; Quesnel, 2003]. They formed true siliceous armour, more or less continuous, which makes a good marker to reconstruct the middle-upper Eocene paleosurface and its geodynamics.

In the northern Lorraine and around the Rhenish shield (Ardenne, Eifel, Hunsrück), the *Pierre de Stonne* is assumed to be of the middle Eocene in the southern Ardenne [Voisin, 1988; Quesnel *et al.*, 2002] or of the lower Oligocene toward the Eifel and the Hunsrück massifs [Kadolski *et al.*, 1983]. According to Tricart [1948, 1956] this lower Tertiary paleosurface was re-shaped during the Mio-Pliocene, before the beginning of the hydrographic network embankment.

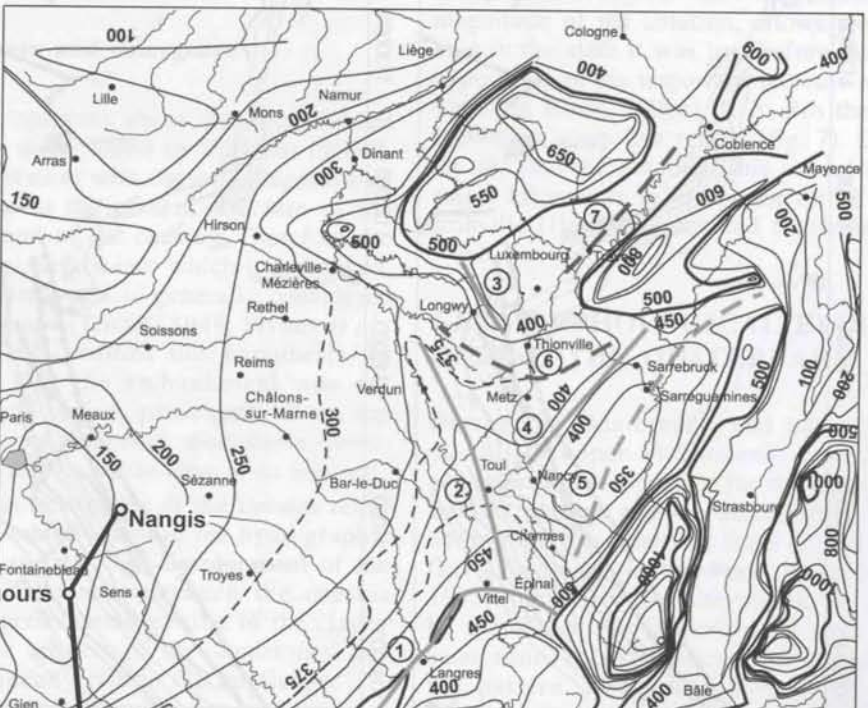
In the southern Paris Basin, these silcretes follow a paleosurface extending from the Massif Central basement to the centre of the basin. The evenness of this paleosurface is noteworthy. The geological section (fig. 2) shows that this silcrete armour is restricted in a 20 m altitudinal interval of the constructed geomorphological surface [Thiry and Simon-Coinçon, 1997]. The South-North Loire-Loing corridor has been stable all along the Cainozoic and gives an invaluable marker to constrain the geodynamic evolution of the southern Paris Basin. It forms a rigid spine around which occurred the regional tilting during the Neogene, the western area became subsiding with development of the Beauce and Sologne lake basins, whereas the eastern area have been dragged with the uplift of the Morvan and northern Massif Central.

PRESENT DAY TOP SURFACE IN THE EASTERN PARIS BASIN

In the eastern part of the Paris Basin, most of the authors [Bleicher, 1900; Vidal de la Blache, 1908; Tricart, 1948, 1956; Liedtke 1989, 1998] note the existence of a surface, which cuts the top of the main cuestas and extends on the old massifs borders. The cartography has been realized particularly by Tricart [1956] and Liedtke [1998]. The contour map has been drawn by Le Roux [2000b] and Le Roux and Harmand [2003] (fig. 3).

Morphology of the main cuestas of the eastern Paris Basin

Relations between detailed morphologies of the cuestas and their structural frame brings valuable information about the



Tresholds (*seuils*) : 1 : Morvan-Vosges; 2 : Barrois; 3 : Borne de fer; 4 : Lorraine
Depressions : 5 : Pre-Vosges; 6 : Metz; 7 : Moselle

FIG. 3. – Contour map of the top surface.
FIG. 3. – *Géométrie de la surface sommitale.*

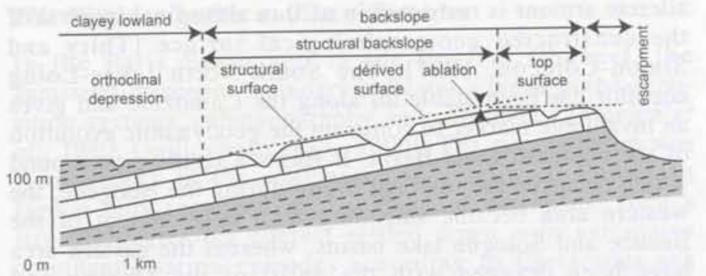


FIG. 4. – Geometrical features of the main cuestas.
FIG. 4. – *Caractéristiques géométriques des cuestas principales.* (Clayey lowland: *plaine argileuse* ; backslope: *revers* ; top surface: *surface sommitale* ; escarpment: *front*).

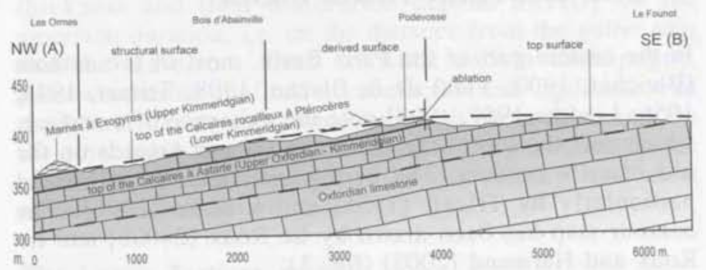


FIG. 5. – Geomorphological cross section on the Côte de Meuse backslope (see section location on fig.6).
FIG. 5. – *Coupe géomorphologique sur le revers de la Côte de Meuse (localisation de la coupe sur la fig. 6).*

progress of their exhumation [Le Roux, 1998; 2000b]. The main geometrical characteristics of the cuestas are defined on figure 4, and illustrated by the geological and morphological cross-section on figure 5. The usual terminology (escarpment, backslope) has been completed to emphasize the conspicuous relations between structure and backslope.

On the highest part of the backslope lies the plateau of the top surface. Its regional envelope, extended to the other cuestas and outwards, cleared of the hydrographical notches, is a slightly undulated surface without any resemblance with the present structure of the basement [Le Roux, 2000b; Le Roux and Harmand, 2003].

On the contrary, the rest of the backslope is greatly influenced by the geological framework. Its envelope is nearly the perfect reproduction of the structure (fig. 6). This fact is visible on the cross section, using the very tight parallelism of the geological structural surface with the topographical envelope surface (which becomes the topographical structural surface...). The two surfaces coincide with a great accuracy at the bottom of the backslope but tend to move apart towards the top: the topographical envelope progressively subsides under the geological structural surface, until its junction with the top surface. This observation reveals a moderate erosion of the lithological formations, without any relation with the hydrographical network of which the action was excluded by the geometric construction. As a result, there is mainly a chemical weathering, which was named "ablation". This explains the

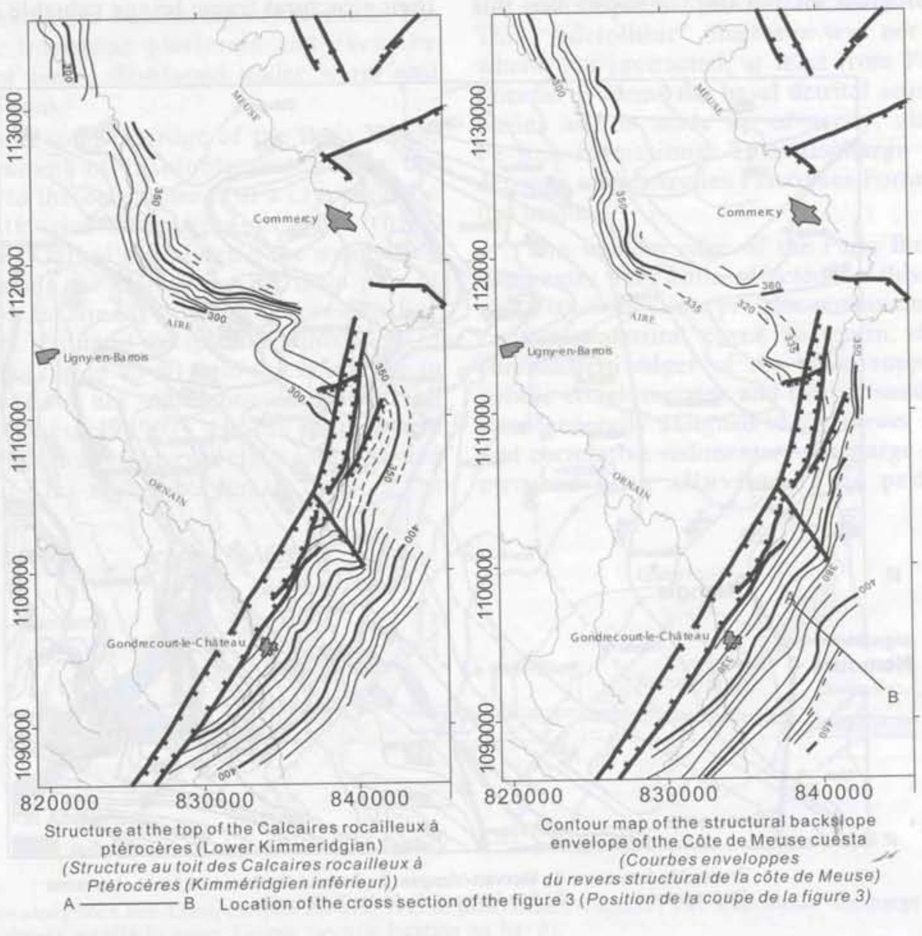


FIG. 6. – Comparison between the morphology of a backslope and the geological structure.
FIG. 6. – *Comparaison entre la morphologie d'un revers de côte et la structure géologique.*

differentiation on the structural backslope between a structural surface *s.s.* at the bottom and a derived surface at the top. Nevertheless, the boundary between the two surfaces is very progressive. Using this feature, the limit between the structural backslope and the top surface corresponds to a clear change of slope and is easy to draw.

Age of the top surface

Most of the authors consider that this surface is the rest of a Tertiary continental levelling, mainly based of the dispersed remnants of a silcrete cover (the *Pierre de Stonne*) assumed to be of the middle Eocene to lower Oligocene age.

Some of them, however, imagine that this top surface results from a removal of an undefined discordant sedimentary cover [Vidal de la Blache, 1908; Baulig, 1928; Capot-Rey, 1937]. In any way, this blanket of paleoweathered products would have been the cause of the river trend and of the erosion of the Triassic and Jurassic formations today exhumed at the crest of the cuestas. For the German authors [Schmittheiner, 1954; Liedtke, 1989] the cuestas relief would have been buried under a debris accumulation during the Tertiary without leaving any trace except the direction of the rivers. According to Le Roux and Harmand [2003] the top surface would be the remains of the basal surface of the Cretaceous transgression, which is assumed to have deposited a very fragile chalky cover on the whole region, like it was the case on the Ardenne and the Eifel massifs. This hypothesis is strengthened by the recent dating of the Barremian [Théveniaut *et al.*, 2002] on the weathering ferralitic profile of the *Borne de fer*, north of Metz.

Embankment of the rivers and emergence of the cuestas

A detailed review of the opinions about the origin of the relief and of the rivers is to be found in Deshaies [1999]. All the authors are in agreement with the non-adaptation of the hydrographic network to the present structure of the Paris Basin and to the trend of the cuestas. Therefore the network existed on the top surface into which it embanked. The beginning of the embankment is generally considered to be of a Plio-Pleistocene age [Tricart, 1948; Pissart *et al.*, 1997], but no direct dating confirms this hypothesis. In addition, it is possible that the embankment was not synchronous over the whole region, particularly if the top surface was overlaid by a Cretaceous discordant cover, because no information is known on the time of its removal.

Nevertheless, the main emergence of the cuestas relief is the consequence of the embankment of the hydrographic network beneath the top surface. The development of the orthoclinal depressions (lowlands) between the cuestas lines (uplands) reveals a preferential wasting of the clayey materials and a moderate erosion of the sandstones and limestones, which consequently rise in the landscape.

Erosion rate and cuesta line retreat

The existence itself of the cuestas relief proves the highest vulnerability to the erosion of the argillaceous formations since the start of the embankment. Regardless of the hydrographic network lowering, in which the mechanical factors have an important part, the resistant formations are subject

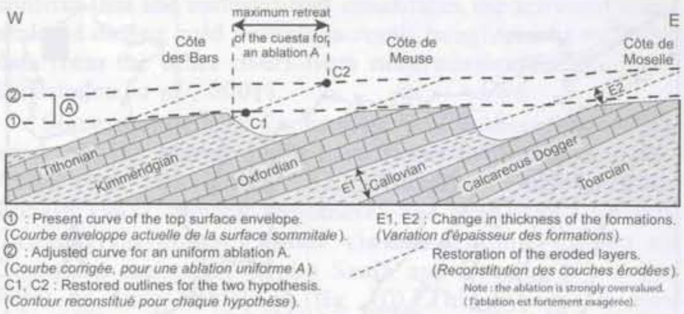


FIG. 7. – Method to estimate the cuesta retreat and restore the geological map of the top surface (estimated length of section 12 km, vertical scale 100 m).

FIG. 7. – *Méthode de construction de la carte géologique de la surface sommitale et de l'évaluation du recul des côtes (longueur approximative de la coupe 12 km, échelle verticale 100 m).*

to a meteoric alteration, mainly of chemical nature (ablation, fig. 4). This chemical weathering should have lowered at the same time the top surface and the structural backslope. It is possible to estimate the ablation on the backslope of the Côte de Meuse [Le Roux, 2001] (fig. 7). Mainly less than 10 meters deep, the lowering locally reaches 20-25 meters along the course of the most embanked rivers. Therefore, while the hydrographic network embedded of 150-180 meters, washing mainly clays, the limestones of the top surface were only lowered of 25 meters as a maximum.

Today, there is no method to measure in the field the retreat of the cuesta lines. However, the assumed hypothesis, about the start of the rivers embankment and about the magnitude of the ablation, allows restoring the geological map in the state it was just before the embankment, in the hypothesis of no important tectonic movements since that time [Le Roux, 2000a]. It is also the way to estimate the maximum scarp line retreat (fig. 7). Directly controlled by the dip and the ablation, this retreat is modest, between 1 and 2 kilometres in the perimeter of Bar-le-Duc (Meuse), Joinville (Haute-Marne) and Neufchâteau (Vosges).

GEOMORPHOLOGICAL EVOLUTION DURING THE QUATERNARY

During the Quaternary, and more probably during the middle to upper Pleistocene, several geomorphological processes are responsible for the landscape evolution of the Barrois plateau and the surrounding regions. The present hydrography is inherited from the former evolution of the fluvial network in the Paris Basin [Cojan and Clauzon, 1995], but incision of the plateau by the streams seams to be specific of the Quaternary climatic fluctuations. At the same time, karsts systems were active and responsible for the pattern of underground water and surface flows. Periglacial evolution of the valley slope led to the formation of the bedded periglacial screes (grèzes litées).

The hydrographic network: fluvial incision and valley evolution

A detailed geomorphological mapping of the different stages of incision and the associated features (alluvial

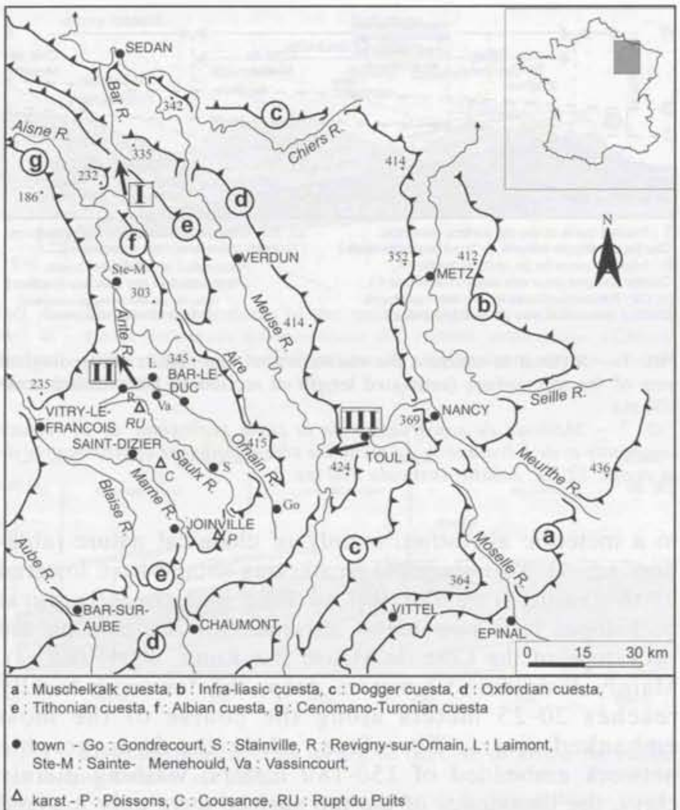


FIG. 8. – Map of the paleo- and present hydrographic network of north-eastern France.
FIG. 8. – *Carte des tracés actuels et des paléo-tracés du réseau hydrographique du nord-est de la France.*

terraces, and slopes) has been realised as the published data were restricted to limited areas [Dewolf, 1965]. Correlations and dating are based on this geomorphological mapping conducted on the Marne catchment basin upstream of Vitry-le-François, and on its tributaries (Saulx and Ornain) (fig. 8).

Incision levels along the Marne valley and its main tributaries

Observations upstream of Vitry-le-François

Seven levels of incision of the Barrois, Ornois or Langres plateaus have been characterized upstream of Vitry-le-François (fig. 9). They correspond either to alluvial terraces or to benches or glacis. These levels are grouped into three distinct periods of incision [Marre *et al.*, 2000; Lejeune *et al*, 2002; Lejeune, 2005]. The first period is represented by large glacis (Ma6 and Ma5) that truncate the "top surface". These morphologies are interpreted as the remnants of two large gutters, 10 and 6 km wide, respectively. These gutters are inset and slightly incise a paleosurface that can be attributed to the Plio-Quaternary [Le Roux, 1980]. The second period corresponds to a clear incision and a calibration of the valley to its present size (1 to 3 km in width). It is represented by three stepped terraces that are situated at different elevations above the present stream, 45-50 m (Ma4), 20-25 m (Ma3) and 10-15 m (Ma2). These terraces correspond either to erosion ledges or to alluvial deposits. The third period is characterized by a clear incision of the rocky substrate that was later filled by fluvial sediments that built a limited floodplain (Ma1) situated 2 m above the present river bed (Ma0).

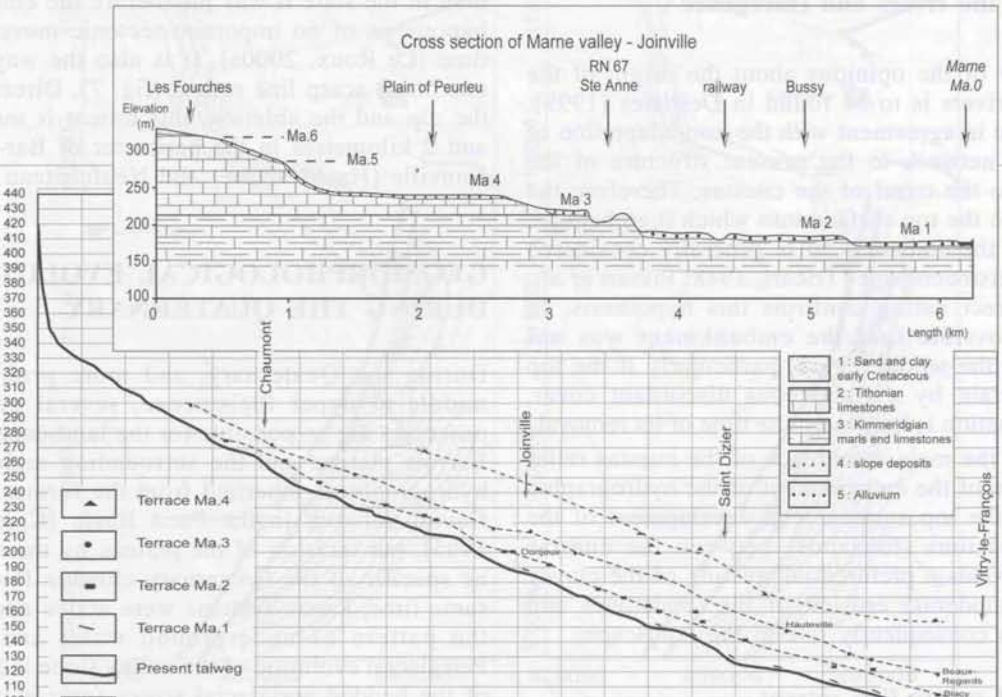


FIG. 9. – Longitudinal profile of the terraces of the Marne and transverse section of the Marne valley in the region of Joinville.
FIG. 9. – *Profil en long des terrasses de la Marne et coupe en travers des niveaux d'incision dans la région de Joinville.*

Alluvial deposits can only be observed in association to incisions related to periods 2 and 3. A classic section is composed of coarse-grained material that is overlain by fine-grained alluvium. The internal organization of the coarse grained material shows thinning and fining upward sequences characteristics of flood deposits. From place to place, channel fills can be observed. These are interpreted as an evolution from braided streams to meandering systems when flow intensity reduced [Cojan, 2004]. The alluvium deposits show hardly any flow structure but display pedogenetic and periglacial features as well as intercalation of bedded periglacial scree. It is proposed that part of this material is of aeolian origin. All these elements confirm that the material that constitutes the terraces accumulated during cold periods, a result in agreement with the data from the other rivers from northwestern Europe [Van Huissteden *et al.*, 2001].

Since middle 19th Century, several authors had envisaged that the Marne might have flown in direction of the Aisne river [Buvignier, 1852; Abrard et Corroy, 1922; Tricart, 1948]. Several hypotheses had been raised for this former river course, either via the tectonic graben of Cousance, the valley of the Saulx and Ornain, or via the Forêt de Trois-Fontaines (fig. 10). This hypothesis was revived by Deshaies [1994] despite the lack of field evidences. The recent geomorphologic studies [Marre *et al.*,

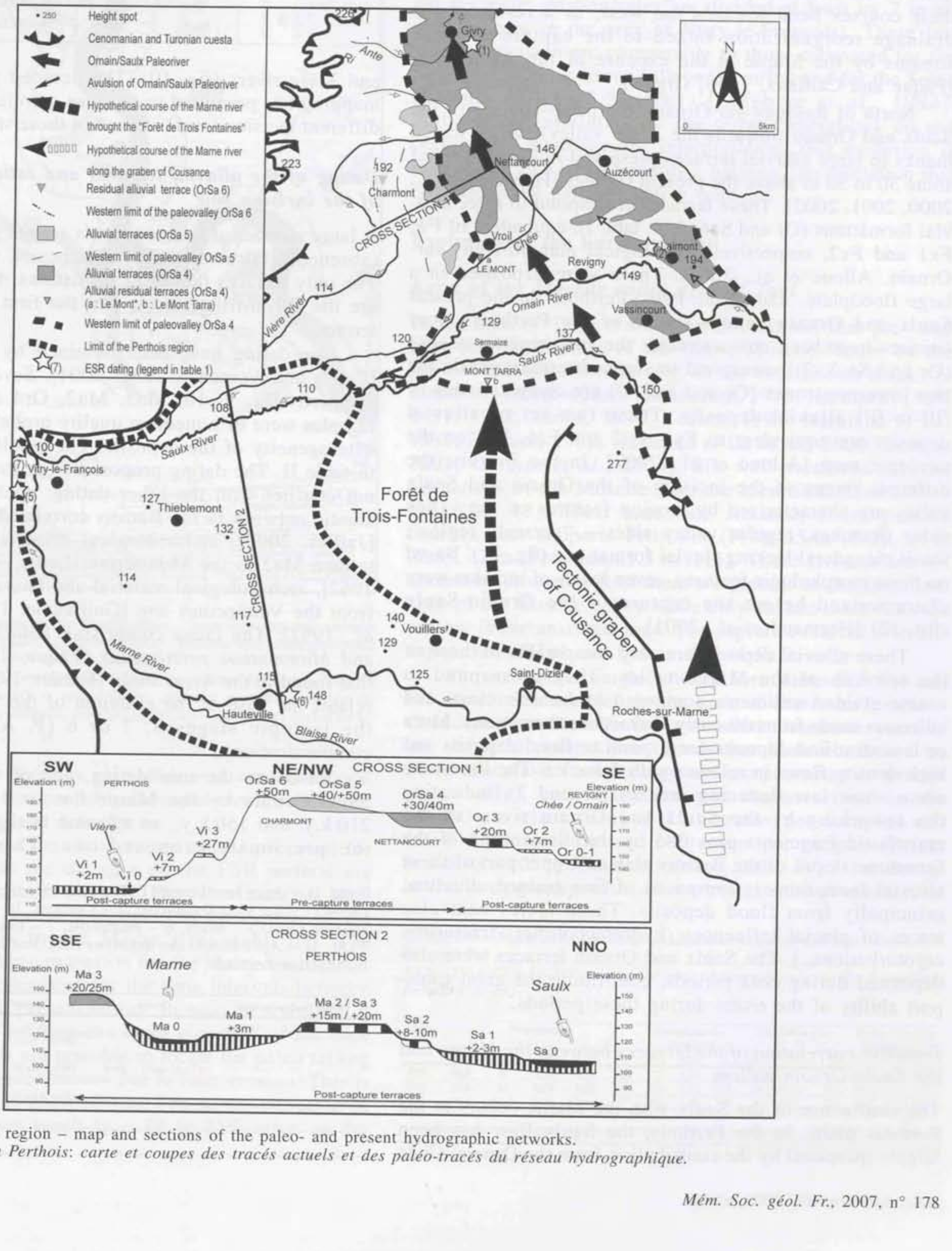


FIG. 10. – The Perthois region – map and sections of the paleo- and present hydrographic networks.
FIG. 10. – *La région du Perthois: carte et coupes des tracés actuels et des paléo-tracés du réseau hydrographique.*

2001, Lejeune *et al.*, 2002] show that no fluvial deposits could be identified along any of these two paths while continuous deposits were found along the present river course. These observations question the hypothesis of a Marne flowing to the north and of a capture of this river towards the Perthois.

Incision stages along the Saulx and Ornain valleys

The upper courses of Ornain and Saulx present north-south valleys that are embanked in the Barrois plateau (plateau elevation 400 m) and then flow in the opened landscape constituted by the early Cretaceous clay and marly formations of the Perthois. In the region of Revigny-sur-Ornain, their courses bend towards the west, as a result of the drainage reorganization linked to the capture of these streams by the Marne at the expense of the Aisne river [Pâque and Cailleux, 1946] (fig. 8).

North of Revigny-sur-Ornain, the paleo-courses of the Saulx and Ornain (towards the Aisne valley) can be traced thanks to large alluvial terraces preserved in inverted relief some 30 to 50 m above the present talwegs [Harmand *et al.*, 2000, 2001, 2002]. These terraces correspond to three alluvial formations (Or and Sa6, 5, 4, tabl. I), equivalent of Fw, Fx1 and Fx2, respectively [geological map Revigny-sur-Ornain, Allouc *et al.*, 2007]. These were deposited in a large floodplain, named the Paleo-Perthois. In the present Saulx and Ornain valleys (north of the Perthois), four terraces have been characterized: the two uppermost ones (Or and Sa 3, 2) correspond to stepped terraces while the two lowermost ones (Or and Sa1, 0) are characteristics of fill-in-fill alluvial deposits. These two set of alluvial deposits are equivalent to Fy1, Fy2 and Fz1, Fz2 on the geologic map [Allouc *et al.*, 2007]. In the Barrois, the different stages of the incision of the Ornain and Saulx valley are characterized by erosion features on the valley sides (benches, regular valley sides – "versants réglés", fossil meanders) lacking fluvial formations (fig. 11). Based on these morphologic features, seven levels of incision were characterized before the capture of the Ornain-Saulx (fig. 12) [Harmand *et al.*, 2001].

These alluvial deposits are very comparable to those of the terraces of the Marne valley. They correspond to coarse-grained sediments composed of Jurassic clasts and siliceous sands from the early Cretaceous formations. More or less stratified deposits correspond to flood deposits and high density flows in relation with debacles. The limestone clasts show low flattening indexes (around 3), indicating the reworking by the Saulx and Ornain rivers of the cryoclastic fragments provided by the dismantling of the limestone slopes of the Barrois plateau Upper part of these alluvial formations is composed of fine grained alluvium, principally from flood deposits. These facies bear also traces of glacial influences (hydrolaccolithes, fracturing, cryoturbations..). The Saulx and Ornain terraces were also deposited during cold periods, confirming the great transport ability of the rivers during these periods.

Tentative correlation of the terraces between the Marne and the Saulx-Ornain valleys

The confluence of the Saulx with the Marne occurs in the Perthois plain. In the Perthois, the Saulx flow has been largely increased by the contribution from the Ornain, Chée and Vière rivers (fig. 10). The detailed geomorphological mapping has permitted to propose correlations between the different incision levels of each of these streams (tabl. I).

TABL. I. – Tentative correlation of the alluvial terraces of the Marne, Saulx and Ornain (* – glacis without fluvial deposits, 0 – Holocene terrace).
TABL. I. – *Essai de corrélation entre les terrasses des vallées de la Marne, de la Saulx et de l'Ornain (* – glacis sans dépôt fluviatile ; 0 – terrasse holocène).*

Valley	terraces	Marne	Saulx	Ornain	Paléo-Perthois (Ornain - Saulx)
Broad valley	Stepped terraces	Ma.6*		Or 10*	
		Ma.5*	Sa 9*	Or 9*	
Present size valley		Ma.4	Sa 8*	Or 8*	
			Sa 7*	Or 7*	
			Sa 6	Or 6	OrSa 6 (Fw)
			Sa 5	Or 5	OrSa 5 (Fx 1)
			Sa 4	Or 4	OrSa 4 (Fx 2)
		Ma.3			
		Ma.2	Sa 3	Or 3 (Fy 1)	
		/	Sa 2	Or 2 (Fy 2)	
	Fill-in-fill terraces	Ma.1	Sa 1	Or 1 (Fz 1)	
		Ma.0	Sa 0	Or 0 (Fz 2)	

Dating of the alluvial terraces and estimation of the incision rate

A large number of incision levels are not suitable for dating (absence of structured fluvial deposits, no fresh section). The only terraces that offer formations that could be dated are the fill-in-fill terraces, and the first levels of stepped terraces.

Age dating have been obtained by the ESR method [Cojan and Voinchet, 2001; 2004]. Several terraces were sampled (fig. 9, 10, Ma3, Ma2, Or4 and Sa4, 5). The samples were of a medium quality probably because of the heterogeneity of the deposits. The results are summarized in table II. The dating proposed from the ESR analysis do not conflict with the other dating: speleothems from the karstic network in the Barrois correlated with terrace Ma2 [Jaillet, 2000], archaeological material that related the terrace Ma2 to the Mousterian [Louis, 1963; Stchépinsky, 1962], archaeological material and fauna from Or and Sa4 from the Vassincourt site [Guillaume, 1982; Guillaume *et al.*, 1992]. The fauna comprising *Palaeloxondon antiquus* and *Mammuthus primigenius* [Pâque, 1943] is similar to that found in the Aisne basin [Gardet, 1937; Patte, 1937]. It relates the base of the alluvium of the Vassincourt site to the isotopic stages 8, 7 or 6 [P. Auguste, personal communication].

Based on the new dating, age of the capture of the Saulx-Ornain by the Marne has to be placed between 210 k.y. and 150 k.y., an age that is slightly younger than the previously proposed one. This time period is

TABL. II. – Ages based on the ESR results. See figures 9 and 10 for site location (1 – Le Vieil Dampierre, 2 – Laimont, 3 – Vroil, 4 – Bettancourt, west of Vroil, 5 – Blacy, 6 – Hauteville, 7 – Loisy, 8 – Donjeux).
TABL. II. – *Ages déduits des datations ESR. Voir les figures 8 et 9 pour la localisation des sites.*

Ornain-Saulx paleoriver		Ornain		Saulx		Marne	
220 ± 15 ka (1)	OrSa 4						
				209 ± 21 ka (3)	Sa 4		
		177 ± 23 ka (2)	Or 4	180 ± 12 ka (4)	Sa 4		
				150 ± 19 ka (4)	Sa 4		
						154 ± 16 ka (5) 150 ± 18 ka (6)	Ma 3
						93 ± 9 ka (7) 112 ± 13 ka (8)	Ma 2

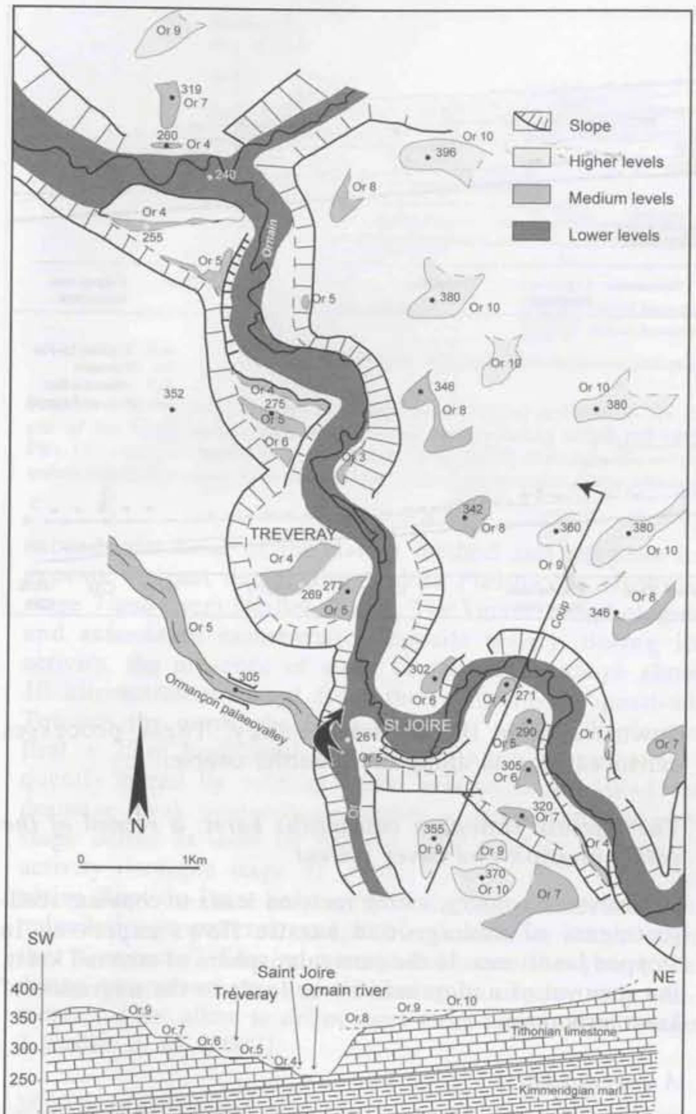


FIG. 11. – Incision phases of the Ornain river – location map and section (higher levels – broad valley, medium levels – present size valley/stepped terraces, lower levels – fill-in-fill terraces).
FIG. 11. – *Les phases d'incision de l'Ornain – carte de localisation et coupe. (niveaux supérieurs – vallée large, niveaux moyens – vallée de taille actuelle/ terrasses étagées, niveaux inférieurs – terrasses emboîtées).*

corresponding to a complex glaciation with several successive cold episodes that probably favoured erosion and sediment supply during the debacles.

An estimation of the incision rate can be proposed for the Marne valley as the dating with the ESR method are fairly consistent (terraces Ma2, 3). The calculation has been made for a period that is subsequent to the capture of the Saulx-Ornain rivers by the Marne river (tabl. III). The capture induced a large extension for the Marne basin. Incision rates can be calculated for the time intervals between Ma3/ Ma2 and Ma2/ present talweg. In must be noted that it is very difficult to estimate the exact elevation of the base of the terrace as it is not possible to locate the paleo talweg corresponding to these terraces due to later erosion. This is important because an error of 1 to 3 m on the elevation of the terrace base may result in a 10 to 25% error on the erosion rate.

TABL. III. – Estimation of incision rates of the Marne river based on data from Ma3 and Ma2 terraces.
TABL. III. – *Estimation des vitesses d'incision de la Marne à partir des données sur les niveaux de terrasses Ma3 et Ma2.*

		Chaumont	Joinville	Saint-Dizier	Vitry-le-François
Ma 2/talweg (90 ka)	Relative elevation of the base of the Ma 2 terrace above present talweg	8 m	7 m	11 m	16 m
	Incision rate	8,6 ± 1,7 cm/ka	7,5 ± 1,5 cm/ka	11,8 ± 2,3 cm/ka	17,2 ± 3,4 cm/ka
Ma 3/Ma 2 60 ka	Distance between the bases of Ma 3 and Ma 2	9 m	20 m	14 m	6 m
	Incision rate	18 ± 3,6 cm/ka	40 ± 8 cm/ka	28 ± 5,6 cm/ka	12 ± 2,4 cm/ka

The capture produced a large increase of incision rate for the first incision step, Ma3/Ma2. It was followed by a net decrease: erosion rates are divided at least by 2 in all sites (except in the area of Vitry-le-François). These last rates of incision are comparable to those estimated for the Somme and Seine lower valleys (5 cm/ky) and for the Seine medium valley (6,5 cm/ky) [Lefebvre *et al.*, 1994]. Although uncertainties on the terrace elevations do not permit any more precise interpretation, this evolution is interpreted as a trend towards a balance, interpretation that conditions the geoprospective scenarii.

Evolution of the karst systems

Karst of the Moselle valley around Toul

In the area of Toul, the alluvial formations that pre– and post-date the capture of the Haute Moselle-Meuse by the present Moselle-Meurthe (fig. 8) are well known thanks to numerous recent studies [Bonnefont, 1975; Harmand, 1989, 1991, 1992; Taous, 1994; Técher, 1995; Harmand *et al.*, 1995; Dorniol, 1997; Harmand et Le Roux, 2000; Losson, 2003; Cordier *et al.*, 2004]. Six well-preserved alluvial formations of the Moselle river are identified (from Fr0 to Fr5) (fig. 13). Their bases are situated, above present bedrock that supports Fr0, 4 m (Fr1), 15 m (Fr2), 24 m (Fr3), 32 m (Fr4) and 39.5 m (Fr5). These terraces are not altered by erosion. All of them are present on the cataclinal zone of the Moselle valley while only the last three ones are present in the anaclinal area. The capture occurred after the deposition of Fr4 and before that of Fr 3.

The materials from the alluvial formations Fr3, Fr4 and Fr5 have been sampled in the area of Pierre-la-Treiche – Chaudeney-sur-Moselle for a detailed characterization of the sediment composition. Study has been conducted on 20-50 mm clasts (morphology and morphometry on granite clasts only), and heavy mineral characterized on the 50-160 μm class (around 150 grains per sample) and 160-315 μm class (around 100 grains per sample) [Beiner *in* Losson, 2003]. The results show (tabl. IV): 1) a change in the petrography with an increase in the proportion of

TABL. IV. – Main sedimentological characteristics of the formations Fr3, Fr4 and Fr5.
TABL. IV. – *Principales caractéristiques sédimentologiques des formations Fr3, Fr4 et Fr5.*

Form.	Petrography					Morphometry (median)			Alteration (%)		Heavy minerals (dominant 3)		
	% Gr	% Qzt	Co/Ba	Gr/Ba	N	Rou	Flat	N	S+C/F+B+R	N	% Z	% G	% A
Fr5	**16,5**	**25**	**1,18**	**0,36**	491	327	1,94	66	26/74	81	**22,7**	**25,0**	**37,8**
Fr4	**28,5**	**24**	**0,94**	**0,55**	395	399	1,89	103	43,5/56,5	124	**10,4**	**4,4**	**76,9**
Fr3	**40,5**	**12,5**	**0,58**	**0,64**	347	385	1,81	139	51,5/48,5	178	**5,6**	**37,5**	**39,7**

Form.- alluvial formation ; Gr- granites ; Qzt- quartzites ; Co/Ba- cover rocks/basement rocks ; Gr/Ba- granites/all the basement rocks ; N- number of counted pebbles ; Rou- roundness ; Flat- flatness ; S+C- sound and with cortex ; F+B+R- friable, brittle and rotten ; Z- zircon ; G- garnet ; A- amphibole.

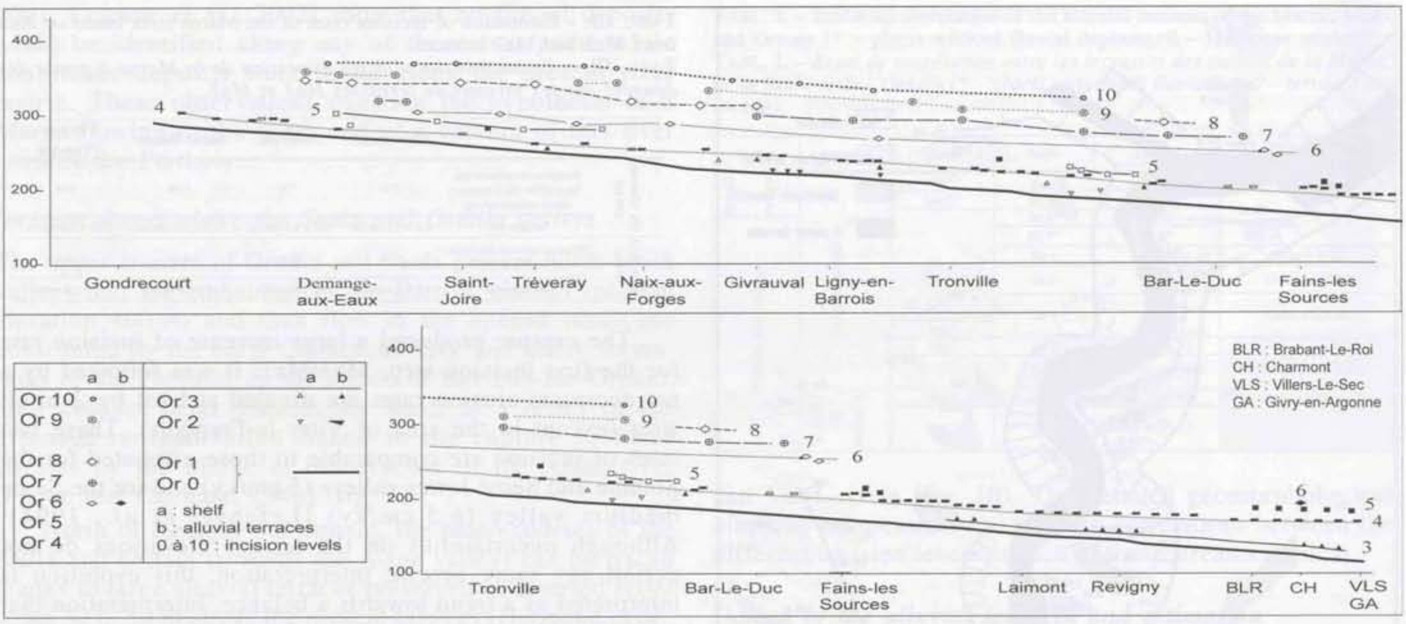


FIG. 12. – Longitudinal profiles of the terraces of the Ornain valley.
FIG. 12. – *Profils en long des terrasses de la vallée de l'Ornain.*

granite (and other siliceous basement rocks) from the oldest to the youngest alluvial formation, 2) a clear difference in the relative proportions of granite and quartzite between Fr4 (antecapture) and Fr3 (postcapture), 3) no major differences regarding the morphometry and alteration, other than the good agreement between the age of the formation and the weathering index, 4) 80% of the heavy minerals are represented by zircon, grenat and amphibole. No trend is observed.

These results will be used to identify the origin of the material that fills the cave systems. The maze formed by the caves developed at Pierre-la-Treiche is composed of anastomosed galleries connected by chimneys. The horizontal pipes developed at elevations equivalent to those of the fluvial formations Fr3 and Fr2, more rarely Fr4 (fig. 13). Their walls show typical morphologies of phreatic and epiphreatic underground paleoflows, fed by waterloss from the fluvial system. The cave fillings are mainly composed of Moselle alluvium, dominantly of Vosgian origin. The analyses show that they originate from antecapture formations Fr5 or Fr4.

The following scenario is then proposed for the development of the Pierre-la-Treiche cave system. The uppermost galleries were created during the accumulation of Fr5. During the valley incision, high and narrow galleries developed, then were filled in by the alluvium coming from Fr4. A second phase of incision of the underground network is observed, may be favoured by a better developed karst structure of the Hayes plateau. Then, these new opened galleries are also filled in with material coming from Fr4, which accumulated in the Moselle valley. Some vadose circulations must be emphasized in these fillings.

As a conclusion, the role of the karstification on the capture of the Haute Moselle-Meuse by the present Moselle-Meurthe seems to be active, although minor when compared to the climatic and epirogenic parameters. Thus, it induced a reduction of the Moselle flow, that probably favoured the sedimentation and exsurgences situated downstream in the Meurthe valley. These processes enhanced erosion along the Meurthe course.

The Barrois Tithonian calcareous karst: a record of the valley incision and cover retreat

In limestone country, valley incision leads to constant readjustments of underground karstic flows expressed in stepped landforms. In the particular sphere of covered karst, the removal of a clay-sand cover leads to the migration of karst structures.

A covered karst

The karstic infiltration zone is bracketed between two thicknesses of 1 and 30 metres of overlying Cretaceous deposits. Without such cover, the diffuse infiltration does not allow organised karstic water flows. Over 30 metres, no infiltration appears possible since most of the drainage follows surficial pathways [Devos *et al.*, 1999]. This part of the Paris Basin gently dip westward and these two thicknesses limits define a roughly North-South area, about 20 kilometres wide [Jaillet and Gamez, 2000], of potentially very active karstic infiltration. Vertical incision of the Marne river and its tributaries locally eroded the Cretaceous sediments and ensured the outcropping of the underlying Tithonian limestones. The study of three karsts of the Barrois (Poissons, Cousance, Rupt-du-Puits) between the valleys of the Marne and the Saulx (fig. 8), can be used to propose a geomorphological model of karst migration associated with the incision of the hydrographic network and the retreat of the non-carbonate formations of the Cretaceous [Jaillet, 2001].

Three karsts studies

The Poissons karst is inactive and filled with iron ore coming from the weathered overlying Cretaceous sediments. It is perched at + 120 + 150 m above present-day base level. A 400 ky U/Th age obtained on a speleothem

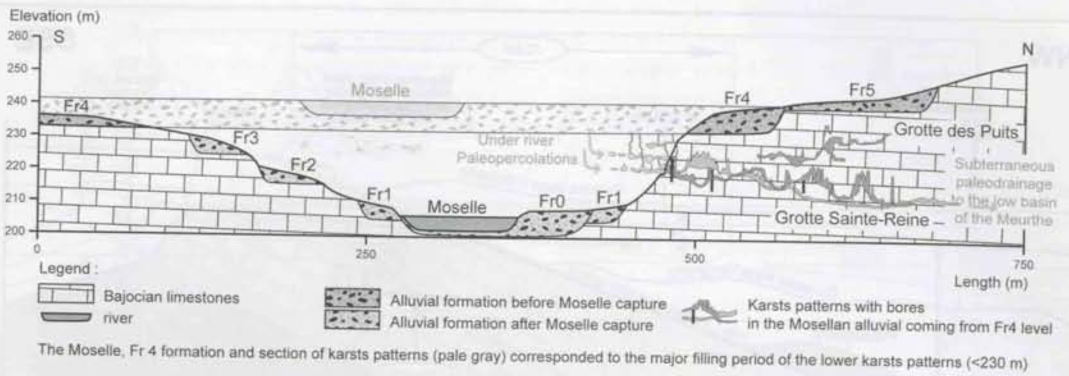


FIG. 13. – Synthetic cross-section of the Moselle valley at Pierre-le-Treiche. i) location and elevation of some cave systems and of the recent fluvial deposits of the Moselle. ii) representation of a period during which the karst system is active (filling during the build up of Fr 4).
FIG. 13. – *Coupe transversale synthétique de la vallée de la Moselle à Pierre-la-Treiche: (i) localisation altitudinale de quelques réseaux karstiques et des unités fluviatiles récentes de la Moselle ; (ii) représentation d'une période de fonctionnement karstique (comblement lors de la mise en place de Fr4).*

exceeds the limit of the dating method and suggests its genesis at least during the Middle Pleistocene (isotopic stage 7 and over) [Jaillet, 2000]. The karstic morphologies and associated endokarstic deposits testify, during its activity, the presence of early Cretaceous outcrops about 10 kilometres eastward from their present-day position. Towards the north, the Cousance karst system displays a first + 75 m horizontal phreatic drainage pattern subsequently bored by vertical shafts related to a +10/+15 m drainage level. Speleothems related to this second incision stage define at least an Eemian s.l. (+100 to +120 kyrs) activity (isotopic stage 5) [Jaillet *et al.*, 2004]. Last, the active Rupt-du-Puits karst system displays perched +15 m paleodrainage patterns compatible in relative height with the "Cousance" Eemian karstic evidence. As yet, U/Th dating on speleothems and ^{14}C dating on organic rich sediments did not allow to define ages older than isotopic stage 2 [Jaillet *et al.*, 2002].

Migration of karsts

This migration of karsts in the Barrois from south to north is demonstrated by the simultaneous karstic record of the base paleo-levels and the cover paleo-extensions (fig. 14). This could be recognized in these different karsts from the following elements: 1) the structure and elevation of the drainage channels and paleo drainage channels of the different karst systems; 2) the survey of the cover thickness needed for the genesis of these channels; 3) the amount of cover eroded for causing the limestone slab to outcrop; 4) the nature of the infill of these channels; 5) the hydrodynamic activity of these channels (active/inactive).

It would thus appear that the Poissons karst is older than the Cousance karst, itself older than that of the Rupt-du-Puits. The dating ranges [Pons-Branchu, 2001; Jaillet *et al.*, 2002] obtained on these three sites confirm this scheme and enable their geomorphological evolution to be gauged chronologically. Thus, the Poissons karst, a marker perched below the derived summit surface [Le Roux, 2000] constitutes the sign of a paleo-extension of the Cretaceous cover some ten kilometres eastwards, contemporary with a base paleo-level of the Marne between 300 and 330 m, that is, + 120 to + 150 m above the present flows (fig. 14). Farther north, the perched drainage channels of the Cousance karst mark a base level at about 240 m (i.e. + 75 m/present system) corresponding to a cover extension that has not been determined or dated, but which must be greater than its present extent. Finally, the Rupt-du-Puits karst is practically present-day (fig. 15). It originates under

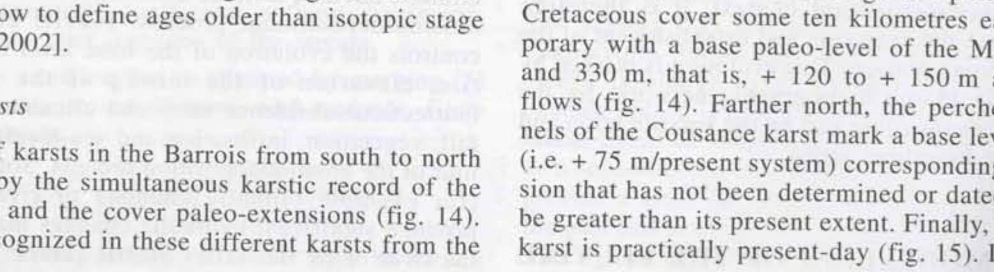


FIG. 14. – Cartography of the migration of the karsts of Poissons, Cousance and the Rupt-du-Puits. Three stages are linked to the incision of the hydrographic network and the retreat of the Cretaceous cover. The extension of the Cretaceous cover of stage 1 [Le Roux, 2000] holds account of a generalized ablation of around fifty meters. The extension of stage 2 is schematised between stage 1 and the current extension.
FIG. 14. – *Cartographie de la migration des karsts de Poissons, Cousance et du Rupt-du-Puits. Les trois stades sont reliés à l'incision du réseau hydrographique et au recul de la couverture crétacée. L'extension de la couverture crétacée au stade 1 [Le Roux, 2000] prend en compte une ablation générale d'environ 50 m. L'extension du stade 2 est schématisée entre le stade 1 et l'extension actuelle.*

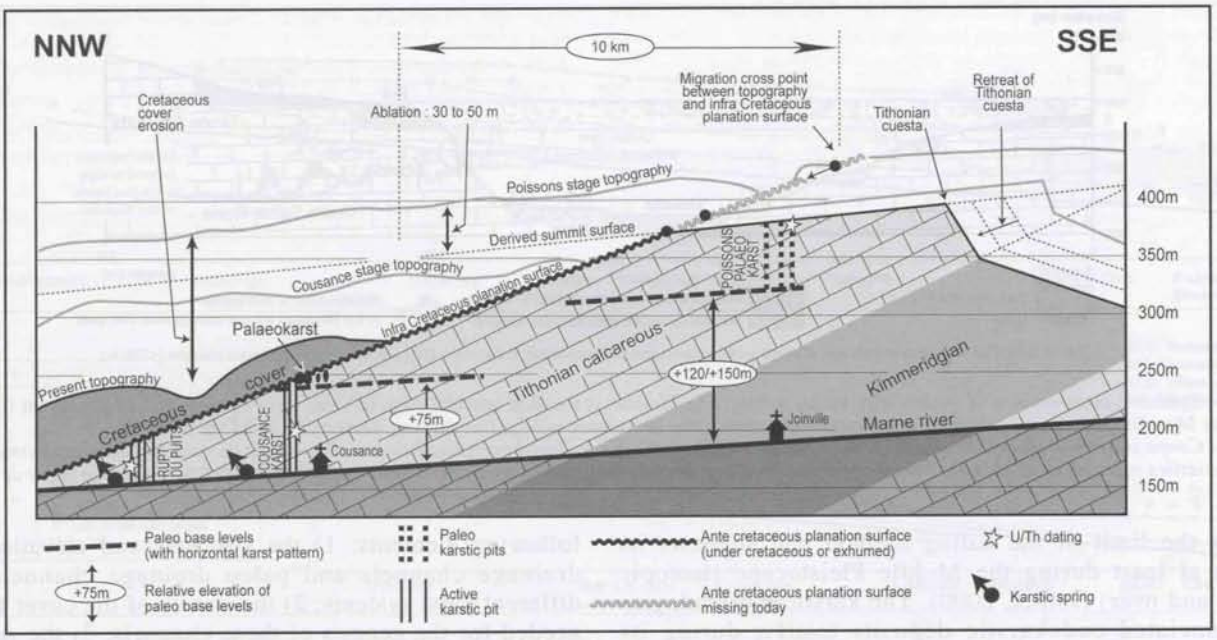


FIG. 15. – Schematic vertical profile along the Marne valley. The three studied karsts are setting in their morphostructural context. Note the contact between the infra-Cretaceous planation surface and various reconstituted topographic surfaces. Note also the position of the paleo base levels together with the position of the three karst systems.

FIG. 15. – Coupe verticale schématique le long de la vallée de la Marne. Les trois karsts étudiés sont replacés dans leur contexte structural. Noter la migration du contact entre la surface infra crétacée et les diverses reconstitutions des surfaces topographiques. Noter aussi la position des différents niveaux de base en fonction de la position des trois karsts étudiés.

the conditions of a present-day eastward extension of the cover of 7 km and a flow level close to the current one.

Through the karsts of the Barrois, their geographical position, their morphostructural context, it is therefore possible to mark out the evolution and establishment of the reliefs of the Tithonian plateau. This evolution is marked by the incision of the Marne hydrographic network, by the retreat of the Cretaceous cover and by the karstification and exhumation of the limestone series.

NUMERICAL MODELLING OF THE FLUVIAL EROSION

A long term fluvial erosion model for the Paris Basin

A simple model for the erosion/deposition processes along river profiles is presented. The model has been used to simulate the evolution of the rivers of the Paris Basin during the last million year. This period is characterized by climatic cycles during which the climate evolved from temperate conditions (interglacial stage) to periglacial conditions (glacial stage) [Imbrie *et al.*, 1992]. Such changes affected deeply the flow of the rivers that were multiplied by 6 to 10 during the glacial stages and also the sediment supply that increased in response to enhanced mechanical erosion during cold episodes [Rotnicki, 1991; Cojan, 1997; Mol *et al.*, 2000]. Such a cyclic change of the fluvial parameters has not been known over the Paris Basin during the tens of million years that preceded the Quaternary. It has had a consequent impact on the present morphology of the river valleys: the rivers are underfit streams that flow in valleys that were calibrated during cold periods by stronger flows [Dury, 1964, 1965].

The model that has been developed takes into account climatic but also tectonic conditions in the evaluation of the erosion/depositional process. Fluvial erosion/deposition controls the evolution of the base level of the topography (i.e. elevation of the talweg of the river). Tectonic (surrection/subsidence rate) and climatic conditions (rainfall, vegetation, infiltration and sea-level) drive the behaviour of the erosion/deposition process. Some isolated events (for example climatic changes or river captures) that produce significant hydraulic changes may be recorded on the river or on the valley profile [knick point – Colson *et al.*, 2000; terraces – Pissart *et al.*, 1997]. The physical model we use is based on the mass conservation law, as models developed by Begin [1981] and Bogaart and Van Baalen [2000]. It expresses the mass conservation at any given time for any point along the stream [z(x,t), x coordinate along the stream]. This equation enables, all along the stream, to consider the lateral flow of sediment, to deal with sediment deposition, slope breaks related to lithologic contrasts, tectonic influence or eustatic variations. The erosion/deposition process at a point (x, z) of the longitudinal profile is:

$$\frac{\partial z(x,t)}{\partial t} = \frac{-\partial q_{s(x,t)}}{\partial x} + B(x,t) \quad (1)$$

where q_s is the sediment discharge in the river per unit width (m^2/s), and B is the volume of lateral inflow of sediment per unit width and per unit length of channel (m/s).

The "transport-erosion-sedimentation law" assumes a proportionality of the sediment discharge to the slope of the channel and to the water discharge (qw):

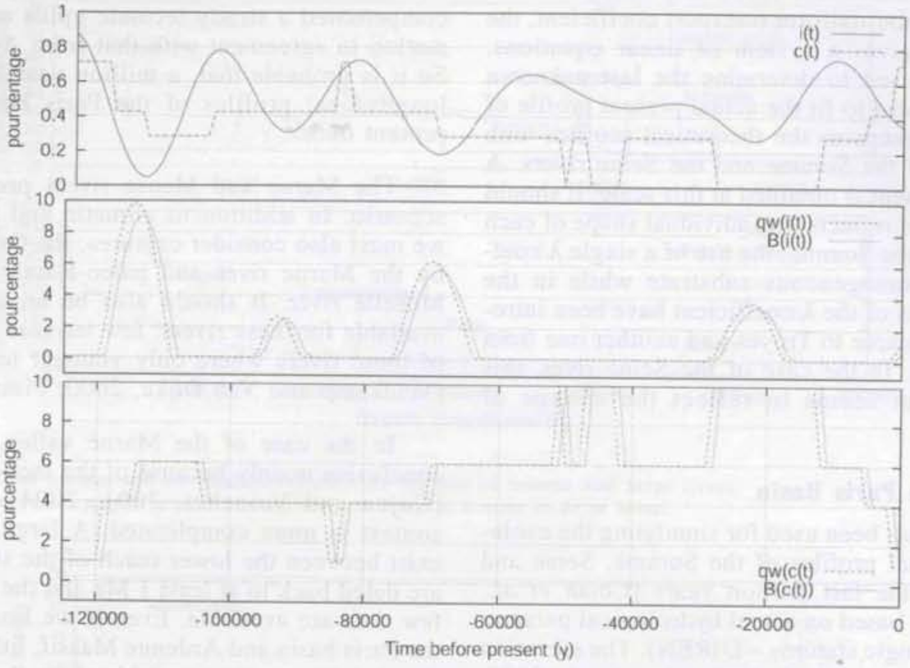


FIG. 16. – Climatic models used for simulations. The Milankovitch cycles and the BIOCLIM climatic signals, are normalised i(t), c(t) respectively and used for the calculus of qw(t) and B(t): the percentage of the maximal water discharge per unit width (m^2/s) in the river, and respectively the percentage of the maximum volume of lateral inflow of sediment per unit width and per unit length of channel (m/s).

FIG. 16. – Modèles climatiques utilisés pour les simulations. Les signaux tirés des cycles de Milankovitch ou de BIOCLIM sont normalisés [respectivement i(t), c(t)] et utilisés pour le calcul de qw(t) (pourcentage de la décharge maximum dans la rivière par unité de largeur) et B(t) (volume maximum d'apport latéral en sédiments par unité de largeur et de longueur du chenal (m/s).

$$qs(x,t) = -\lambda(x,t) * \left(qw\,(x,t) * \frac{\partial z(x,t)}{\partial x} \right) \qquad (2)$$

where λ is a "transport" coefficient without dimension, considered constant over stretches of the stream.

The diffusion equation that is obtained by merging (1) and (2) can be easily solved by numerical methods: finite elements in this study.

$$\frac{\partial z(x,t)}{\partial t} = \lambda(x,t)\frac{\partial}{\partial x}\left(qw\,(x,t) * \frac{\partial z(x,t)}{\partial x} \right) + B\,(x,t)$$

Value of the parameters (qw, B and λ) must be known at each point in time and space. For qw and B, we propose an interpolation/extrapolation model based on two main hypothesis:

1) these parameters can be split to obtain a spatial and a temporal component, which are independent:

$B(x,t) = B(x)*B(t)$ and $qw(x,t) = qw(x)*qw(t)$

2) the spatial models follow a power function [Cojan *et al.*, 2003]:

$B(x) = AB*x^{BB}$ and $qw(x) = Aqw*x^{Bqw}$

We can deduce from (1) and the first hypothesis that the condition of erosion is:

$\frac{\partial z(x,t)}{\partial t} < 0$ giving

$$\frac{\lambda}{B(x)} * \left(qw(x) * \frac{\partial^2 z}{\partial x^2} + \frac{\partial qw(x)}{\partial x} * \frac{\partial z}{\partial x} \right) + \frac{B(t)}{qw(t)} < 0 \qquad (3)$$

(we suppose that *B(x)* and *qw(t)* are strictly positive).

This equation shows that the term B(t)/qw(t) largely controls the erosion/deposition process: a low value is in favour of erosion, while a high value furthers deposition. The signals B(t) and qw(t) can be built by many ways: temperature fluctuations [Zagwijn, 1989; Fauquette *et al.*, 1999], insolation curve [Berger and Loutre, 1991], $\delta^{18}O$ oceanic record [Funnel, 1995]. We propose to use the insolation signal as Veldkamp and Van Dijke [2000] associated to a sophisticated model [BIOCLIM, 2002] (fig. 16). Both present a main advantage: they can cover long periods in the past and in the future as well [Berger and Loutre, 1991]. The figure 17 shows that the predicted erosion/deposition periods are in accordance with the observations for the last 120 k.y.

The first hypothesis enables also to use actual data (river flow and width, drainage basin surface) to fit the values of the parameters of the spatial model. A special emphasis is given to the expression of the lateral sediment supply that is determinant in the erosion/deposition process as shown by Bogaart and Van Baalen [2000]. At equilibrium (we suppose the river had enough time to reach a steady-state), the diffusion equation can be solved and it gives the equilibrium-longitudinal-profile equation:

$$z_e(x,t) = Z0\ (1 - (x/L)^{1-Bqw}) + (CC/\lambda)\ (x/L)^{1-Bqw}\ (1 - (x/L)^{BB+1}) \qquad (4)$$

where $CC = B(L,t)/qw(L,t) * L^2/(BB+1)(BB+2-Bqw)$

x=0 at the source, x=L at the mouth and Z0=elevation at the source.

The equation is given for the simplest case of an uniform and invariant "transport" coefficient, and for the following boundary conditions: z(0,t)=Z0, z(L,t)=0. In a more general case of non-uniform transport coefficient, the continuity condition gives a system of linear equations. Equation (4) can be used to determine the last unknown value: λ that is calculated to fit the actual present profile of the river. Figure 18 compares the theoretical profiles with the present profiles of the Somme and the Seine rivers. A relatively good agreement is obtained at this scale. It should be noted that the model reflects the individual shape of each profile. In the case of the Somme, the use of a single λ coefficient reflects the homogeneous substrate while in the Seine model two values of the λ coefficient have been introduced (one from the source to Troyes and another one from Troyes to the mouth). In the case of the Seine river, this change of coefficient seems to reflect the change of lithology.

Some results for the Paris Basin

The proposed model has been used for simulating the evolution of the longitudinal profiles of the Somme, Seine and Marne rivers during the last million years [Cojan *et al.*, 2003; Gargani, 2003], based on actual hydrological parameters (data from hydrologic stations – DIREN). The elevation and the age of the terraces [ref. *in* Antoine *et al.*, 2000; Antoine, 1994 for the Somme and *in* Lautridou *et al.*, 1999 for the Seine] have been considered to define the scenario and to determine the initial profile.

To reproduce the terraces distribution along the valley slope, a steady tectonic rise of 60 to 75 m/Ma had to be considered. The results show that through the last million years the longitudinal profiles of the Seine and the Somme rivers may be considered to have been at the equilibrium, and that the erosion at the beginning of a climatic cycle compensated a steady tectonic uplift of 60, 75 m/Ma, estimation in agreement with that from Antoine *et al.* [2000]. So it is probable that, a million year ago, the paleo-rivers longitudinal profiles of the Paris Basin looked like the present ones.

The Marne and Meuse rivers present more complex scenario. In addition to climatic and tectonic parameters, we must also consider captures: the Ornain and Saulx river by the Marne river and paleo-Haute Meuse river by the Moselle river. It should also be noted that less data are available for these rivers: few terraces in the upper reaches of these rivers where only younger terraces are preserved [Veldkamp and Van Dijke, 2000; Pissart *et al.*, 1997].

In the case of the Marne valley, the results are not conclusive mainly because of the lack of old terrace dating [Cojan and Voinchet, 2001, 2004]. The Meuse valley context is more complicated. A large contrast in the data exist between the lower reach of the stream where terraces are dated back to at least 1 Ma and the upper reaches where few data are available. Even if we limit the simulations to the Paris basin and Ardenne Massif, lithologies and tectonic components are very variable along the stream. A plausible scenario can be proposed from the terraces succession and their dating [Van Balen, 2000; Pissart *et al.*, 1997]. The PaleoMeuse longitudinal profile was at the equilibrium, but following the capture of the paleo-haute Meuse river by the Moselle river, the Meuse river lost a large part of its flow and therefore was no longer able to erode the tectonic uplift. Unfortunately, the simulation doesn't confirm the envisaged scenario in the upper reaches of the river.

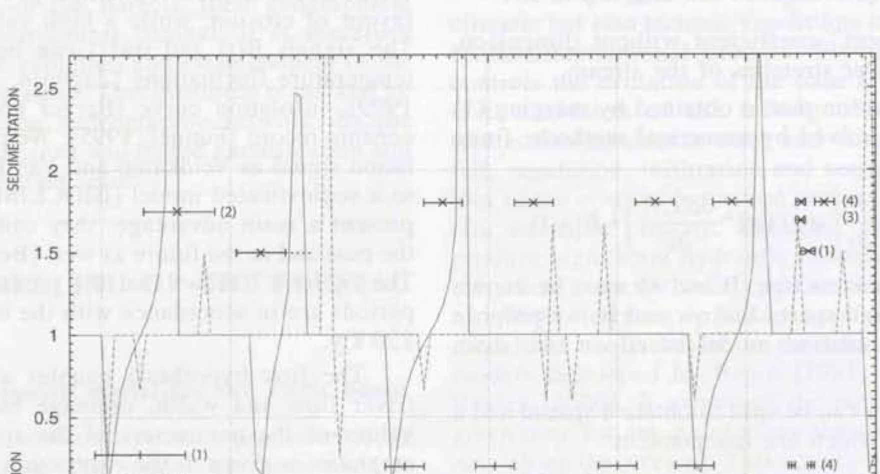


FIG. 17. – Predicted erosion/deposition periods are in accordance with the observations for the last 120 ky. The ratio $B(t)/qw(t)$ control the erosion/deposition process: a low value favors erosion, a high value furthers deposition. The resulted ratio obtained with the i(t) signal (M.F. Loutre, BIOCLIM) or with the c(t) signal (BIOCLIM, 2002) are both matching the observations [1 – Laurent *et al.*, 1994; 2 – Antoine *et al.*, 1994; 3 – Vandenberghe *et al.*, 1994, 4 – Van Huisden *et al.*, 2001].

FIG. 17. – *Les périodes d'érosion/dépôt prédites sont en accord avec les observations sur les derniers 120 ka. Le rapport B(t)/qw(t) contrôle le processus d'érosion/dépôt : une faible valeur favorise l'érosion alors qu'une forte valeur favorise le dépôt. Les rapports obtenus, que ce soit avec le signal i(t) [M.F. Loutre, BIOCLIM] ou c(t) [BIOCLIM, 2002], donnent des résultats en bon accord avec les observations.*

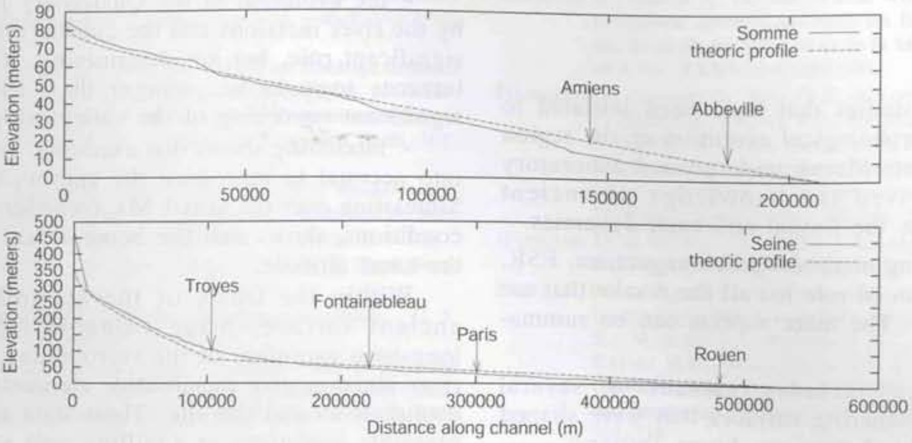


FIG. 18. – Comparison of the present and the modelled profiles for the bed of Somme and Seine rivers.
FIG. 18. – *Comparaison entre les profils actuels et modélisés du lit de la Somme et de la Seine.*

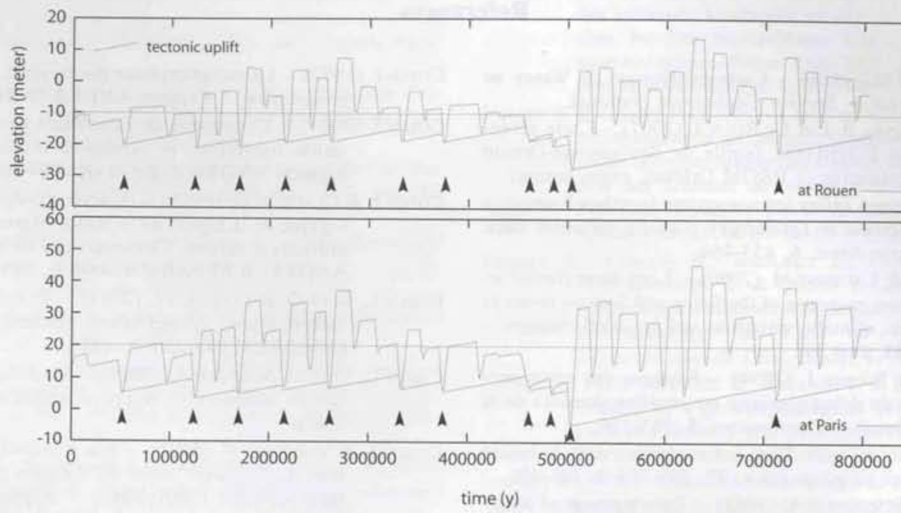


FIG. 19. – Predicted elevation for the Seine at Paris and at Rouen for the next 800 ka. Elevations are those of the theorical equilibrium profile (river bed) which is slightly different from the present one (at t = 2000 years, profile elevation in Paris 15 m, in Rouen –13 m, arrows indicate step-in-step terraces). This prediction is obtained with the insolation signal and takes into account a steady tectonic uplift (60 m/Ma) and eustatic fluctuations. The result seems to be realistic for the range of the variations. Elevation variations show that amplitude of deposit/erosion during the next 1 Ma would not bring major changes in the profile elevation, tectonic uplift being stable. Maximum incision would occur near 500 ka with a profile lower than the present equilibrium profile of nearly 15 m in Rouen and 20 m in Paris
FIG. 19. – *Simulation prédictive de l'altitude de la Seine à Paris et à Rouen pour les prochains 800 ka. Les altitudes correspondent à celles d'un profil théorique à l'équilibre (lit de la rivière) qui est légèrement différent du profil actuel à t = 2000 ans, l'altitude du profil est de 15 m à Paris et de –13 m à Rouen, les flèches indiquent les terrasses étagées. Cette simulation est obtenue à partir des fluctuations du signal d'insolation et en prenant en compte une charge tectonique régulière de 60 m/Ma. Ainsi que les variations eustatiques. Les résultats obtenus paraissent réalistes quant aux gammes d'amplitudes obtenues. Les variations d'altitude montrent que l'amplitude des dépôts/érosion au cours du prochain Million d'années n'apporterait pas de changements significatifs dans l'allure des profils, la composante tectonique restant stable. Le maximum d'incision se présenterait vers 500 ka avec un profil plus bas que le profil actuel de près de 15 m à Rouen et 20 m à Paris.*

The model is simple: the equations can be solved easily and its parameters can be determined from some actual data easily accessible. The model can be run to study the effect of the climate on the erosion/deposition capacity of streams at the scale of geological times and so constitutes a useful tool for predictive estimations. The results obtained are encouraging even if problems still occur in complex cases such as that of the Meuse river. A first run of simulation conducted on the Seine river for the next 800 000 years using the insolation data (M.F. Loutre /BIOCLIM, 2002) and the average tectonic rise of 60 m/Ma is presented on figure 19 for a profile at the equilibrium. This prediction takes into account the isostatic and eustatic fluctuations, shows the erosion/deposition stages and their amplitude evolution along time. Maximum incision would occur at 510,000 years and it amplitude would be in the order of some tens of meters around Paris. The result seems to be realistic for the range of the variations. The simulation shows no trend in the elevation of the equilibrium profile over 80 ka, indicating that the influence of the future climatic cycles would be similar to that of the past ones.

CONCLUSIONS

The multidisciplinary studies that have been initiated to characterize the geomorphological evolution of the region around the Meuse/Haute-Marne underground laboratory site have deeply revived the knowledge of ancient paleosurfaces as well as the fluvial and karst dynamics.

Fieldwork and dating methods (paleomagnetism, ESR, U/Th) have played a crucial role for all the results that are presented in this paper. The main aspects can be summarized as follow:

– the "top surface" includes remnants of several well-identified paleoweathering surfaces that were shaped at various periods: early Cretaceous, lower Tertiary;

– the evolution of the Quaternary landscape is driven by the river incisions and the cuestas retreat. Karst plays a significant role, but not determining. Remnants of fluvial terraces seem to be younger than 300 ka, indicating a significant reworking of the valleys slopes;

– modelling shows that a tectonic uplift has to be taken into account to reproduce the amplitude of the incisions. Simulation over the next 1 Ma, considering similar tectonic conditions, shows that the Seine would roughly remain at the same altitude.

Within the frame of the geoprospective analysis, ancient surfaces bring valuable information on the long-term evolution of the surrounding massifs, while the river incision give quantitative elements on the landscape evolution around the site. These data allowed to estimate plausible evolutions at a million year scale.

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