Paleoweathering and paleosurfaces from northern and eastern France to Belgium and Luxembourg:
geometry, dating and geodynamic implications

Florence QUESNEL (1)

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Paleoweathering and paleosurfaces

Following the Variscan orogeny, northern and eastern France, as well as Belgium and Luxembourg, were affected by four main episodes of emergence highlighted by paleoweathering. These episodes are marked by major discordances on the map scale (Fig. 1) and correspond to four phases of vertical deformation of the lithosphere: Permo-Triassic to Jurassic, Lower Cretaceous, Palaeogene and Neogene-Quaternary. The corresponding erosion surfaces may remain at equilibrium for periods of up to tens of millions of years (Thiry, 2000); as a result, these surfaces are characterized by their duration and not their age (Wyns, 1991 and 2002). They can also be overlain by transgressive deposits, and then eventually exhumed at a later date.

Methodology

The study comprises four aspects: i) analysis of the plane surfaces (benches) based on a Digital Elevation Model with a sufficiently fine step, between 50 and 250 m (presented with a step of 500 m on Fig. 2); ii) compilation and study of the paleoweathering, attributed to four main intervals of time: Permo-Triassic to Jurassic, Lower Cretaceous, Palaeogene, and Neogene to Quaternary; iii) a critical synthesis of data and geometrical modeling of the paleosurfaces using the GIS tool; iv) interpretation of isohypse maps of the paleosurfaces and reconstruction of the successive vertical deformations, constrained by lithospheric geodynamics on the Europe-wide scale.

Geomorphological analysis of benches

Once the Quaternary incision is cancelled out, the plateaus and knolls of the benches make up several large glacis (Fig. 2): i) North of the Ardenne, the benches of Brabant, Entre-Sambre-et-Meuse (ESEM), Condroz and Limbourg; ii) the extensive glacis of Artois and the Picardy plateau, located in continuity with the Caux glacis and plunging under the Tertiary in Flanders and Hainaut; it appears to correspond to the Palaeogene surface exhumed during the Neogene-Quaternary; iii) in the NE Paris Basin, a glacis can be traced from the Thiérache to Lorraine - then towards Burgundy - and is seen abutting against the relief of the Ardenne and the Hunsrück in the North and the Vosges in the East - as well as the Morvan in the South -; it descends with a gentle slope towards the Champagne Region in the SW - also towards the NW -; (iv) the glacis of the Ardenne summits, the Hautes Fagnes and the Vosges.

Contributions from the study of paleoweathering

In the studied area, **paleoweathering attributed to the Permian and Trias** is known over thicknesses of several tens of metres developed at the expense of granites under the Triassic cover in the Vosges and at the bottom of the Rhine Graben in Alsace. Argillaceous palaeosols with dolomitization and silicification are described within the Buntsandstein deposits of Lorraine, as well as in the Vosges, the Saar and the Sierck threshold (Durand, 1978; Courel *et al*., 1980; Meyer, 1987; Muller, 1987; Bock *et al*., 2001). In Luxembourg and eastern Belgium, the Ardenne basement is also weathered beneath deposits attributed to the Upper Permian or Triassic (Renier, 1902; Autun, 1954; Boulvain *et al*., 2000; Yans, 2002a). We may also note the existence of Permo-Liassic paleokarsts on Devonian limestones in Belgium (Baele, 1998 and 1999), while Hettangian fillings are observed in Palaeozoic limestones of the Boulonnais and the southern edge of the Ardenne (Voisin, 1974).

Note: This summary provides an overview of the work being carried out by several teams in France, Belgium and Luxembourg within the framework of the following projects: **Sedimor** (ANDRA-BRGM Partnership), "**Déformations lithosphériques cénozoïques de l'Europe de l'Ouest**" (INSU IT), "**Reliefs de la France**" and "**Carte géologique de la France**" (BRGM). It is a preliminary version of a longer article to appear in 2003 in Géologie de la France (see Quesnel *et al*., unpubl. cited in the references).

(1) BRGM, CDG/MA, 3, avenue Claude-Guillemin, BP 6009, 45060 Orléans Cedex 2, France. f.quesnel@brgm.fr

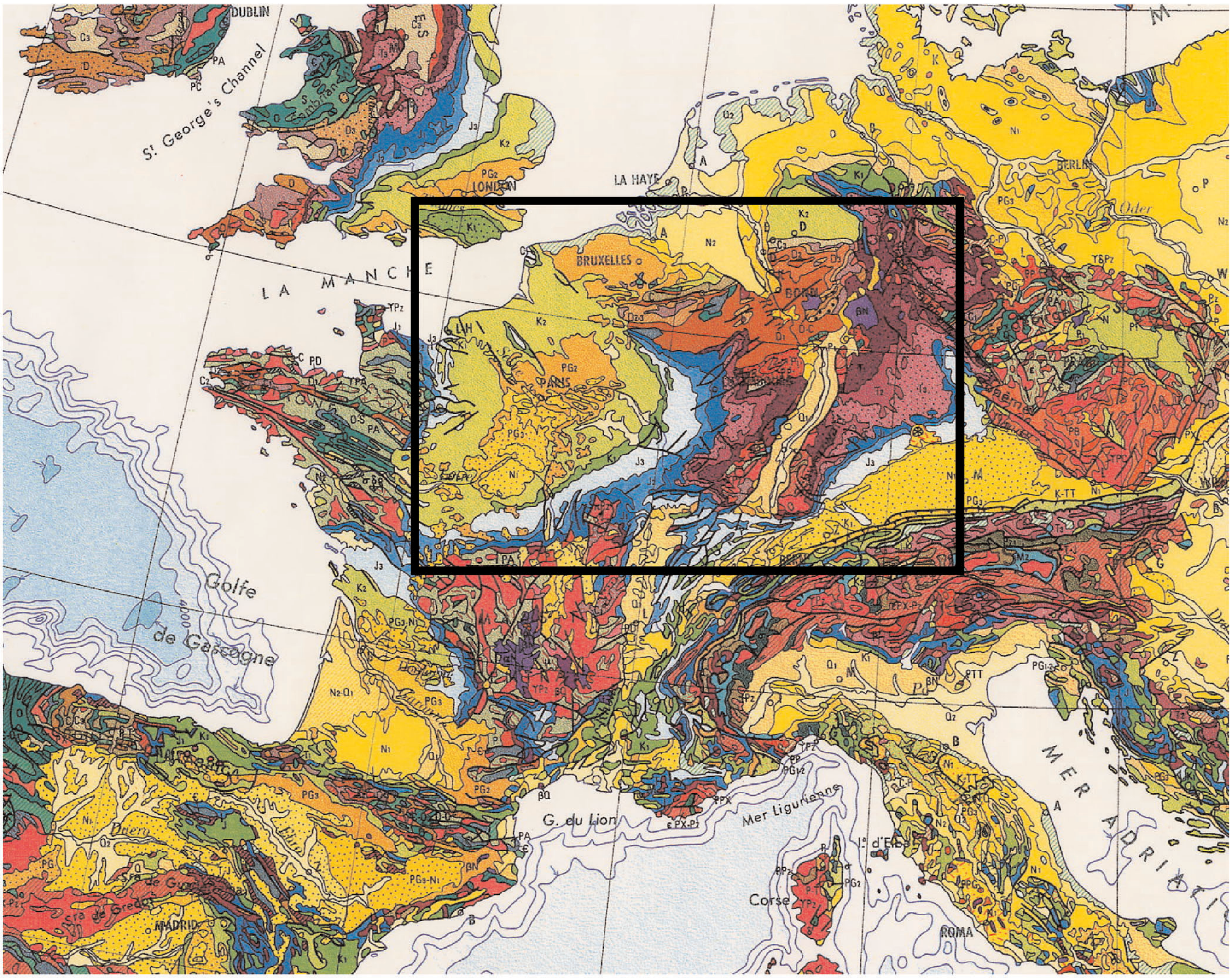

Fig. 1.- Geological map of Europe (© CCGM UNESCO).

From the end of the Jurassic, a strongly regressive regime is established in the North of France (much earlier in Brabant and the Ardenne), with episodes of continentalization varying in duration from one point to another across the basin according to the advance of the Cretaceous Tethys onto the paleotopography.

During the Early Cretaceous, a fluviatile to deltaic complex (Wealden facies) develops from England towards the regions of Bray, Boulonnais and the Mons Basin, extending as far as the Champagne and the Orléans area. The zone to the north and east of the Wealden trough (Upper Lorraine, the Ardenne and Brabant) is subject to weathering along a paleosurface that has been very little studied as a whole up to the present work. In France, close to Luxembourg, a ferricrete known as the "Borne de fer" is dated at 120-130 Ma by paleomagnetism (Théveniaut *et al*., 2002). This horizon caps a well-developed weathering profile and represents a residual infra-Cretaceous relief above the major Lorraine glacis. To the west and north of the "Borne de fer", this surface is marked by ocreous profiles and pockets of "fer fort" (strong iron, also called "Siderolithique" in French, which is equivalent to the German "Bohnerz"), as well as silicification of the Jurassic substratum, sometimes mingled with the Wealden sands and sealed by glauconitic Albian sediments (Voisin, 1978, 1994; Casanova *et al*., 2002; Quesnel *et al*., 2002). Lateritic weathering profiles, studied in boreholes in the Aube, are also sealed by the Aptian transgression (Ferry *et al*., 2001). Towards the South, as far as Saint-Dizier and Joinville, a strongly karstified surface concentrates ferruginized materials attributable to the Lower Cretaceous (Casanova *et al.*, 2001). In the Boulonnais, the Wealden continental facies are overlain by marine Aptian. In the Bray, iron-bearing epigenetic replacements due to meteoric water are interstratified in Wealden sands and are sealed by marine Albian.

On either side of the Franco-Belgian border, occurrences of Wealden have been known for a long time (Gosselet, 1888) as pockets in dolines affecting Jurassic limestones and in "crans" (giant cryptokarsts) of the Palaeozoic formations. The famous *Iguanodon*-bearing bed in the Coal Measures of Bernissart (Mons Basin) has made it possible to reconstruct the Wealden paleoenvironments (Casier, 1960). Regional studies as well as boreholes are currently in progress to specify their geometry and stratigraphy (Yans *et al.*, 2002b). The kaolin deposits that mark out the Ardenne plateau, related to the well-developed weathering profiles as observed on the Transinne plateau, could also be Early Cretaceous. However, some authors envisage even younger ages (Voisin, 1995; Dupuis *et al.*, 1996; Yans *et al.*, 2002a). The Brabant basement is also affected by thick weathering profiles in Flanders, where boreholes studies show rubefaction and kaolinization over thicknesses of 50 to 80 m, sealed by a few 10s of metres up to 600 m of Cretaceous and Tertiary marine deposits (Mees and Stoops, 1999). Vergari (1997 and 1998) studied a spectacular type of weathering (the "ghost rocks" or pseudo-endokarst) developed at the expense of Palaeozoic limestones on the northern edge of the Namur synclinorium, attributing this intense weathering to a drowned regime during the Albo-Aptian. Finally, Dupuis and Vandycke (1989) evoke a very extensive dissolution of the Visean anhydrites known at depth under the present-day Mons Basin, favoured by the uplift of Brabant at the end of the Jurassic and the beginning of the Cretaceous.

The **Cretaceous transgression** then takes place diachronously onto a discordance ranging from the Aptian in Lower Normandy and the Aube, to the Middle Albian in the Mons Basin up to the Campano-Maastrichtian in the Hautes Fagnes, now at an elevation of 650-700 m above sea level (Bless *et al.*, 1991). Moreover, the studies carried out by Quesnel *et al*. (1996 and 2000) on the Clay-with-flints showed that Chalk was present until the end-Maastrichtian in the western Paris Basin. It is probable that this occurred in the same way in the NE Paris Basin, since Maastrichtian Foraminifera are reworked in the lowermost Tertiary deposits of Champagne (Blanc and Guillevin, 1974). Thus, during the end-Cretaceous, the Chalk Sea probably covered all the basins of NW Europe along with most of the Ardenne Massif (Colbeaux *et al.*, 1977). However, the deposition of this Chalk was locally (and sometimes largely) masked by later weathering and erosion (Quesnel, 1997). Several eustatic falls are recorded in the Upper Cretaceous deposits of NW European basins, in particular at the Turonian-Coniacian boundary. This latter is expressed as small karstic features and a massive silicification in the Silicite of the northern part of the Mons Basin (Baele, 1999 and 2003). Le Roux (2000) accepts that the Cretaceous transgression is generalized over the NE Paris Basin, evoking a rapid retreat of the sea at the end of the Cretaceous and the development of river systems during the shaping of the continental surface. These rivers ran towards coastal areas that remained located within the Ile-de-France, Belgium and Germany respectively in Tertiary times. Although Le Roux (2000) described the river system as generally maintaining the same pattern in this part of NE France - with gradual incision of the substratum - other processes appear to have existed on the post-Cretaceous continental surface: paleoweathering is also developed. A study of the its remnants enables us to reconstruct the **Palaeogene paleosurface**.

In the North of France (Barrois, 1879; Gosselet, 1891) and in Limbourg (Albers and Felder, 1981), as well as in Normandy (Quesnel, 1997) and England (Isaac, 1981, 1983; Curry, 1986), **end-Cretaceous emergence** led to the development of paleo-profiles of Clay-with-flints, which were mostly subsequently eroded and reworked at the base of the Palaeocene, Eocene and Oligocene transgressions as beach ridges of green-coated flint and flint-bearing conglomerates (Landenian, Tongrian and Rupelian). In the Palaeogene, other major weathering profiles were developed at the expense of the Jurassic, Triassic and basement terrains. While some remnants of these profiles are preserved, for example in Upper-Lorraine on the main glacis below the Borne de fer, the majority of the profiles are truncated or completely eroded. It is thus necessary to identify other markers of the Palaeogene surface, i.e.:

- "Landenian" sands of the Rocroi plateau (Voisin, 1996) dated as Sparnacian at Régniowez (Quesnel *et al*, 2002);

- quartzitic silcretes (Pays de Caux sandstones and Landenian sandstones), cropping out from Normandy to Belgium and whose Sparnacian age is demonstrated at Varengeville (Dupuis and Steurbaut, 1987; Dupuis *et al*., 1997 and 1998);

- the "Pierres de Stonne" (Barrois, 1879; Tricart, 1949; Voisin, 1981 and 1988) cropping out on the benches of Ardennian Thiérache and northern Argonne, as well as in Upper Lorraine, Gaume and Luxembourg (Baeckeroot,1929; Lucius, 1945; Désiré-Marchand, 1984), in Limbourg and at the German-Dutch border to the South of Roer (Van den Broek & Van der Waals, 1967), these latter being possible equivalents of the "Braunkohlenquartzit" in Germany. The "Pierres de Stonne" exhibit all the characteristics of pedogenic silcretes (cutans and siliceous caps on intraformational gravels) described by Thiry (1981 and 1999) from the Eocene of the Paris Basin.

All these different deposits are used as markers to reconstruct the geometry of the Palaeogene surface (Quesnel *et al*., 2002). These very well developed silicifications should not be confused with the "Meulières" (Millstones) (Ménillet, 1993), nor the poorly developed

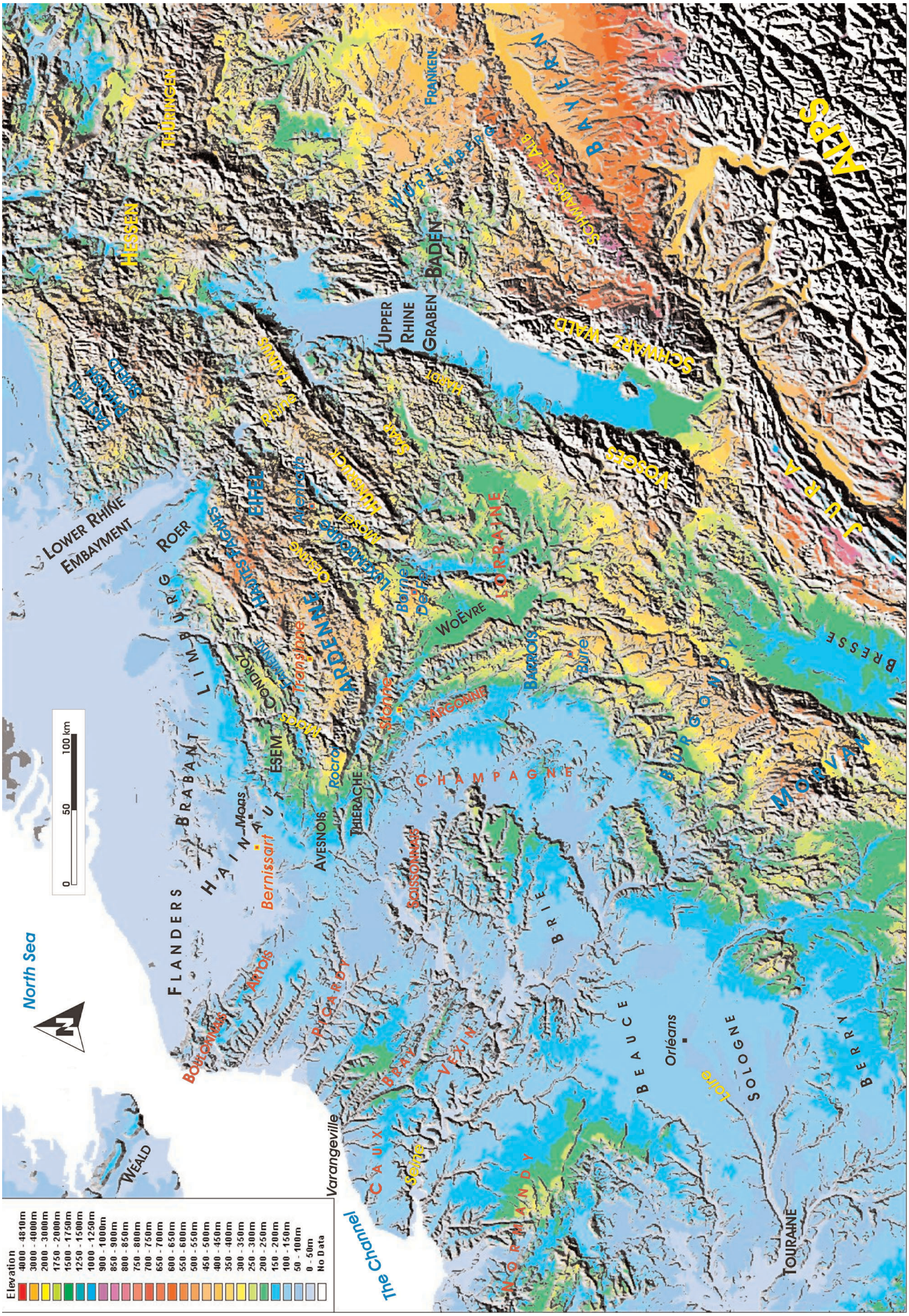

Fig. 2.- Elevation of benches (European DEM with a step of 500 m) with the names of natural regions and some localities mentionned in the text.

Plio-Quaternary silicifications affecting the Miocene lignitic sands of the Lower Rhine Embayment (Demoulin, 1990).

The youngest weathering profiles are for the most part rather thin, comprising:

- in Lorraine, brown leached soils ("Sol brun lessivé") of **end-Pliocene to Quaternary** age and less than 3 m thick (oxidation sometimes penetrating down to 30 m depth), developed on Jurassic and Triassic limestones and marls;

- end-Pliocene to Quaternary Millstones Clay ("Argile à Meulières") developed on Tertiary limestones in Brie, Beauce and Champagne (Ménillet, 1993);

- Clay-with-flints extending from Normandy to Belgium, which has been studied by many authors (Bonte, 1954 and 1967; Matthieu, 1975, Albers and Felder, 1981; Juvigné and Renard, 1991; Laignel, 1997; Quesnel, 1997; Quesnel *et al*., 2000 and 2003).

In the southern Pays de Caux, this latter regolith is younger than the deposition of the Lozère sands, so it must be of **late Pliocene to Quaternary age** (Cavelier & Kuntz, 1974; Tourenq *et al*., 1991). North of the Pays de Caux, in Belgium and England, the currently observed Clay-with-flints is developed after the stripping away of Sparnacian clays, so its age is **end-Pliocene to Quaternary** (Bonte, 1954; Catt, 1986; Quesnel, 1997). The weathering profiles here are not (mineralogically) very evolved, while the roof of the Chalk is very irregular with many karstic pockets that are often deep. They are also considerably enriched in external constituents (30 to 35%) derived from Palaeogene and Pliocene sands and clays and Quaternary loess and alluvium (Laignel, 1997). This Clay-with-flints marks out the exhumed Palaeogene continental paleosurface. Finally, we can find Clay-with-flints that was developed both after the deposition and beneath the permeable cover of the **Pleistocene** alluvium of the Seine and Maas river (Lefebvre, 1984; Quesnel, 1997; Quesnel *et al*., 2000, 2003; Juvigné and Renard, 1991). Farther north, in eastern France and in Belgium, the exhumed Palaeogene surface picked out by the Pierres de Stonne, the Pays de Caux sandstones and the Landenian sandstones (quartzitic silcretes) merge with the Plio-Quaternary surface on the plateaus, where it continues to evolve by incision and karstification (Le Roux and Harmand, 1998; Jaillet, 2000).

Furthermore, in Belgium, **extensive Miocene crypto-karsts** with halloysite are developed in the Dinantian and Devonian limestones of ESEM and Condroz (Calembert, 1945; Ertus, 1990; Dupuis, 1992; Nicaise, 1998). No equivalents of these structures are known in NE France, where some Quaternary karsts have been studied only in Jurassic limestones, particularly by means of tracers and speleological explorations (Gamez, 1995; Jaillet, 2000). In Belgium, Pleistocene karsts are also present in Palaeozoic limestones, for example at Han and Rochefort (Quinif and Vandycke, 2000). The dating of speleothems and stalagmitic floors makes it possible to study their history in detail and characterize the tectonic activity (recording and dating of earthquakes by the growth of later speleothems).

Correlations between paleosurfaces and paleoweathering

Each topographic bench identified on the Digital Elevation Model can be assigned to one or another paleosurface by the analysis and interpretation of weathering features and their associated residual deposits (Wyns, 1991). Thus, benches containing markers such as the Pierres de Stonne, as well as the Landenian sands, sandstones and conglomerates, are assigned to the Palaeogene paleosurface. Otherwise, those benches prolonging the contact of the Cretaceous over the Jurassic or the basement – as well as benches with dated occurrences of iron or containing Wealden deposits and/or karsts – are assigned to the infra-Cretaceous paleosurface (Quesnel *et al*., 2002). The compilation of a GIS-structured database (ArcView software, © ESRI) and the digital cartographic synthesis of the data make it possible to reconstruct the present-day hypsometric contours of the infra-Cretaceous and Palaeogene continental paleosurfaces. The corresponding maps can be compared with the structural maps of the basins of Paris, Belgium and Holland. Most of the lineaments that displace the plateaus and segments of the paleosurfaces correspond to faults also offsetting the formations of the Mesozoic substrate or basement. These features are attributable to the different tectonic events affecting the NW European lithosphere since the end of the Variscan orogeny. We can also observe scarp slopes and cuestas that are long established and little deformed up to the present day.

Geodynamic implications

The period of **infra-Cretaceous** emergence is not isolated in the European geodynamic context, but corresponds to the inception of a system of rifts in the North Sea, Holland and Germany-Poland, as well as the opening of the Bay of Biscay (Ziegler, 1988 and 1990). This occurs in parallel with the development of a rift (subsequently failed) that led to the uplift of Brabant, the Ardenne and northern France (Quesnel *et al.*, 2002). Values of paleo-uplift (Fig. 3) are derived from the paleokarsts records, and are compared with Apatite Fission Tracks data (Vercoutere & Van den Haute, 1993).

In the absence of any preserved **Palaeogene** regoliths, the Pierres de Stonne, silcretes and Sparnacian sands can be taken even more to indicate the paleoweathering that accompanied vertical updoming with a large radius of curvature. Along with these markers, we may also consider the fluvial deposits

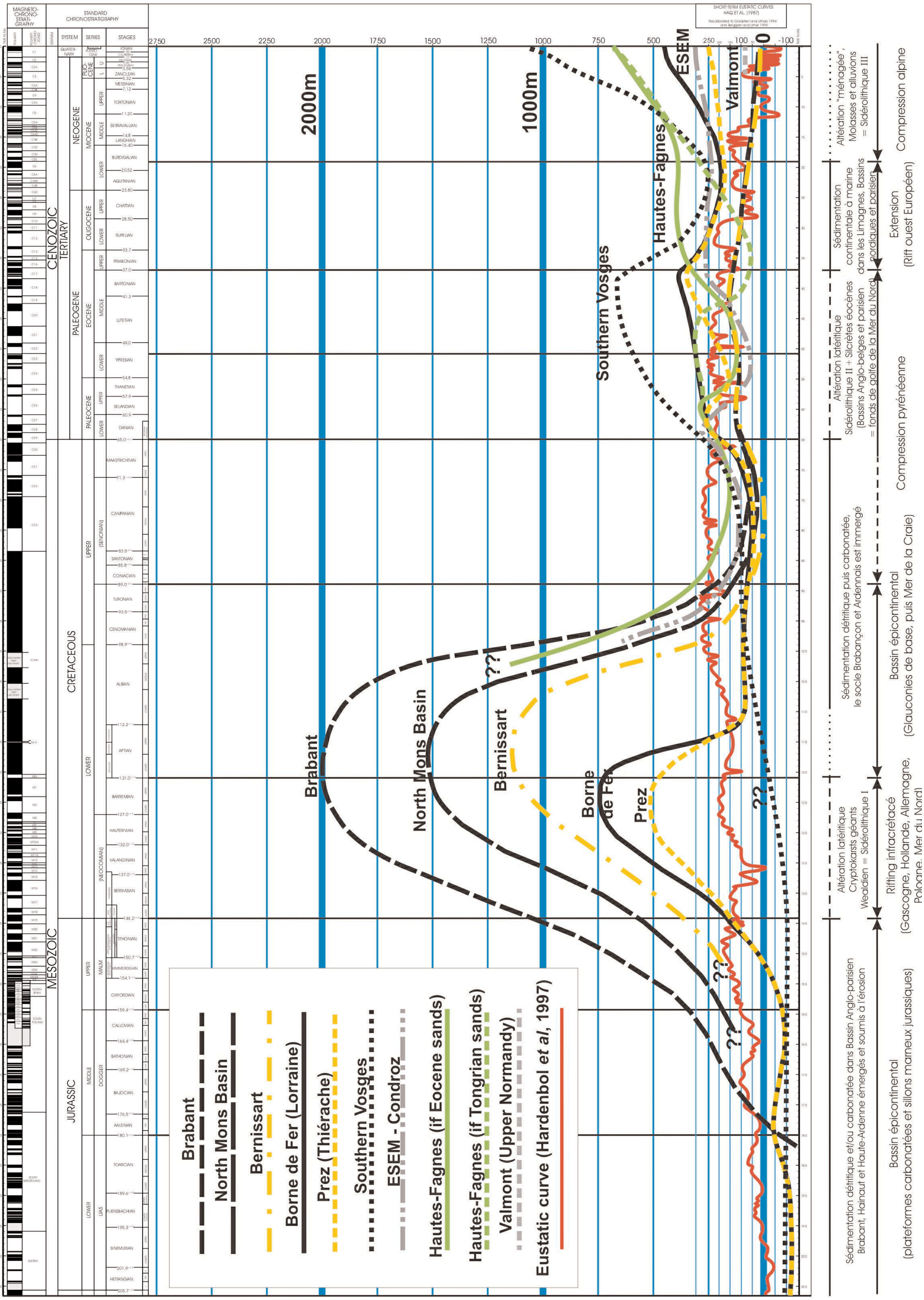

Fig. 3.- Evolution of paleotopographies since the Jurassic (Quesnel et al., unpubl.) compared with paleo-sealevels derived from the eustatic curve of Hardenbol et al. (1997).

developed in the Eifel region (paleo-Saar and Mosel: Löhnertz, 1978 and 1994) and the Rhine Graben (conglomeratic cones: Duringer, 1998 and 1999). In the context of the compression of Africa and Eurasia (Bergerat, 1987; Ziegler, 1988 and 1990), and the buckling of the NW European lithosphere (Wyns, 1991 and 1999; Michon, 2001), the general spread of silcretes over the continental paleosurface during the Eocene can be explained by the onset of tectonic inversion. The formation of silcretes follows the development of major weathering profiles in the Palaeogene and precedes the deposition of continental carbonates (Wyns, 2002). Some authors also invoke the role of Palaeocene uplift related to the initiation of volcanic activity on the North Atlantic mid-ocean ridge, followed by a phase of rapid subsidence (Nadin & Kusmir, 1995; Dupuis *et al*., 1998).

For the **Neogene to Quaternary** interval, the observed regoliths (cryptokarsts of ESEM and Condroz, leached brown soils and Clay-with-flints on the plateau as well as below the Pleistocene terraces) and stepping of benches can be explained at the same time by eustatic variations and the uprise of certain sectors possibly related to mantle diapirism and volcanic activity on the Rhenish Shield (Fuchs *et al*., 1983; Ritter *et al*., 2001; Rorhman *et al*., 2002). Lastly, it is appropriate to invoke the reactivation of Variscan faults (Gosselet, 1908; Bouroz, 1956; Vandycke, 1992 and 2002; Colbeaux *et al*., 1993; Rollin, 2000; Mansy and Lacquement, 2002) which could account for differential uplift in the cover of certain tectonic blocks. Such effects may be linked to different stress fields during the Pyrenean-Alpine orogeny. We still need to elucidate the inter-relations and respective roles of the mechanisms leading to these vertical movements, and to quantify their amplitude through geological time as well as their effects on paleo-circulation in hydrogeological systems.

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