

Continental France and Belgium during the early Cretaceous: paleoweatherings and paleolandforms

Médard Thiry, Florence Quesnel, Johan Yans, Robert Wyns, Anne Vergari, Hervé Theveniaut, Régine Simon-Coinçon, Caroline Ricordel, Marie-Gabrielle Moreau, Denis Giot, et al.

▶ **To cite this version:**

Médard Thiry, Florence Quesnel, Johan Yans, Robert Wyns, Anne Vergari, et al.. Continental France and Belgium during the early Cretaceous: paleoweatherings and paleolandforms. Bulletin de la Société Géologique de France, 2006, 177 (3), pp.155-175. 10.2113/gssgfbull.177.3.155 . hal-03753668

HAL Id: hal-03753668
https://brgm.hal.science/hal-03753668

Submitted on 18 Aug 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Bull. Soc. géol. Fr., 2006, t. 177, n° 3, pp. 155-175

Séance spécialisée :
Paléogéographie : cinq lustres d'avancées
Paris, 8-9 mars 2004

Continental France and Belgium during the early Cretaceous: paleoweatherings and paleolandforms

MÉDARD THIRY[1], FLORENCE QUESNEL[2], JOHAN YANS[3], ROBERT WYNS[2], ANNE VERGARI[4], HERVÉ THEVENIAUT[2], RÉGINE SIMON-COINÇON[1], CAROLINE RICORDEL[1], MARIE-GABRIELLE MOREAU[5], DENIS GIOT[2], CHRISTIAN DUPUIS[3], LAURENT BRUXELLES[6], JOCELYN BARBARAND[7] and JEAN-MARC BAELE[3]

Key words. – Paleoweathering, Paleokarst, Paleolandform, Paleogeography, Lower Cretaceous, France, Belgium,

Abstract. – During the early Cretaceous, successive tectonic phases and several sea level falls resulted in the emersion of the main part of western Europe and the development of thick "lateritic" weathering. This long period of continental evolution ended with the Upper Cretaceous transgressions. During this period, the exposed lands displayed a mosaic of diverse morphologies and weathered landscapes.

Bauxites are the most spectacular paleoweathering features, known for long in southern France. Recently, new residual outcrops have been identified, trapped in the karstic depressions of the Grands Causses. Other bauxitic formations, containing gibbsite, have also been recognised, occurring with the Clay-with-Jurassic-cherts in the southeastern border of the Paris Basin. These bauxitic formations overlay Jurassic limestone and are buried beneath Upper Cretaceous marine deposits. The recognition of bauxites up north into the southern Paris Basin significantly widens the extension of the Lower Cretaceous bauxitic paleolandscapes.

On the **Hercynian basements** thick kaolinitic weathering mantles occur. They have been classically ascribed to the Tertiary. The first datings of these *in situ* paleosoils, by means of paleomagnetism and/or radiogenic isotopes, record especially early Cretaceous ages. This is the case for the "Siderolithic" formations on the edges of the French Massif Central, but also for the kaolinitic profiles in the Belgian Ardennes. In the Flanders, the Brabant basement is deeply kaolinised beneath the Upper Cretaceous cover. These paleosoils show polygenetic evolutions. The relief of these basement paleolandscapes may have been significant. There where probably high scarps (often of tectonic origin) reaching 200 m in elevation or beyond, as well as wide surfaces with inselbergs, as in the present day landscapes of tropical Africa and South America.

On the **Jurassic limestone platforms** occur diverse kaolinitic and ferruginous weathering products. Around the Paris Basin they show various facies, ranging from kaolinitic saprolites to ferricretes. Due to the lack of sedimentary cover, the age of these ferruginous and kaolinitic weathering products has been debated for long, most often allocated to the Siderolithic *sensu lato* (Eocene-Oligocene). Recent datings by paleomagnetism have enabled to date them (Borne de Fer in eastern Paris Basin) back also to the early Cretaceous (130 ± 10 Ma). These wide limestone plateaus show karstified paleolandforms, such as vast closed and flat depressions broken by conical buttes, but also deep sinkholes in the higher areas of the plateaus and piedmonts. The depth of the karst hollows may be indicative of the range of relative paleoelevations. Dissolution holes display seldom contemporaneous karst fillings, thus implying that the karstland had not a thick weathering cover or that this cover had been stripped off before or by the late Cretaceous transgression. Nevertheless, some areas, especially above chert-bearing Jurassic limestone or marl, show weathering products trapped in the karst features or as a thick weathering mantle.

In the **Paris Basin**, the Wealden gutter looked like a wide floodplain in which fluvio-deltaic sands and clays were deposited and on which paleosoils developed during times of non-deposition. The edges of the gutter were shaped as piedmonts linked up with the upstream basement areas. The rivers flowing down to the plain deposited lobes of coarse fluvial sands and conglomerates. The intensity of the weathering, the thickness of the profiles and their maturation are directly dependent on the duration of the emersion and the topographic location relative to the gutter. Near the axis of the gutter, where emersion was of limited duration, the paleoweathering features are restricted to rubefaction and argillization of the Lower Cretaceous marine formations. On the other hand, on the borders of the basin and on the Hercynian basement, where emersion was of longer duration, the weathering profiles are thicker and more intensively developed.

The **inventory** of the Lower Cretaceous paleoweathering features shows the complexity of the continental history of this period. Moreover, the preserved weathering products are only a part of this long lasting period, all the aspects relative to erosion phases are still more difficult to prove and to quantify. In this domain, apatite fission tracks thermochronology (AFTT) can be helpful to estimate the order of magnitude of denudation. Residual testimonies and subsequent transgressions may enable to estimate relative elevations, but in return, we presently have no reliable tool to estimate absolute paleoelevations. In the work presented here, the inventory enabled to draw a continental

1. Ecole des Mines de Paris, 35 rue St Honoré, F-77305 Fontainebleau, France, et CNRS-UMR 7619 Sisyphe "Structure et fonctionnement des systèmes hydriques continentaux". medard.thiry@ensmp.fr
2. BRGM, CDG, BP 6009, F-45060 Orléans cedex 2, France
3. Faculté Polytechnique, Service de Géologie fondamentale et appliquée, rue de Houdain 9, B-7000 Mons, Belgique
4. Laboratoire Central de Gralex, 35 rue du faubourg, B-1430 Quenast (Rebecq), Belgique
5. IPGP Laboratoire de Paléomagnétisme et de Géomagnétisme, 4 Place Jussieu, F-75252 Paris cedex 05, France
6. Institut National de Recherches Archéologiques Préventives, ZA les Champs Pinsons, 13 rue du Négoce, 31650 St-Orens-de-Gammeville
7. Département des Sciences de la Terre, Université Paris Sud, F-91405 Orsay cedex, France
Manuscrit déposé le10 novembre 2004; accepté après révision le 4 novembre 2005.

Downloaded from http://pubs.geoscienceworld.org/sgf/bsgf/article-pdf/177/3/155/2966832/155.pdf
by BRGM user

paleogeographic map showing the nature of the weathering mantles and the paleolandscape features, just as paleoenvironments and paleobathymetry presently appear on marine paleogeographic maps. For the future, the challenge is to make progress in dating the paleoweathering profiles and especially in the resolution of these datings, in order to correlate precisely the continental records with the different events which trigger them (eustatism, climate, regional and global geodynamics). The final goal will be to build up a stratigraphic scale of the "continental geodynamic and climatic events" in parallel with "sequential stratigraphy" in the marine realm.

La France et la Belgique continentales au Crétacé inférieur : paléoaltérations et paléotopographies

Mots-clés. – Paléoaltération, Paléokarst, Paléopaysage, Paléogéographie, Crétacé inférieur, France, Belgique,

Résumé. – Au Crétacé inférieur des mouvements tectoniques successifs et plusieurs chutes du niveau eustatique ont amené l'émersion d'une grande partie de l'Europe du NW et le développement de puissantes altérations « latéritiques ». Durant cette période, les terres émergées offraient une mosaïque de paysages différenciés dans leurs morphologies et leurs altérations.

Les **bauxites** sont les paléoaltérations les plus spectaculaires, reconnues de longue date dans le Sud de la France. Récemment, de nouveaux affleurements ont été identifiés piégés dans les dépressions karstiques des Grands Causses et des argiles à chailles contenant de la gibbsite ont été reconnues sur la bordure sud-est du bassin de Paris. La reconnaissance de bauxites jusque dans le Sud du bassin de Paris élargit considérablement l'étendue des paléopaysages bauxitisés.

Sur les **massifs anciens** existaient d'épais manteaux d'altérites à kaolinite dont les premières datations par paléomagnétisme et/ou par radio-isotopes enregistrent notamment des âges du Crétacé inférieur. C'est le cas des formations sidérolithiques en bordure des grabens du Massif central français et du profil kaolinique de Transinne en Ardenne belge. En Flandres, le socle du Brabant est fortement kaolinisé sous la couverture du Crétacé supérieur. Ces paléosols montrent des évolutions polyphasées. L'amplitude des paléopaysages du socle pouvait être importante. Il existait probablement de grands escarpements (souvent d'origine tectonique) pouvant atteindre ou dépasser 200 m, ainsi que de vastes surfaces à inselbergs.

Sur les **plates-formes calcaires jurassiques** les altérites présentent des faciès variés avec saprolites kaoliniques, formations rubéfiées, argiles à pisolithes et cuirasses ferrugineuses. Dans le bassin de Paris, des datations récentes par paléomagnétisme ont permis de préciser pour elles aussi (Borne de Fer près de Longwy), un âge crétacé inférieur (130 ± 10 Ma). En Périgord-Quercy, ces plates-formes calcaires présentaient des paysages karstifiés avec de vastes cuvettes à fond plat, accidentées de buttes coniques, et des puits profonds dans les zones les plus hautes. Souvent ces paléoformes de dissolution montrent très peu de remplissage intra-karstique contemporain, donc les surfaces karstiques ne comportaient pas de couverture notable d'altération ou bien elle avait été érodée. Toutefois, certaines régions, en particulier celles liées aux calcaires à chailles et aux marnes, montrent des altérites piégées dans les paléokarsts ou en épaisse couverture d'altération.

Dans **le bassin de Paris** la gouttière wealdienne constituait une plaine d'inondation avec dépôts de sables, d'argiles et développement de paléosols pendant les périodes de non-dépôt. Les bordures de la gouttière formaient de vastes piedmonts raccordés au socle, et plaquées de lobes sableux et conglomératiques liés aux fleuves qui se jetaient dans la gouttière. L'intensité des altérations, la puissance des profils et leur maturation sont directement dépendantes de la durée de l'émersion et des situations topographiques vis à vis de la gouttière. Au centre, les paléoaltérations se limitent à des rubéfactions et argilisations des formations marines et fluvio-deltaïques du Crétacé inférieur, en revanche, sur les bordures et sur les massifs cristallophylliens les altérites sont épaisses et matures.

En conclusion**,** l'**inventaire** des paléoaltérations du Crétacé inférieur montre la complexité de l'histoire continentale de cette période. En outre, les altérites préservées ne sont qu'un volet de ces longues périodes continentales, tous les aspects relatifs aux phases d'érosion sont encore plus difficiles à mettre en évidence et à quantifier. Dans ce domaine, les données de la thermochronologie traces de fission sur apatite peuvent permettre de caractériser les épaisseurs de terrains dénudés. L'inventaire a permis de tracer une carte paléogéographique du continent crétacé inférieur faisant apparaître la nature des altérites et des paléopaysages différenciés, tout comme les cartes paléogéographiques marines indiquent les environnements de dépôt et les paléobathymétries. Pour l'avenir, le défi est de progresser dans les datations des paléoprofils d'altération, et surtout dans la résolution de ces datations, afin de corréler plus finement les enregistrements continentaux avec les divers phénomènes ayant pu les engendrer (eustatisme, climat, tectonique globale et régionale). L'objectif est d'établir une "stratigraphie continentale des événements géodynamiques et climatiques" qui puisse être mise en parallèle avec la "stratigraphie séquentielle" des domaines marins.

PROBLEMATICS

Contrary to what is usually thought, land areas are much larger than the subsiding sea areas where most of the sediments deposit. Nevertheless, geological records of the ancient continents are scarce, for some fully missing, and often blurred by successive and superimposed evolutions. At best, continents preserve only restricted testimonies of their evolution, displaying a patchwork of reliefs and weatherings discontinuous in time and space. However, the study of paleoweatherings and paleolandscapes is not useless. As most basin deposits are of continental origin, it is necessary to reconstruct the paleolandscapes with their weathering mantles and the environments that lead to their genesis. From this point of view, paleoweatherings are of prime importance: they supply the basins with soluble and

Downloaded from http://pubs.geoscienceworld.org/sgf/bsgf/article-pdf/177/3/155/2966832/155.pdf
by BRGM user

solid compounds; they enable to define the paleoenvironments, paleoclimates and paleogeographies. Paleoweathering mantles also act as an exchange interface with the atmosphere and thus take part in global climatic changes. Lastly, they contribute to stratigraphic correlations and indirectly enable to draw up uplift and erosion rates and rhythms.

Progress in dating paleoweatherings and azoic continental formations as well as the input of geochemical models have deeply renewed the interpretation of paleoweatherings and their contribution to sedimentary deposits. In the end, datings will enable to build up a "continental stratigraphy" of ancient climates and geomorphological events. Geochemical models enable to specify conditions of formation of unusual paleoweatherings, without equivalent in present day landscapes, and to take into account global climatic changes. These aspects are essential for paleogeographic and paleoclimatic reconstructions and should finally enable to estimate the mass balance between weathering/erosion/sedimentation.

The short term purpose may be to draw on paleogeographic maps the types of paleoweatherings and diverse paleolandscapes in the continental areas, in the same way as facies and deposit environments are shown on paleogeographic maps in the marine areas [Dercourt *et al.*, 1993; Dercourt *et al.*, 2000]. The longer term challenge will be to build up a stratigraphic chart of "continental geodynamic and climatic events" which can be put in parallel with "sequence stratigraphy" in marine realms.

The early Cretaceous is suitable for such a "paleocontinental" exercice. A combined tectonic uplift, more or less intense according to the areas, together with several sea level drops, lead to the emersion of most of NW Europe and the development of thick "lateritic" profiles. This long period of continental evolution ended with the drowning of the territory, diachronic according to the areas, from Aptian-Albian to Campanian-Maastrichtian. During the early Cretaceous, the emerged areas displayed then a patchwork of landscapes with diverse morphologies and paleoweathering products. Here after, we will successively examine in France and Belgium (fig. 1) the nature of paleosoils, describe paleotopographies and paleolandscapes and finally attempt a mapping of the Lower Cretaceous continent.

WEATHERING PRODUCTS

Bauxites

Bauxites are the most outstanding product of weathering of this period. Berthier [1821] recognised aluminium hydrate as the main component of the red formations in the Alpilles Massif, near the Baux-de-Provence village, eponymous site of the bauxite. Until recently, bauxitic formations had only been recognised in the South of France, in an area stretching over 600 km, from the flanks of the Maures Massif to the central part of the Pyrenean chain.

Provence

The bauxites of Provence are typical karst bauxites [Bardossy and Combes, 1999]. They gave rise to several genetical hypotheses: autochthonous with *in situ* evolution

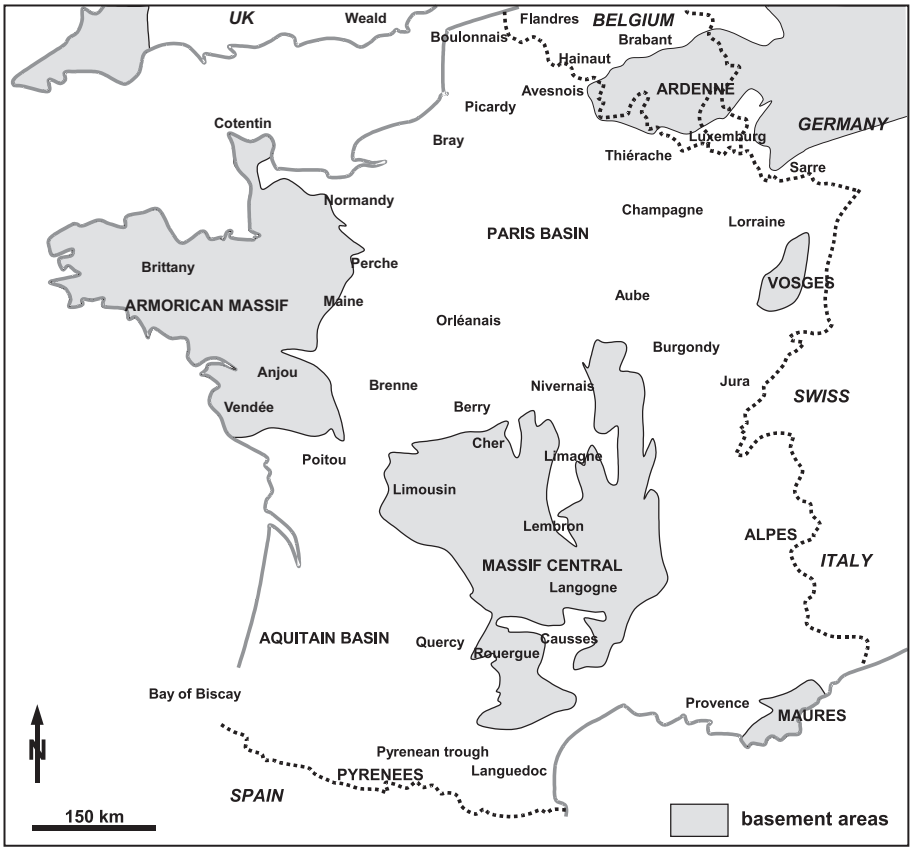


FIG. 1. – Map of the study area showing location of the main regional names quoted in the text.
FIG. 1. – *Carte de localisation des principales régions citées dans le texte.*

Downloaded from http://pubs.geoscienceworld.org/sgf/bsgf/article-pdf/177/3/155/2966832/155.pdf
by BRGM user

of residues derived from limestone dissolution [de Lapparent, 1930], allochthonous with deposition of reworked laterite and bauxite in karst depressions [Valeton, 1966; Nicolas, 1968], and parautochthonous with input of already weathered materials in karst depressions where the bauxite evolution was completed [Bonte, 1965; Rousset, 1969; Combes, 1990]. Recent studies of the vertical and lateral evolution of profiles, micromorphology, as well as the mineralogical and geochemical composition [Cantinolle *et al*., 1984; Guendon and Parron, 1985], have shown that at least the bauxites of the NW area (Alpilles) result from *in situ* alteration with an increasing differentiation towards the top of the profiles, typical for autochthonous lateritic profiles. Actually, the "sedimentary" features, earlier used to demonstrate an allochthonous origin, result from internal redistributions due to karst drawdowns and collapses (MT, observations in the Brignoles and Cannet areas).

The Cretaceous structural frame intervenes in the development of bauxites: the thickest profiles are bound to the top of structural domes with footwalls of old limestone formations, whereas they are reduced in the depressions where they overlie more recent formations [Laville, 1981]. The bauxites of Provence rest on karstified footwalls of Jurassic to Barremian age; their roof reaches into the Cenomanian to Campanian [Lajoinie and Laville, 1979]. Most authors accord to consider that bauxite developed on the emerged area during a relative short time covering the Albian and early Cenomanian [Masse et Philip, 1976; Laville, 1981]. This bauxitic "province" was more or less directly linked to Sardinia in the south and to the Massif Central in the west, without prejudging if the basement was cropping out in these areas [Rousset, 1975; Masse and Philip, 1976; Combes, 1990].

To the north, the white, red and ocre sand facies of the "ocres d'Apt" result from weathering of Albian and Lower Cenomanian marine glauconitic sands and have been interpreted as correlative with the development of bauxite further south [Guendon *et al*., 1983].

Pyrenean trough

In Languedoc and Ariège, the bauxites are linked to the Pyrenean axial basin. In Ariège, the bauxites formed at several times during Aptian and Albian, interbedded in dated formations. This results in some peculiar facies, altered during early diagenesis, with pyrite, berthierite, etc. [Combes, 1990]. These bauxites interbedded within the Cretaceous marine formations may result from *in situ* evolution of already weathered detrital inputs during times of low sea level (parautochthonous) [Combes and Peybernès, 1991]. Moving away from the Pyrenean trough, the bauxites are not longer interbedded within the Cretaceous formations, nevertheless the gap between footwall and roof formations is relatively short (Barremian/Cenomanian), while this gap is substantial as one approaches the cratonic upstream areas.

Causses

Unknown on the Grands Causses, bauxite has been found for the first time on the eastern part of the Causse of Hospitalet and in the southern part of the Causse of Campestre [Bruxelles *et al.*, 1999; Bruxelles, 2001, 2003]. Almost twenty outcrops are localized at the edge of several karstic depressions. Other outcrops have been recently found on the Causse of Sauveterre, always in similar situations. The footwall of the bauxite consists of Kimmeridgian to Bathonian karstified limestones. The roof is formed by marshland, mangrove and coastal sand deposits of Coniacian age (fig. 2).

Apart from numerous scattered blocks resting on the surface and revealed by agricultural ploughing, outcrops of bauxite appear as doline fillings sometimes several metres thick. In those formations several levels display paleosoils with nodular structures and bioturbations, but the most current facies is massive, made of red clay, containing scattered dark red pisolites. Light coloured facies also exist. The upper part of the deposit is kaolinitic, with gibbsite and boehmite and often enriched with iron oxides.

Paris Basin

In the Paris Basin, bauxitic formations, with about 10 to 25% of gibbsite, have recently been recognised, occurring with the Clay-with-Jurassic-cherts that cover extensive surfaces on the southeastern border of the Paris Basin (Nivernais) [Thiry *et al*., 2005]. The gibbsite is connected to red formations that are true *in situ* paleosoils over the Callovian-Oxfordian limestone. The thick weathering mantle of Clay-with-Jurassic-cherts, locally containing gibbsite, may have developed after sea withdrawal during late Tithonian and before the Albian transgression. The old minings of Siderolithic iron ores are related to these Clay-with-Jurassic-cherts. Thereby, the Siderolithic iron deposits, typical for the southern borders of the Paris Basin [de Grossouvre, 1886], may also be of early Cretaceous age.

On the southwestern border of the Paris Basin (Maine-et-Loire), 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].

These bauxitic formations of the Paris Basin, together with the bauxite deposits in southern France, most probably related to a major bauxitic event during the lower Cretaceous, but developed at different times due to the emersion episodes in the basins. Recognition of bauxites up into the

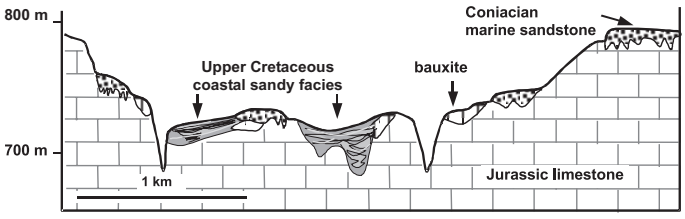


FIG. 2. – Schematic section of the paleokarsts in the Grands Causses. Bauxites are residual and localized at the edge of the depressions. On the other hand, the Upper Cretaceous deposits are relatively little deformed, indicating that those wide karstic depressions have not really been active after the deposition of these formations. The recent reactivation is particularly linked with the valley downcutting and has partly cleared out the sinkholes.

FIG. 2. – *Coupe schématique des paléokarsts des Grands Causses. Les bauxites y sont résiduelles, localisées en bordure des dépressions. En revanche les dépôts du Crétacé supérieur sont relativement peu déformés, indiquant que ces grandes dépressions karstiques n'ont plus vraiment fonctionné après le dépôt de ces formations. La réactivation récente est surtout due à l'incision des plateaux et a entraîné la vidange des poches.*

Downloaded from http://pubs.geoscienceworld.org/sgf/bsgf/article-pdf/177/3/155/2966832/155.pdf
by BRGM user

Paris Basin widened substantially the extension of the bauxitised domain.

Kaolinitic and ferruginous paleosoils on the basement

On the Hercynian and older massifs occur significant blankets of kaolinitic paleosoils and saprolites, which, because of their geographic link with the Tertiary deposits, had classically been related to the Siderolithic *sensu lato* (Eocene-Oligocene). Without dated sedimentary cover, stratigraphic assignment of these paleosoils often has been speculative and the first datings by paleomagmetism and/or radio-isotopes called into question these stratigraphic attributions, in particular in the Ardenne and Massif Central.

French Massif Central

The red formations at the edge of the Cher graben (near Montluçon, Chazemais and St-Désiré) and at the edge of the Limagne de Brioude graben (Boudes and Augnat in the Lembron area) are classical sites of the "Siderolithic" formations from the Massif Central [Boulanger, 1844; de Launay, 1892-93; Giraud, 1902; de Lapparent, 1930; Tapsoba, 1967; Deschamps, 1973]. New data about these paleoweathering formations come from detailed studies, particularly micromorphological ones, which enable to show how they evolved in the paleolandscapes, and from applying paleomagnetism techniques which enable to date these azoic formations overlying the basement.

"Siderolithic" formations in the Lembron area

The red formations of the Lembron crop out outstandingly at Boudes (Puy-de-Dôme). The "Les Mottes" section shows several variegated units [Thiry *et al.*, 2004] (fig. 3). The succession of iron mottled and bleached horizons could be interpreted as superposed paleosoils. Actually, micromorphological studies of these horizons show that they relate to a single and thick paleoweathering profile. From top to bottom there are: an upper leached horizon with ferruginous rhyzolithe-like pipes, in which the bleaching decreases with depth; a middle clayey, hydromorphic, illuviated horizon, with accumulation of iron oxides in pisolites; a lower mottled horizon which corresponds to a saprolite with partial leaching of the iron oxides near the water table. The massive brick-red horizon at the base of the section is a mature paleosoil on which the leaching of the above profile was superimposed. The upper horizon with a silcrete relates to a younger ferruginous paleosoil on which the pedogenic silicification was superimposed.

All the detrital elements of these formations are derived from the basement or eventually from the Permian-Carboniferous formations. In thin sections, there has never been identified detrital elements, which could relate to Mesozoic cherts or sandstones. This implies that at time of deposition of the Lembron red formations, the basement was out cropping and devoid of any Mesozoic cover or residual formations coming from the weathering of such a cover.

Datings by paleomagnetism have been performed for 6 sites in the Lembron area. They have been obtained by comparing the recorded paleomagnetic directions in the samples with the apparent wandering path of the Eurasian pole [Besse and Courtillot, 2002]. Dating of the paleosoils has been difficult because several magnetisations are superimposed in these formations. The multiplicity of the signals may come from the superimposition of several weathering phases in these profiles and/or stresses induced by tectonics in the clayey materials. The recognition of the primary magnetisation has not been feasible for all the studied sites, nevertheless it was possible to determine a characteristic direction of magnetisation, unfortunately still marred by a relatively broad uncertainty. The paleoweathering profiles in the Lembron area may date back to 140 Ma, with an uncertainty circle encompassing all ages between 140 and 80 Ma [Ruellan *et al.*, 2003; Thiry *et al.*, 2004]. To refine the dating, it is necessary to increase the number of sites and to widen the studied area.

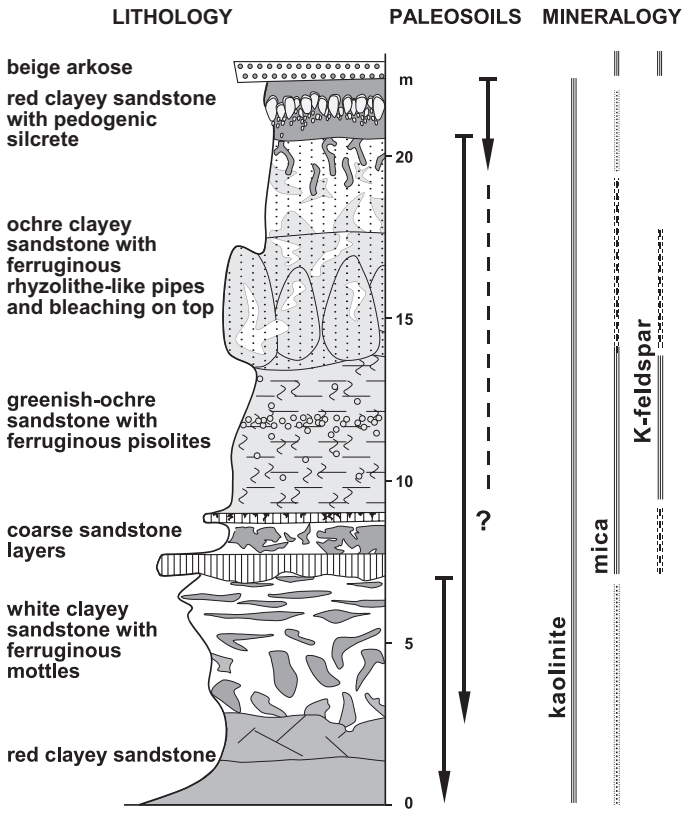


FIG. 3. – Lithology of the « Les Mottes » section (Boudes, 63). The micrography and mineralogy show three superimposed paleosoils. The uniform red formation at the base corresponds to a mature paleosoil on which was superimposed the bleaching of the overlying main profile. The top layer with silcrete relates to a younger lateritic paleosoil, on which were superimposed even younger pedogenic silicifications. A whole of 67 samples of this section has been kept for paleomagnetism dating.
FIG. 3. – *Lithologie de la coupe du Cirque des Mottes (Mottes Est) (Boudes, 63). L'analyse micrographique et minéralogique montre la superposition de 3 paléosols qui se télescopent. L'ensemble rouge homogène de la base correspond à un paléosol évolué auquel s'est superposé le lessivage du profil médian. Le niveau supérieur à silcrète, correspond à un paléosol ferrugineux plus récent, auquel se sont superposées des silicifications pédologiques encore plus jeunes. Au total, 67 échantillons de cette coupe ont été retenus pour la datation paléomagnétique.*

"Siderolithic" formation in northern Massif Central

In the Cher graben and on its western edge, red formations assigned to the "Siderolithic" also occur. The detailed study of an area on the border of the graben (Saint-Désiré, Châteaumeillant 1/50 000 geological map) enabled to show

Downloaded from http://pubs.geoscienceworld.org/sgf/bsgf/article-pdf/177/3/155/2966832/155.pdf
by BRGM user

paleoreliefs buried by two sedimentary sequences, over 65 m thick, and crowned by a red hardpan [Simon-Coinçon *et al*., 2000; Quesnel *et al.*, 2006].

The red hardpans relate to paleosoils that mark out tight "glacis" anchored on the paleoreliefs. These paleosoils show pedogenic, macro and micromorphological organisations that enable to clarify their development. The hardpans are leached ferruginous soils, displaying differentiated toposequences, they have later been silicified by impregnation of clayey materials by opal [Thiry and Turland, 1985; Thiry, 1999].

Paleomagnetism datings have also been carried out on the red hardpans of the Cher graben. The highly pedogenitised profiles (nodular, with numerous bioturbations and illuviations) yielded no exploitable paleomagnetic signals. Only the slightly pedogenitised profiles, but ferruginised and silicified, with illuviations restricted to the intergranular pores, yielded interpretable signals. The upper part of the profiles gives an age around 120 to 130 Ma, the lower part of the profiles gives ages centered around 50 Ma [Théveniaut, 2003; Quesnel *et al*., 2003]. The two ages correspond, either to a more or less continuous evolution of these profiles over the whole time interval, or to resumption of the weathering after burial and then exhumation of the profiles. Anyway, it is the ferruginous alteration, which is dated, the silicification is subsequent to the latest event dated by paleomagnetism.

"Siderolithic" formation in southern Massif Central

Near Langogne (Lozère), red kaolinitic paleosoils developped on a coarse alluvial fan deposited against a fault scarp. The paleosoils show well preserved pedogenic features (termites burrows, illuviation and hydromorphic features, nodules...) but considering the heterogeneity of the deposits they do not display clear pedogenic horizons. Thus it is not possible to state if they represent one or several superimposed paleosoils.

Paleomagnetism datings have been performed for 2 sites. 56% of samples give high temperature consistent signals with well clustered caracteristic component ($\alpha_{95}=6^{o}$). The age proposed is around 160 Ma (Ricordel, unpublished data).

Weathering mantles of the southwest of the Massif Central

At the end of the Jurassic (Tithonian), the sea withdrew, leaving large limestone platforms on each side of the crystalline basement of the Rouergue. During the major part of the early Cretaceous, the region would have evolved under continental conditions, enduring periods of erosion and lateritic weathering.

The existence of a weathered cover on the old basement is attested by the abundance of kaolinitic sandy clays in the transgressive Upper Cretaceous sediments of the Aquitaine platform. Quartz grains inherited from the basement were reworked together with mica, tourmaline heavy minerals. Without any weathering, Upper Cretaceous sediments show corroded quartz grains with cracks and holes filled with iron oxide. The Rouergue basement should have been outcropping since the end of the Jurassic and 10 m and more thick weathered mantles still exist on the plateaus [Simon-Coinçon, 1989]. Those weathered covers are incised by paleovalleys filled with fluviatile deposits of post-Jurassic age and are fossilized by continental Lower Tertiary sediments. Some profiles of more than 10 m thick show the transition from red-sandy kaolinite clay with goethite at the top to rubified coarse-grained granitic sand at the bottom. Those weatherings may be contemporaneous with the lateritic paleosoils known elsewhere on the Massif Central.

Armorican Massif and its edges

The rift shoulders related to the opening of the Bay of Biscay might have induced important relief on the southern edge of the Armorican Massif during the early Cretaceous [Wyns, 1996; Guillocheau *et al*., 2003; Wyns *et al.*, 2003]. No direct data is available about the massif cover of this period; the outlying deposits of the Albian-Cenomanian transgression only supply indirect indications. The importance of detrital deposits and the nature of associated heavy minerals show that the basement was cropping out and provided sediments during the transgression [Juignet, 1971; Louail, 1984]. The evidences are mostly given on the borders where weathering profiles are sealed by the Cenomanian transgression.

On the southern edge of the Armorican Massif, in Anjou, Poitou and Vendée, the ante-Mesozoic basement is composed of igneous, metamorphic and sedimentary rocks and shows kaolinitic weathering profiles, mainly truncated by erosion during the Cenomanian transgression. The thickness of preserved saprolite usually reaches 10 to 15 m, or less, depending on the extent of subsequent truncations [Steinberg, 1967]. Ante-Albian to Cenomanian paleoweathering also occurs on the basement and the Jurassic marls and limestones on the northeastern edge of the Armorican Massif in Mayenne, Maine [Juignet, 1974; Vérague, 1974], Lower Normandy in the Cinglais area, the "campagnes" of Caen and Falaise, in the "Pays d'Auge", "Bocage", Cotentin [Juignet, 1965; Rioult and Juignet, 1965; Pellerin, 1967; Ménillet *et al.*, 1997; Gigot *et al.*, 1999; Maurizot *et al.*, 2000; Vernhet *et al*., 2002], in the Alençon plain and on the Flamanville granite [Vérague, 1996**].**

In Brittany, on the basement of the Armorican Massif without any Meso-Cenozoic cover, paleoweathering is sometimes thick (40 to 50 m, even 90 m), rich in kaolinite (worked in various deposits) and sometimes includes ferricrete or silcrete, but never any bauxite. These weathering profiles have been fully described, their stratigraphic setting precised [Milon, 1932; Durand and Milon, 1959; Durand, 1960; Estéoule-Choux, 1967, 1983; Bellion, 1979; Wyns, 1991, 1996; Thomas, 1999; Boulvais *et al.*, 2000; Brault, 2002]. Two kinds of occurrences are singled out. Many of the kaolinitic profiles are capped by siliceous slabs ("ladères" and "Sabals" sandstones), ascribed to the Eocene, thus the underlying saprolites have been attributed to the Paleogene [Estéoule-Choux, 1967]. Other kaolinitic profiles are located on benches higher than the Paleogene surface and devoid of any silicification. This geometric relationship and the lack of silcrete on the highest surfaces suggest an older age for the latter. The hypothesis may be envisaged that paleoweathering of these high surfaces of Brittany might be Lower Cretaceous, even ante-Liassic, as few occurrences recognized on the edges of the Armorican Massif [Wyns, 1991]. Nevertheless without any direct dating

Downloaded from http://pubs.geoscienceworld.org/sgf/bsgf/article-pdf/177/3/155/2966832/155.pdf
by BRGM user

it cannot be ruled out that palaeoweathering underlying silicifications may be older as well.

Belgium

Weathering profiles of the Brabant Massif

The upper part of the Brabant Massif consists of thick weathering profiles covered by late Cretaceous to Cenozoic marine deposits [Legrand, 1968; Stoops, 1992; Mees and Stoops, 1999]. These profiles, recognized by several boreholes, can be 80 m thick and are developed on the chlorite-, feldspars- and muscovite-bearing Lower Paleozoic phyllites. The weathering is characterized by the preservation of rock textures, the destruction of chlorite and feldpars, and by the correlative neoformation of kaolinite and iron oxides [Mees and Stoops, 1999]. Part of the muscovite is preserved and no relative nor absolute iron enrichment can be observed. Only the deep saprolite horizons are preserved since the upper ones and the paleosoils have probably been eroded during the Upper Cretaceous transgression.

"Ghost rocks" of Hainaut

"Ghost rocks" are peculiar weathering products outcropping in southwestern Brabant (western Hainaut) [Vergari, 1998]. They formed in siliceous limestone of Paleozoic age by selective dissolution of the carbonate fraction of the rock. Sedimentological features, stratification and lithological variations are preserved in the resulting saprolite which shows density and coherence decrease and porosity increase. Minimum collapse of the weathering products is ensured by the rigidity of the unweathered silica framework. The "ghost rocks" postdate Wealden karsts and are sealed by transgressive sediments of Cenomanian-Turonian age [Vergari and Quinif, 1997; Quinif *et al.*, 1997].

Weathering profiles of the Ardenne area

The kaolinitic weathering profiles of the Ardenne area are only located on plateaus. They reach 65 m depth in the Transinne quarry (Haute-Lesse area). Contrary to those of the Brabant Massif, the kaolinized weathering profiles of the Ardenne are usually not covered, thus their age remains approximate without any specific dating. Apatite fission tracks thermochronology points to a paroxysmal uplift of the Brabant and the Ardenne after the end of the Jurassic and before the late Cretaceous [Vercoutere and Van den Haute, 1993]. Moreover, the geometric and temporal continuity of the paleosurfaces suggests that weathering occurred after this paroxysmal uplift of the massifs and before the Campanian-Maastrichtian transgression that covered the Haute-Fagnes area in the North [Bless and Felder, 1989; Dupuis, 1992; Dupuis *et al.*, 1996]. This age range does not preclude possible later weathering phases in areas without Cretaceous cover [Voisin, 1981; Demoulin, 1995].

In the weathering profile of Transinne, the formation of kaolinite, iron and manganese oxides is the result of a polyphase saprolitisation on the Devonian slates and sandstones [Dupuis *et al.*, 1996; Yans, 2003]. Various dating methods have been used to date this profile (fig. 4) [Yans, 2003]:

– the K-Ar method on hollandite suggests an early Cretaceous age (from 125 and 135 Ma) in the upper part of the profile, and a late Cretaceous age (from 88 and 94 Ma) in the intermediate part of the profile,

– the paleomagnetism method on iron oxides also suggests an early Cretaceous age (around 110-120 Ma) in the upper part of the profile,

– the oxygen isotope ratios of kaolinite of the upper part of the profile are in agreement with the values usually admitted for the early Cretaceous in Europe [Gilg, 2000].

The succession of datings, from the top to the bottom of the profile, is consistent with the downwards progression of weathering and could indicate a stepwise phenomenon controlled by eustatism. Moreover, in the neighbouring Sarre area, Lippolt *et al.* [1998] suggest a weathering age comprised between 120 and 142 Ma, by using the U/Th/He method on supergene goethites upon volcanic Permian rocks.

Kaolinitic and ferruginous weathering products on the Jurassic

On the wide limestone plateaus, outcropping as a results of the late Jurassic withdrawal of the sea, weathering led mainly to the development of deep and surficial karsts. The karsts may be covered or uncovered depending on the insoluble residue of the limestone and the erosion (tectonics).

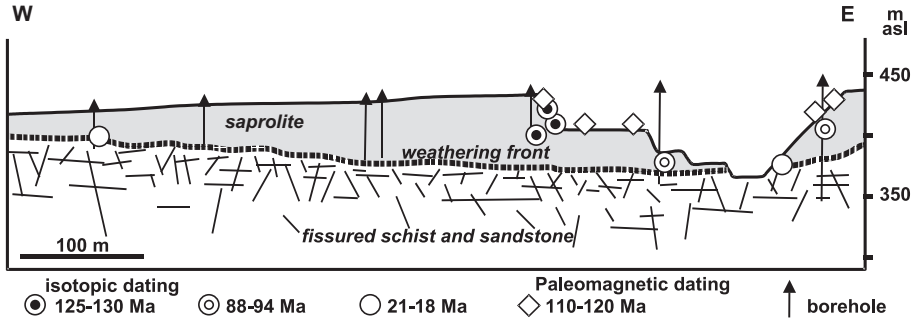


FIG. 4 – Schematic sketch of the Transinne saprolite (Haute-Lesse, Ardenne, Belgium). The quarry cuts a 65 m thick weathering profile. The ages of the profile are suggested by using several and independent dating methods. Ages decrease with depth, suggesting a regular downward progression of the paleoweathering front [Yans, 2003].

FIG. 4. – *Coupe schématique de la saprolite de Transinne (Haute-Lesse, Ardenne, Belgique). La carrière entaille un profil d'altération épais d'environ 65 mètres. Les âges du profil, issus de plusieurs méthodes indépendantes de datation, sont globalement de plus en plus jeunes en profondeur, suggérant un enfoncement progressif du front d'altération* [*Yans, 2003*].

Downloaded from http://pubs.geoscienceworld.org/sgf/bsgf/article-pdf/177/3/155/2966832/155.pdf
by BRGM user

The most often described occurrences are kaolinitic claystones with iron pisolites, which have been actively mined during the 19th century over the whole western Europe. The weathering products are specific, clay-rich, often devoid of skeleton grains, besides from the cherts. The clay content and the lack of skeleton grains led to weathering profiles with poorly differentiated horizons and disturbed by clay swelling and shrinkage and karst collapses. Only few examples of such paleosoils occur in present day landscapes (Cuba, the Far-East, Indonesia) and have been relatively little studied comparatively to paleosoils developed on igneous or volcanic rocks. The lack of references makes the genetic characterisation of these paleosoils especially difficult.

Jurassic rings of the Paris Basin

In the Paris Basin the Lower Cretaceous deposition area is reduced to a NW-SE gutter connected to the Alpine sea, extending from the Bray to Burgundy and its surface fluctuated depending on the eustatic variations. On both sides of the gutter, the Jurassic formations are cropping out and were submitted to weathering.

The weathering mantle is less prominent or less well preserved in the northwestern part of the gutter, corresponding to the continental realm of the Wealden deposits. Elsewhere, successive removals occurned during the Berriasian, Barremian, Aptian and Albian, which are related to epirogenic movements [Juignet, 1974; Robaszynski, 1981; Guillocheau *et al.*, 2000].

In the Boulonnais, the Jurassic limestones are sometimes weathered beneath the Wealden deposits [Amédro and Robaszynski *in* Mansy *et al*., 2006]. In Normandy and Maine, older and older Jurassic formations are buried under younger and younger Cretaceous deposits. Southwestwards on the edge of the Armorican Massif weathering facies beneath the Cretaceous transgression surface have been described since the first geological works of the 19th century [de Caumont, 1828; Blavier, 1842; Bonnissent, 1870] and continued to interest geologists during the 20th century [Bigot, 1939; Dangeard, 1944; Dufay, 1955; Elhaï, 1963; Juignet, 1965; Rioult and Juignet, 1965; Pellerin, 1967, 1968]. Nevertheless these have not always been interpreted as being of early Cretaceous age, because of subsequent erosion and weathering phases which make the Infra-Cretaceous surface coincide more or less with the Paleogene weathering surface or the Neogene erosional surface. Paleokarsts with iron ore pockets were described on the Jurassic limestones beneath the first transgressive Albian and Cenomanian deposits [Blavier, 1842; Dangeard, 1936, 1944; Rioult *et al.*, 1966]. In the Lisieux area, the Oxfordian calcareous sandstones "Sables de Glos" are entirely decarbonated beneath the Aptian and Albian sandy deposits, leading to several meters of bright beige sands with ferruginous veins and overlain by the "couche violette" which is attributed to a ferruginisation of the Wealden deposits [Groult, 1959; Juignet, 1965]. Rioult *et al*. [1966] made a detailed review of these paleoweathering occurrences of lower Normandy.

In the southeastern part of the Wealden gutter paleoweathering is thickest and best preserved beneath the Upper Cretaceous transgression. In the Aube, study of the facies ascribed to the Wealden deposits enabled to show that these are not deposits but true lateritic weathering profiles developed on marine Hauterivian deposits and sealed by the Aptian transgression [Ferry *et al.*, 2001]. Near the boundary between the Meuse and Haute-Marne departments, Meyer [1976] studied sections in the Lower Cretaceous sediments and described kaolinitic paleosoils with quartz grain corrosions occurring in the Wealden facies sealed by subsequent marine deposits. In Champagne and southern Lorraine ferruginisation is recorded in the Upper Valanginian and Lower Barremian deposits [Casanova *et al.*, 2001; Quesnel *et al*., 2002] and iron ore was mined in the paleokarsts perforating the Tithonian limestone [Corroy, 1925]. Those iron ores exhibit typical pisolitic and ferricrete structures, illuviation features and corroded quartz. The study of the Villers-le-Tourneur borehole shows the weathering of the Oxfordian formations [Giot *et al*., 2003]:

– at the bottom of the Albian "Sables Verts", boulders of massive ferricrete are reworked in a conglomerate and associated with well rounded quartz gravels;

– underneath a saprolite (locally worked for ochre pigments) preserved on 2 to 4 m thickness, entirely decarbonated and strongly enriched in iron oxides, still shows the original bedding with silicified fossils;

– substratum oxidation is complete as far as about 5.5 m and spreads in a diffuse way and along fractures extending to 9.5 m in a hardly permeable substratum composed of marl and marly limestone.

In Lorraine, the back slope of the Mosel cuesta shapes a calcareous plateau of subconstant elevation (380-400 m), known as the "Pays Haut" (High Land) and underlying the "Fer fort" (iron ore) deposits [Jacquot, 1849; Wehmann, 1911; Faber *et al.*, 1999; Quesnel, 2003]. The "Borne de Fer" butte at Ottange (Moselle) near the Luxemburg border overlooks the plateau by around 40 m and is crowned by an *in situ* ferricrete formed at the expense of the karstified Bajocian limestones and marls. These ferruginous formations were ascribed to the Siderolithic *sensu lato* and usually to the Eocene [Faber *et al.*, 1999]. Nevertheless a re-examination of these formations showed that it is not a standard ferralitic ferricrete but a quartz rich layer cemented by goethite [Quesnel *et al*., 2003]. The ferricrete is overlain by red clay composed from 95 to 100% of kaolinite in the fine fraction and containing goethitic nodules (fig. 5). Paleomagnetic datings were carried out on the ferricrete by comparing the paleomagnetic directions recorded by the samples to the apparent wander path of the Eurasian pole. The datings gave a 130 ± 10 Ma age (Barremian) for the "Borne de Fer" formation [Théveniaut *et al*., 2002].

On the southeastern margin of the Wealden through, there are a few surficial residual formations preserved on Jurassic plateaus, beyond the ring of Cretaceous sediments, particularly in Puisaye. It is only southwards, in Nivernais, that preserved Clay-with-Jurassic-cherts contain layers of pisolitic iron ores, worked during the 19th century, and locally gibbsite. Those Clay-with-Jurassic-cherts can reach 40 m thickness. Chert and small rounded quartz conglomerate, interbedded between the Clay-with-Jurassic-cherts and the Cenomanian to Campanian flint-bearing weathered formations, point out that weathering of the Jurassic limestones predates the Upper Cretaceous trangression (fig. 6) [Thiry *et al.*, 2005]. Those chert and pisolitic iron formations

Downloaded from http://pubs.geoscienceworld.org/sgf/bsgf/article-pdf/177/3/155/2966832/155.pdf
by BRGM user

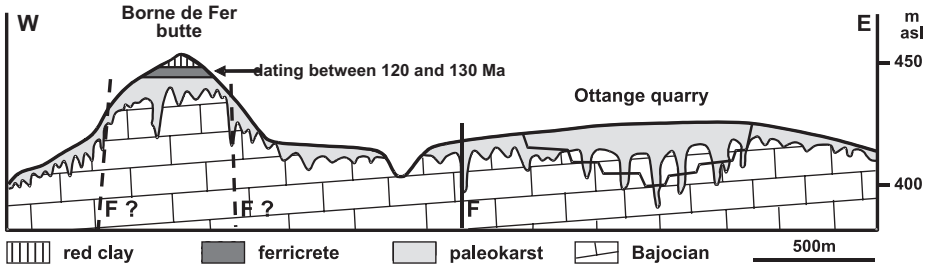


FIG. 5 – Geologic section across the "Borne de Fer" butte and the Ottange Quarry (Moselle) showing the distribution of the weathering facies (paleokarst, ferricrete and red clay with nodules). The butte overlooks by about 40 m the plateau which is ascribed to the Paleogene surface [Quesnel *et al.*, 2003, submitted]. The weathering profiles formed at the expense of the Bajocian limestones and marls are from 15 to more than 40 m thick, depending on whether situated above a karstic pocket or not.

FIG. 5. – *Coupe géologique en travers de la butte de la Borne de Fer et de la carrière d'Ottange (57), montrant la répartition des faciès d'altération (paléokarsts, saprolite, ferricrète et argile rouge à pisolites). La butte domine d'environ 40 m le plateau qui est attribué à la surface paléogène* [*Quesnel* et al., *2003*]. *Les profils d'altération, formés aux dépens des calcaires et marnes bajociens, sont épais de 15 à plus de 40 m, selon que l'on se trouve à l'aplomb d'une poche karstique ou non.*

spread on the leftbank of the Loire river, near La Charité-sur-Loire. We may link them up with the pisolitic iron ores of Berry and as far as the vicinity of Bourges.

Wealden facies: some correlated continental deposits

In the Paris Basin the expression "Wealden facies" is applied to a set of mainly continental sediments, interbedded between the Jurassic and the strata ascribed to the Barremian or to the first Aptian-Albian marine layers if necessary. The Wealden facies are known in the Bray, the Boulonnais, the Ardennian edge, the centre of the Paris Basin. They extend in the Mons Basin, where the Barremian to basal Aptian sediments are mainly continental Wealden facies as well and contain a few marine layers [Yans, 2003; Yans *et al.*, 2005a]. In the southeastern Paris Basin ferruginisations occur on marine beds ascribed to the Hauterivian and Barremian [Ferry *et al.*, 2001].

The Wealden deposits are located along a NW-SE gutter; their thickness ranges from 50 to 150 m in the Bray, 0 to 65 m in the Boulonnais, it reaches 200 m in the centre of the Paris Basin and more than 150 m at Hautrage in Belgium. They are missing (eroded?) on the edges of the gutter and may reach 800 m in England [Allen, 1989; Ruffel, 1995; Juignet, 1974; Médioni and Robaszynski, 1980; Rusciadelli, 1996; Guillocheau *et al.*, 2000]. The gutter is clearly subsiding within an area with a pronounced relief where erosion was active. Erosion shaped the angular unconformity which led the Upper Cretaceous formations to overlie older and older Jurassic strata away from the gutter axis, until overlying the Ardennian and Brabant basement northwards and the Armorican basement southwards.

The major part of the deposits is formed of sand and clay, and kaolinite is the prevailing clay mineral. They are fluviatile facies, with sandy channels, flood plain clays and frequent plant remains. On the edge of the gutter coarser facies often appear, including conglomerates, for example above the coal measures of northern France [Gosselet, 1911, 1913]. Coarse facies occur locally all around the gutter and must be interpreted as alluvial fans of fluvial tributaries supplying the Wealden deposits. In some cases Wealden deposits are connected to paleokarst, filling decato hectometric pockets from 3 to more than 20 m depth. It is the case on top of the partly decalcified Tithonian sandstones of the Boulonnais [Bonte and Godfriaux, 1958; Mansy *et al.*, 2006]. In the Hirson and Trélon area numerous pockets and sinkholes in the Jurassic limestones are filled by fluvio-palustrine sediments also ascribed to the Wealden by their palynologic content [Carpentier, 1926]. Some remnants are also recorded on the Paleozoic formations of the Avesnois.

The oxidised facies of the Wealden deposits, mainly ferruginous sandstones and variegated clays, are classical facies of flood plain deposits. If they actually correspond to paleosoils settled between the deposition and/or flood

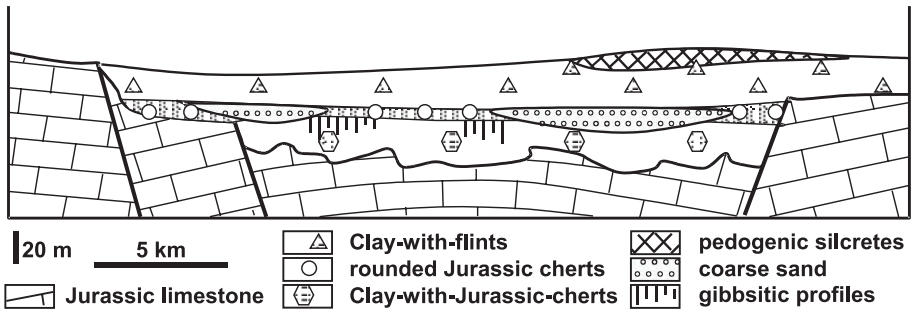


FIG. 6. – Sketch of stratigraphic relations between the different kinds of weatherings and residual formations in the south east of the Paris Basin (Nivernais). The rounded chert bearing formations beneath the Clay-with-flints show that the Clay-with-Jurassic-cherts was formed before the Upper Cretaceous transgression.

FIG. 6. – *Schéma des relations stratigraphiques entre les différentes paléoaltérites et formations résiduelles du SE du bassin de Paris (Nivernais). Les formations à chailles roulées à la base des formations à silex montrent que les argiles à chailles se sont formées avant la transgression du Crétacé supérieur.*

Downloaded from http://pubs.geoscienceworld.org/sgf/bsgf/article-pdf/177/3/155/2966832/155.pdf
by BRGM user

episodes, they do not have the same meaning as paleosoils described on the basement or the gutter sides. They are oxidation facies of freshly deposited pyritic alluvium, quickly formed at the time of air exposure and usually not associated with any weathering of silicates. The flow and alluvial sheet oxidising phenomena on the edges of the fluvial drains are probably the most important processes taking place.

Finally must be mentioned the "puits naturels" (natural pits), which perforate the Mons Basin substructure and may reach 1200 m depth with sandy-clayey fillings. The Bernissart "Cran" in Belgium (near Condé-sur-Escaut, Nord) contains some famous Iguanodons accumulations [Casier, 1960]. Recent palynologic studies enabled to attribute a middle Barremian to basal Aptian to the black clay containing the Bernissart Iguanodons [Yans, 2003; Yans *et al.*, 2005a,b]. These natural pits occur in places of the Mons basin. They are not paleokarsts *sensu stricto* but collapse hollows developed from the dissolution of Visean anhydrite beds at around 1500 to 2000 m depth [Leclercq, 1980; Dupuis and Vandycke, 1989].

PALEOTOPOGRAPHIES

Recognition and characterisation of some weathering products imply directly the occurrence of specific landscapes and/or paleotopographies: it is obvious for the weathering mantle developed on the Jurassic limestones, it corresponds to karstlands. Nevertheless, here after rather than attempting to infer the landscapes from the weathering types, we will seek to recognise geometric elements of the paleolandscapes, in order to specify their nature and their extent. We will thus examine successively the features of the wide limestone platforms, the basement areas, and finally the lowlands near the deposition areas.

Paleokarsts on the wide limestone platforms

Paleokarsts were well developed on large and massive emerged limestone platforms. They are essentially known as dissolution landforms fossilized later by Upper Cretaceous transgressions in Lower Normandy and Maine [Rioult *et al.*, 1966; Pellerin, 1967; Juignet, 1974; Ménillet *et al.*, 1997], in Poitou and Brenne [Wyns *et al.*, 2003], in the Grands Causses and Quercy [Astruc, 1988; Simon-Coinçon and Astruc, 1991; Bruxelles *et al.*, 1999], and they are often devoid of contemporaneous filling. It would mean that karstic surfaces did not include an appreciable weathering mantle. Yet, few exceptions show weathering products on and in karsts, sealed by Upper Cretaceous transgressive sediments. The development of a weathering mantle is directly dependent on the amounts of insoluble minerals in the limestones. The presence of marls and cherts in Jurassic formations highly contributed to the development of weathering mantles, it is especially the case on the edges of the Armorican Massif [Pellerin, 1967; Estéoule-Choux *et al.*, 1971; Quesnel *et al.*, unpublished] and in the Nivernais on the hinge of the Morvan [Thiry *et al.*, 2005].

Quercy and Grands Causses

Limestone platforms of the Quercy and Grands Causses underwent erosion since their emersion at the end of the Jurassic, and weathering features and paleolandscapes of Lower Cretaceous age have been preserved. In Quercy, the reconstitution of paleolandscapes is allowed by the recognition of paleomorphologies buried by Cenomanian deposits [Astruc, 1988]. The ante-Cenomanian substratum was not flat. It was affected by large undulations, often exploited by erosion. The flexure of the western part of the Quercy was exacerbated and formed a WNW-ESE scarp, from Cahors to the Grésigne. South of Souillac, the Upper Jurassic sediments form a 60 m high cliff, incised by paleovalleys. Those paleovalleys have been invaded during the onset of the transgression by coastal marshes and mangroves with deposition of lignite (near Sarlat). Other morphologies, exhumed from their Cretaceous cover, exist to the east on the Jurassic Causses. They show some flagstones and silicified residual sandstones. Those morphologies show large flat karstic depressions with flat bottom and conical buttes, which evoke tropical karsts (west of Gourdon, Berganty south of St-Cirq-Lapopie).

In the Grands Causses, the presence of autochthonous bauxite reveals a long period of continental weathering during which the first landscapes were formed [Bruxelles, 2001]. Bauxitisation results from multiple and complex processes, but the last phase occurred in karstic traps. The doline of Luc-Bas (typical depression of the current landscape of the Grands Causses), and a dozen of similar depressions called "grands sotchs", were initiated during the early Cretaceous and constitute the wall of the bauxite. The doline of Luc-Bas has preserved its sedimentary filling: clay, sand, gravel, lignite and marl beds. Bauxite subsists as veneers against the sides of the doline and covers lapies. Some ferruginised Upper Cretaceous limestone and calcareous sandstone seal the "grands sotchs" filling, the bottom of large depressions and the top of karstic buttes. The paleolandscapes predate the Upper Cretaceous (Coniacian) transgression.

In the Grands Causses, relief amplitudes were higher than in Quercy. Large flat depressions present many karstic buttes up to 60 m high and are punched by 40 m deep "grands sotchs" (fig. 2 and 7). This elevation contrast may be explained by a higher relative altitude in the Grands Causses than in the Quercy and possibly by a later fossilization of the paleokarst by the marine deposits. No indication of ancient endokarst exists in the Grands Causses nor in Quercy, this may point out either a relative high water table that limited vertical development of the karstification, or a more massive, not fractured, limestone plateau. The present day endokarts developed later, after the fracturing triggered by the Pyrenean orogeny, with re-exploitation of the Cretaceous paleokarsts during the Cenozoic.

Provence

In Provence, the landscapes in which the bauxite was formed may not be barely different. The mining pits enabled to expose the karst morphologies at the base of the bauxite, but also to precise the distribution of the bauxite profiles in the paleolandscape. The structure of the Provence basin shows anticlines forming heights on which the bauxite layer is thick, but nevertheless punched by limestone domes and pinnacles, and lowlands where bauxitisation is less intense and may have developed later, with

Downloaded from http://pubs.geoscienceworld.org/sgf/bsgf/article-pdf/177/3/155/2966832/155.pdf
by BRGM user

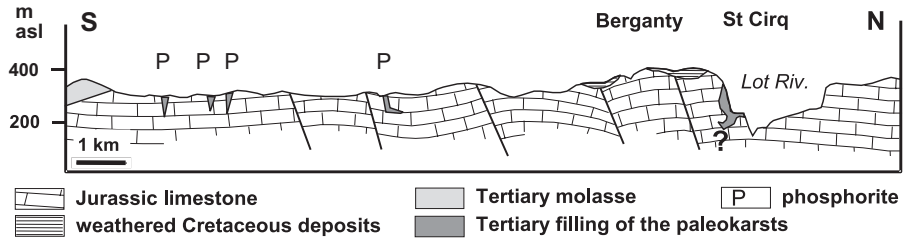


FIG. 7. – Section across the limestone plateaus in the eastern part of the Quercy (Causse of Limogne). Several paleokarst morphologies have been preserved below remants of the Cretaceous paleosurface: large sinkholes near St-Cirq-Lapopie, as well as surface topographies near Berganty. Deep galleries of the karstic network and phosphorite result from a reactivation of the karstification during the Tertiary, essentially after the removal of the Cretaceous cover.

FIG. 7. – *Coupe des plateaux calcaires dans la partie orientale du Quercy (Causse de Limogne). Différentes morphologies de paléokarst ont été conservées sous les témoins de la paléosurface crétacée : de grands conduits comme à St-Cirq-Lapopie, ainsi que des formes de surface comme à Berganty. Les galeries profondes du réseau et celles des gisements de phosphorite résultent d'une reprise de la karstification pendant le Tertiaire, essentiellement après déblaiement de la couverture crétacée.*

wide zones of barren limestone [Rousset, 1969; Laville, 1981].

Lorraine and Ardennian Thiérache

In Lorraine, the karstic features filled by clay with "Fer fort" beneath the weathering mantle of the "Borne de Fer" (whose top ferricrete is dated as 130 ± 10 Ma) reach some 50 m depth in the Bajocian limestone of the Ottange Quarry. In the same area, fresh exposures (road works west of Thionville) show solution pipes in the limestone and weathering of the Liassic marls at least 50 to 100 m below the Infra-Cretaceous paleosurface. Moreover, paleokarsts filled by pisolitic iron ore (attributable to the facies of Ottange and the "Borne de Fer") are well known southwards in the area of Joinville and Poissons down to 80 m below the current surface of the plateaus (Le Roux and Harmand, oral comm.).

In Ardennian Thiérache, karstic pockets with Wealden fillings in the Bathonian limestone reach 20 to 30 m depth, those of the Hirson and Trélon area show similar depth, seldom until 50 m. In the Boulonnais the karstic pockets occurring in the Tithonian formations and filled by Wealden clay are decametric as well [Mansy *et al.*, 2006].

Thus during the early Cretaceous the areas of northern and eastern Paris Basin probably exhibited plateaus whose elevations were 50 to 100 m above the local base level.

Belgium

In Belgium, the natural pits with Iguanodons correspond to particular geologic conditions. These are not karstic features, but collapse structures related to the dissolution of thick anhydrite deposits at 1500-2000 m depth [Leclercq, 1980; Dupuis and Vandycke, 1989]. Due to our poor knowledge of this peculiar mechanism, it is impossible to get paleotopographic indications from the current depth of these collapse pits. It is also difficult to reconstruct the paleolandscapes with these scattered pits whose density within the plateau is unknown.

Lower Normandy and Maine

In Lower Normandy and Maine, the karstic features ascribed to early Cretaceous (sealed by the Albian-Cenomanian transgression) are comparatively shallow, often less than 10 m. In Maine, the compilation and detailed survey of the borehole logs indicate few karstic features in the Jurassic limestones, which are generally less than 20 m deep beneath the Cenomanian deposits (Giordano, oral comm.; Quesnel, unpublished). If the paleokarst depth criterion is taken to assess paleoelevations, it is thus likely that during the early Cretaceous Lower Normandy and Maine exhibited lower elevated Jurassic plateaus than northeastern France, Causses and Quercy.

More upstream, westwards and southwards, the Infra-Cretaceous unconformity surface denuded the Armorican Massif basement before the Cenomanian transgression. This indicates a stronger epeirogeny than in the Jurassic rings, but this may not imply higher paleoelevations.

Paleolandscapes on the basements

On the Hercynian and older massifs, the paleolandscape amplitude may have been significant. Probably there have been high scarps (often fault scarps), which might have reached or exceeded 200 m of elevation. There were also wide areas with inselbergs, similar to the present day African and Brasilian tropical landscapes.

Ardenne, Brabant and Armorican Massif

These massifs were exposed during the early Cretaceous and probably included large plateaus with thick saprolites, as suggested by the remaining weathering profiles on the Ardenne. The saprolites have been buried by Upper Cretaceous and Cenozoic sediments on the Brabant. The plateaus have also been cut by quite deep valleys, draining the surface waters and carrying the eroded detritic materials to the Wealden gutter, the North Sea and the Atlantic Ocean.

The current geometry of these paleosurfaces is sloping towards the basins, for example in the Ardenne, from 700 m elevation in the Hautes Fagnes, to 200-300 m in the southern Lorraine and finally 0 m towards the NW at the North Sea coastline. We suggest that the Lower Cretaceous geometry should be almost the same as the current one. However, the current repartition of the elevations, and thus the correlative slopes, may be quite different because of the possible reactivation by different geodynamic processes since the early Cretaceous.

Downloaded from http://pubs.geoscienceworld.org/sgf/bsgf/article-pdf/177/3/155/2966832/155.pdf
by BRGM user

Northern Massif Central

On the edge of the Cher graben (Saint-Désiré, geological map 1/50 000, sheet Châteaumeillant), the red hardpans, dated around 120 to 130 Ma by paleomagnetism, are linked to graded piedmonts anchored either on paleorelief forms armed by the basement quartzites or on fault scarps apparently active at that time [Simon-Coinçon *et al.*, 2000]. The coarse deposits at the upper part of the sequence, without sorting nor marked sedimentological organisation, are linked to sheet flow deposits (without hierarchised hydrographic network) which shaped such piedmonts under contrasted climatic regimes with long dry periods broken by heavy rains. These piedmont paleolandscapes superimpose and intersect older paleolandscapes formed of deep meandering paleovalleys with steep slopes, incised into the basement (fig. 8). It may not be excluded that these large paleovalleys are actually inherited from Triassic paleovalleys, even Permian ones, exhumed and reshaped during the end of the Jurassic and the early Cretaceous.

At Loze locality, the paleovalley crowned by the red hardpan is about 110 m below the top of the Sainte-Agathe hill and the whole difference of elevation between the paleoreliefs and the paleovalley floors is at least of 150 to 200 m. This arrangement of deep paleovalleys fringing basement scarps and paleoreliefs highlights a more or less winding network heading towards the NE, where the red hardpans are buried under the Upper Eocene lacustrine deposits of the Cher graben. The Lower Cretaceous paleotopography was well differentiated in this area, probably due to scarps formed along reactived Hercynian faults and which have been degraded and incised by erosion and weathering. Furthermore, Jurassic chert pebbles within some sections show the magnitude of the erosion that led to scour the Jurassic at the time of downcutting of these paleovalleys.

Lembron, in the centre of Massif Central

Three topographical units are distinguished in the Lembron area: (1) the western plateau, which corresponds to a flat granite surface sparsely covered by Tertiary sediments up to 50-60 m thick with basalt flows on top; (2) a scarp, which is the transition unit between the plateaus (the *montagne*) and the plain (the *limagne*); the scarp is complex, i.e. it is stepped and shows large embayments infilled with ferrugineous sand and clay fluviatile deposits, refered as "Siderolithic" sediments; (3) the eastern plain which is formed by Tertiary sediments and sparse outcrops of bedrock where the sedimentary cover has been eroded.

The geometry of the basal red "Siderolithic" formation is complex. It can be summarized into two main arrangements: (1) crowning of basement heights such as dome structures or inselbergs (fig. 9) or (2) as infills of paleovalleys that incise the basement at the scarp foot (Vallée des Saints). Some relics of these sediments are also

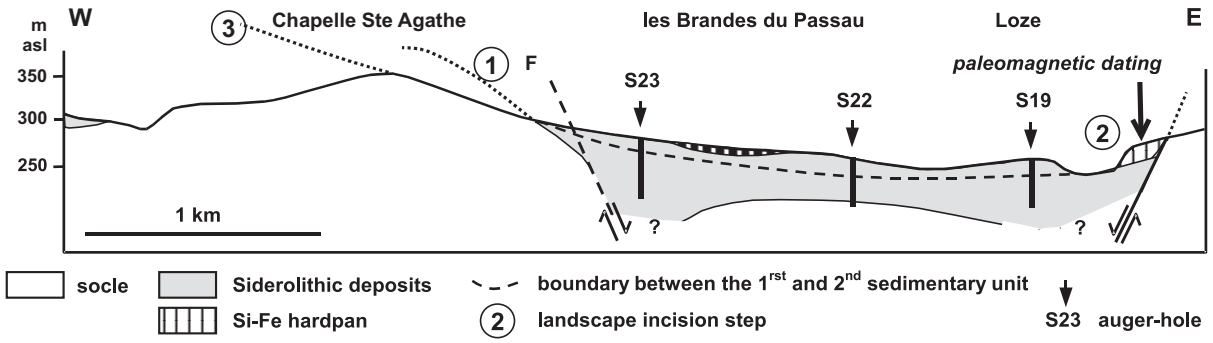


FIG. 8. – Geological section built after the field survey and auger hole data. The Siderolithic facies fill paleovalleys and partly drown basement paleoreliefs armoured by quartzite. The upper unit which shapes the glacis capped by the red hardpans, has been deposited after a tectonic event and intersects the former paleovalley profiles.

FIG. 8. – *Coupe géologique construite à partir des levés de terrain et des résultats des sondages. Le "Sidérolithique" remplit des paléovallées et ennoie en partie des paléoreliefs de socle armés de quartzite. L'unité supérieure qui façonne les glacis armés par les cuirasses rouges s'est mise en place après une rupture tectonique et recoupe le profil des anciennes paléovallées.*

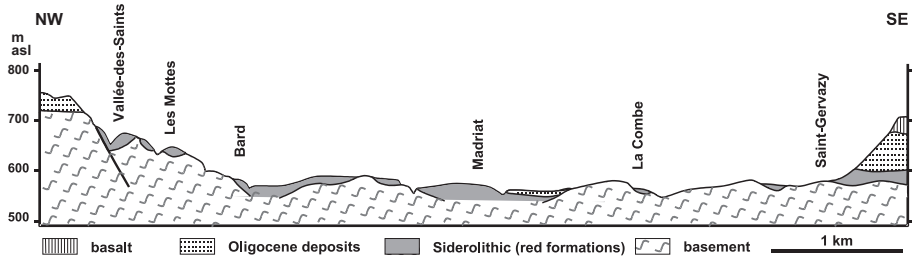


FIG. 9 – Geological section across the Lembron area. Note the basement paleoreliefs overlain by Siderolithic formations, thus contributing to their preservation. The fault bordering the basement scarp had late movements, but obviously it had also early movements, which allowed the red formation to be trapped in fault angles.

FIG. 9. – *Coupe géologique à travers le Lembron. Noter les paléoreliefs du socle contre lesquels s'appuient les formations rouges et qui ont contribué à leur préservation. Si la faille qui limite l'escarpement a eu des rejeux tardifs, elle a vraisemblablement aussi eu des rejeux précoces qui ont permis le piégeage des sédiments dans les angles de faille.*

Downloaded from http://pubs.geoscienceworld.org/sgf/bsgf/article-pdf/177/3/155/2966832/155.pdf
by BRGM user

preserved on the surface of basement benches. It is clear that the red formations have fossilized paleotopographic morphologies.

A flat basement surface with inselbergs is observed near the base of the scarp. This surface is likely the result of the denudation of its former thick paleosoil cover. Erosion is thought to have removed the soft paleoweathering mantle until it reached down the irregular weathering front. Irregularities of the resulting surface thus mimic the ancient contact between saprolite and parent rock but are also due to remnant lithologies that resisted more to erosion such as siliceous rocks. Erosion also affected the scarp where it formed valleys, steps and large embayments. The resulting landscape has subsequently been preserved by multi-phased sediment deposits. Erosion of the weathering mantle covering the nearby basement provided substantial detrital material for these deposits and paleosoils also developed within the deposits during the periods of relative (tectonic?) stability. This paleolandscape may be compared to the present day wide encased surfaces with inselbergs from Africa and South America.

Eocene and Oligocene sediments deposited later and largely encompassed the extension of the red formations. Erosion of this cover with subsequent rejuvenation of the outcrops of "Siderolithic" formations is explained by recent tectonic playbacks.

Transitional piedmonts on the edge of the old basement

Massif Central edges

On the old massifs edges, large piedmonts formed. For example, it is the case of the southeastern Paris Basin where a thick cover of Clay-with-Jurassic-cherts was developed and the regularity of which testifies for the absence of noteworthy erosion. Elsewhere, particularly around the crystalline massifs, erosional wedges were formed on Jurassic limestones, fossilized by Upper Cretaceous transgressive deposits; this shows the relative surrection of the massifs and the removal of an important thickness of sediments during the whole early Cretaceous.

So in the southwest of the Massif Central (Quercy) Upper Cretaceous sediments lie on older and older Jurassic strata eastwards and in the Grands Causses they cover older and older strata northwards and westwards (fig. 10). The observed erosional bevels reveal the importance of weathering and erosion during the early Cretaceous. The Jurassic sediments have been totally eroded upon the Massif Central.

Wealden gutter and its tributaries

In the Paris Basin and in the English Channel, a strongly regressive context prevailed with successive continentalisation episodes at the Jurassic/Cretaceous boundary [Maniez *et al.*, 1980; Guillocheau *et al.*, 2000]. From the Valanginian onwards, several major marine incursions coming from the Tethys occurred in the SE and invaded partly the emerged paleotopography. A fluviatile complex of Wealden facies flowing down from England [Allen, 1989] built a clastic body that formed a cone from the Bray down to the Champagne to the east of Orléans (fig. 11). It formed a flood plain landscape with shifting channels, hydromorphic soils which developed between the flood periods, and humid zones with luxuriant vegetation as testified by the frequency of lignitic deposits and the abundance of fossil wood.

The flood plain was supplied by the Armorican Massif southwards and the Brabant and Ardenne northwards. Several fluviatile tributaries flew in the Wealden gutter as indicated by the remnants studied north of the gutter in the Avesnois, Ardennian Thiérache, Champagne, Boulonnais [Gosselet, 1888; Delépine, 1925; Carpentier, 1926; Bonte, 1955; Voisin, 1978; Mansy *et al.*, 2006], and south of the gutter in Normandy, Maine, Perche, Poitou and Anjou [Juignet, 1965, 1974; Rioult *et al.*, 1966; Pellerin, 1967, 1968; Louail, 1984; Vérague, 1996]. The paleovalleys of the northern Massif Central [Simon-Coinçon *et al.*, 2000; Quesnel *et al.*, 2006] probably led also to this wide regional depression. The lateral tributaries might have been embanked as would indicate the paleomorphologies of the northern Massif Central and the basal geometry of the conglomerates overlying the coal measures of northern France [Gosselet, 1911, 1913].

In the SE of the gutter, the Aptian transgression sealed the paleotopography and its weathering profiles. Moreover Burgundy underwent a severe erosion after Hauterivian and before Albian, more than 100 m in some places, scouring the Valanginian and Hauterivian marine deposits and even locally removing some Tithonian formations and part of the Kimmeridgian. This erosion is due to a strong epeirogeny on the Burgundy threshold that shaped a continental surface before the return of the Albian transgression [Rat, 1968]. These processes occurred probably during the Barremian

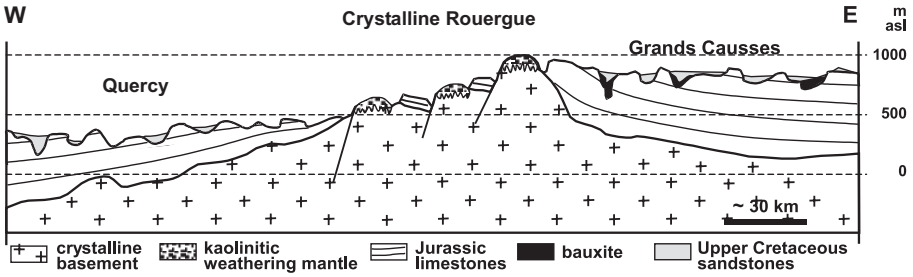


FIG. 10. – Schematic section through the SW of the Massif Central. Note the stratigraphic bevels of the Jurassic transgressive deposits on the Rouergue basement and the higher elevations in the Grands Causses with regard to those of the Quercy, as well as the "sotch"-like sinkholes.
FIG. 10. – *Coupe schématique à travers le SW du Massif Central. Il faut noter les biseaux stratigraphiques de la transgression jurassique sur le socle du Rouergue, l'altitude relative plus élevée des Grands Causses par rapport au Quercy, ainsi que l'existence de sotchs.*

Downloaded from http://pubs.geoscienceworld.org/sgf/bsgf/article-pdf/177/3/155/2966832/155.pdf
by BRGM user

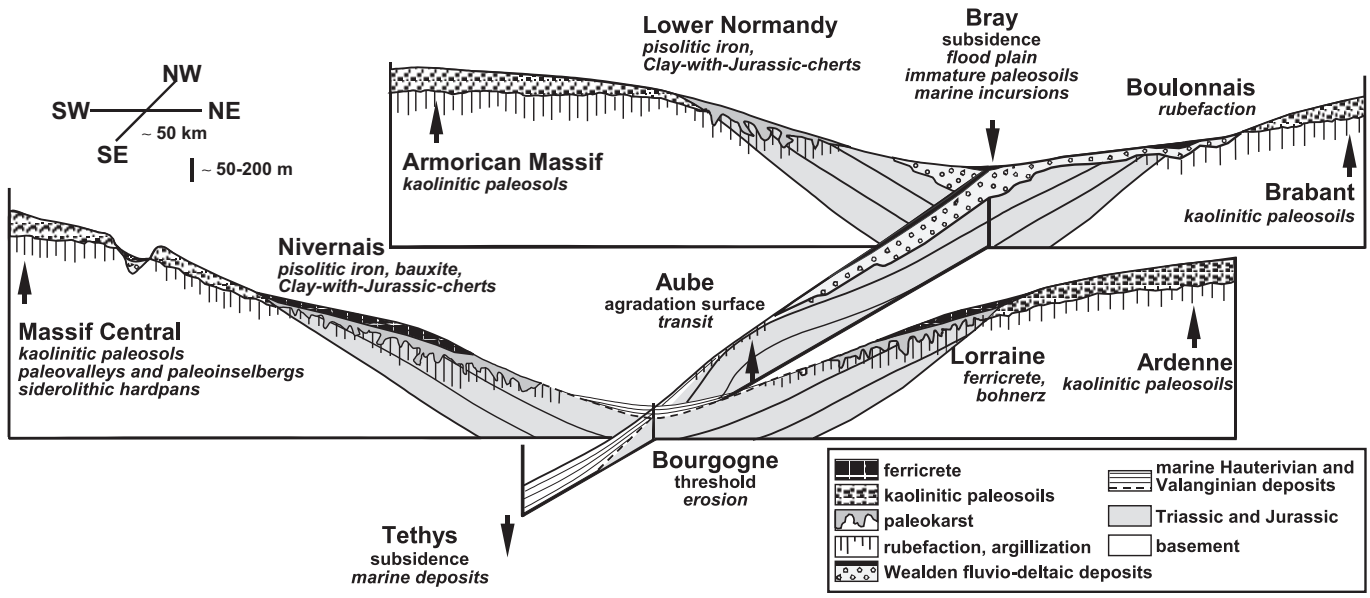


FIG. 11. – Structural sketch of the Wealden gutter and its edges during the Barremian. The fluvio-deltaic complex accumulated in a wide flood plain behind the Burgundy threshold. Paleoweathering is as intense and mature as far from the gutter axis. This results from the combined effects of elevation and emersion duration.

FIG. 11. – *Schéma structural de la gouttière wealdienne et ses bordures au Barrémien. Le complexe fluvio-deltaïque wealdien s'est accumulé dans une vaste plaine d'inondation en arrière du seuil de Bourgogne. Les paléoaltérations sont d'autant plus intenses et matures qu'on s'éloigne de l'axe de la gouttière, c'est là le résultat des effets conjugués de l'altitude et de la durée de la continentalisation.*

and part of the Aptian, while continental clays deposited in the Bray.

On the gutter sides the weathering intensity, the profiles thickness and their maturation depend directly on the emersion duration (ie on the distance from the gutter axis) and the elevation related to the vertical evolution of the lithosphere (uplifts on paleorifts shoulders for instance). Thus in Aube and Champagne paleoweathering confines to rubefaction and argillization of the Lower Cretaceous formations with short emersion [Ferry *et al*., 2001]. Further on the edges of the gutter, in Lower Normandy, Maine, Nivernais and Lorraine, the paleosoils are highly developed and in Nivernais and in Lorraine the weathering facies are more leached and mature. The thickest and most mature profiles are found on the Hercynian basement in Ardenne, Brabant, Massif Central and Brittany. Nevertheless, in the current state of knowledge of these weathering profiles, it is difficult to estimate the erosion effect of the Upper Cretaceous transgression and the subsequent Tertiary episodes.

Paleoelevations and erosion

Defining absolute paleoelevations of continental areas still represents a challenge whereas the magnitude of the topographies might be locally or regionally defined using paleokarst depth. A quantitative determination of paleoelevations is under progress using several techniques but significant results might be expected only in the future. A qualitative determination is however possible from global geodynamic modeling [Wyns, 1991] or low-temperature thermochronology and especially apatite fission track analysis [Gallagher *et al.*, 1998].

The analysis of about one hundred samples, mostly from the surface, has been carried out for the entire Massif Central and its borders [Siddall *et al.*, 1996; Pagel *et al.*, 1997; Barbarand *et al*., 2001, 2003; Peyaud *et al*., 2005]. From a general point of view, several domains appear where thermal history has been different: while some areas have been under erosion, others have been under sedimentation. Fission-track ages are increasing from south to north showing that Mesozoic vertical movements have been more important in the south of the Massif Central.

High temperatures (> 110°C) are recorded from apatite fission-track thermochronology (AFTT) in the south of the Massif Central during the early Cretaceous [Barbarand *et al*., 2001; Peyaud *et al*., 2005]. These high temperatures have been interpreted as the consequence of the deposition of a thick (2 000 m) sedimentary cover during the early Cretaceous (Neocomian) [Barbarand *et al*., 2001; Séranne *et al.*, 2002]. Erosion of this sedimentary cover has occurred in two steps: Mid-Cretaceous for areas which form today the regional heights and end of Cretaceous/beginning of Tertiary for areas today at the lowest elevation, following an escarpment retreat [Séranne *et al.*, 2002].

For the NW of the Massif Central (Limousin), highest temperatures are recorded during the Jurassic and are interpreted as evidence of a larger extent of the Aquitaine Basin on the Massif Central basement. This sedimentary cover has been removed through progressive erosion or successive pulses of erosion.

Samples from the Morvan Massif have also undergone two phases of erosion: one at the end of the Variscan orogeny, the other at the end of Cretaceous/beginning of Tertiary. Between these two erosions, high temperatures (80-90°C) are recorded during the Cretaceous [Barbarand *et al.*, 2003]. These results suggest the deposition of a Mesozoic sedimentary cover on the Morvan, constituted mainly of Upper Cretaceous chalk deposits.

Downloaded from http://pubs.geoscienceworld.org/sgf/bsgf/article-pdf/177/3/155/2966832/155.pdf
by BRGM user

North of the Wealden gutter (south of the Brabant Massif and Dinant syncline), deposition of a thick (3 000 m) sedimentary cover is suggested from AFTT data from late Paleozoic to early Mesozoic [Vercoutere and Van den Haute, 1993]. Erosion of this cover has occurred at the end of Jurassic/beginning of Cretaceous. High paleoelevations might be considered during this erosional episode.

Mesozoic erosion has also been recorded in the Bohemian Massif and the Rhenish Massif using AFTT. A thick cover (> 1000 m) has been eroded between the end of Jurassic and the late Cretaceous [Wagner *et al.*, 1997; Coyle *et al.*, 1997; Glasmacher *et al.*, 1998].

These studies show clearly a large erosional event during the early and late Cretaceous with a large extension throughout Europe, with nevertheless differential behaviours between some basement area.

PALEOGEOGRAPHY OF THE "WEALDEN" CONTINENT

The various weathering products of the early Cretaceous in France and Belgium are of a noteworthy homogeneity, with deep weathering profiles, widespread kaolinite and bauxite development, and frequency of the iron oxyde accumulations within lateritic materials and true ferricretes. The nature of weathering products points to similar global conditions, especially climatic conditions, all along this period. Other thick and well developed kaolinitic paleoprofiles are known during the same period in northern and central Europe [Lidmar-Bergström *et al.*, 1999; Migon and Lidmar-Bergström, 2001]. Other ones such as those of UK (Dartmoor, Scotland), Iberian peninsula, northern Africa, etc, may be of similar age, pending more investigations and datings.

The several weathering occurrences may not show the same stratigraphic bracketing, this is related to more local conditions. Local and/or regional paleogeographies and geodynamics, resulting in emersions at different times and of different duration, rule the distribution of weathering occurrences in time and space. During the early Cretaceous, the highland areas may never have been flooded and underwent continuous weathering, whereas the lowland areas and basin margins have been only sporadically emerged for shorter times. Gathering paleoweathering features on serial paleogeographic maps does not enable to have a general overview of the continental features. We chose to gather all the informations on a single paleogeographic map referred as "Wealden" continent, referring to the Weald Basin in UK, where continental conditions prevailed from the Purbeckian (late Berriasian) until the early Aptian [Allen, 1989], even if some of the studied paleoweathering features (i.e the bauxite in Provence) developed until the Aptian.

The inventory of Lower Cretaceous paleoweathering mantles and paleolandscapes enables to draw the paleogeographical map of continental areas in France and Belgium at this time (fig. 12). This map can be used to discuss the role of parameters involved in the distribution of the different occurrences and associated processes, namely: climate, eustatism and tectonic movements.

– Northwards (Brabant, Ardenne and Rhenish Massif) and southwards (Armorican Massif and Massif Central), old basements and detrital sediments of Triassic and Jurassic age are covered by kaolinitic saprolites and more or less deep karsts are formed within Paleozoic and Jurassic limestones.

– In the central area, the Wealden gutter which is affected by weaker weathering, acts as a supply of detrital sediments to the Tethys sea.

– Bauxites, which were typically formed in southern areas, can be encountered northwards where they reached the Anjou and Nivernais regions.

The originality of the early Cretaceous period lies in the great intensity and latitudinal extension of kaolinitic and bauxitic weathering processes. For this reason, it is possible that bauxites may have been formed even further to the north. Thick kaolinitic weathering mantles of this period have been reported in areas as far to the north as Scandinavia [Lidmar-Bergström *et al.*, 1999]. For comparison, modern kaolinitic weathering processes are restricted within the latitude range 15° South and North in Africa and South America and below the Cancer Tropic (North 22,5°) in monsoon areas of Asia.

The great geographical extension of kaolinitic paleosoils and saprolites is not necessarily associated with warm and wet climatic conditions but rather to the high CO_2 concentration in the Lower Cretaceous atmosphere, as it is known to greatly enhance silicate hydrolysis and carbonate dissolution [Berner, 1994; Ekart *et al.*, 1999]. Relative to modern atmospheric conditions, the same weathering balance is achieved with only a third of rainfall intensity if the atmosphere is ten times enriched in CO_2 as it was in Cretaceous times [Schmitt, 1999]. Considered alone, bauxite development may indicate higher temperatures, which enhance silica solubility. However, care should be taken in such interpretations given the fact that CO_2 concentration fluctuated during early Cretaceous times [Robinson *et al.*, 2002], and cold conditions prevailed during some periods of the Mid-Cretaceous, especially in the southern hemisphere [Price, 1999; Pirrie *et al.*, 2004]. Moreover, datings on paleosoils and saprolites are still too scarce and their time resolution too low to identify CO_2 fluctuations in the early Cretaceous atmosphere. It should also be kept in mind that the geological record from paleosoils is often strongly biased. As a typical example, under alternating pedoclimatic conditions, soils that formed under dryer conditions have low probability to be preserved if wetter climatic conditions come to prevail, due to subsequent alteration [Thiry, 2000]. On the other hand, kaolinite, which formed under wet conditions may not alter under dryer conditions. It results from this differential behaviour that kaolinite dominates weathering products preserved in the geological record and may lead to misinterpretation of the pedogenic processes in terms of paleoclimate.

Elevation, i.e. topography, plays a role in weathering development as it governs the drainage and water renewal in soils [Wyns, 1991, 2002]. This applies to upper horizons of soils but also, and maybe to a greater extent, to the deeper horizons where downwards weathering proceeds within the saprolite. Once the landscape is cut by valleys, the groundwater flow potential is created and groundwater discharges even in coastal plains, provided adequate climatic conditions occur. Moreover, in steep reliefs, erosion prevails on chemical weathering and mature weathering profiles do not form or have little chance to be preserved [Thiry, 2000]. There is a subtle equilibrium between tectonic uplift, which sustains the

Downloaded from http://pubs.geoscienceworld.org/sgf/bsgf/article-pdf/177/3/155/2966832/155.pdf
by BRGM user

drainage potential, and overall lowering and smoothing of the surface due to weathering and erosion processes. Thus, paleokarsts are excellent traps for the preservation of weathering products against continental erosion or marine transgression; this explains the frequency of paleo-weathering remnants on weathered Jurassic limestone platforms.

The exposure time of formations to the atmosphere, i.e. weathering duration, is another important parameter that also has to be taken into account. The development of thick weathering profiles is a slow process and the formation of a surface covered by mature kaolinitic soils requires one to several million years. The distribution and the characteristics

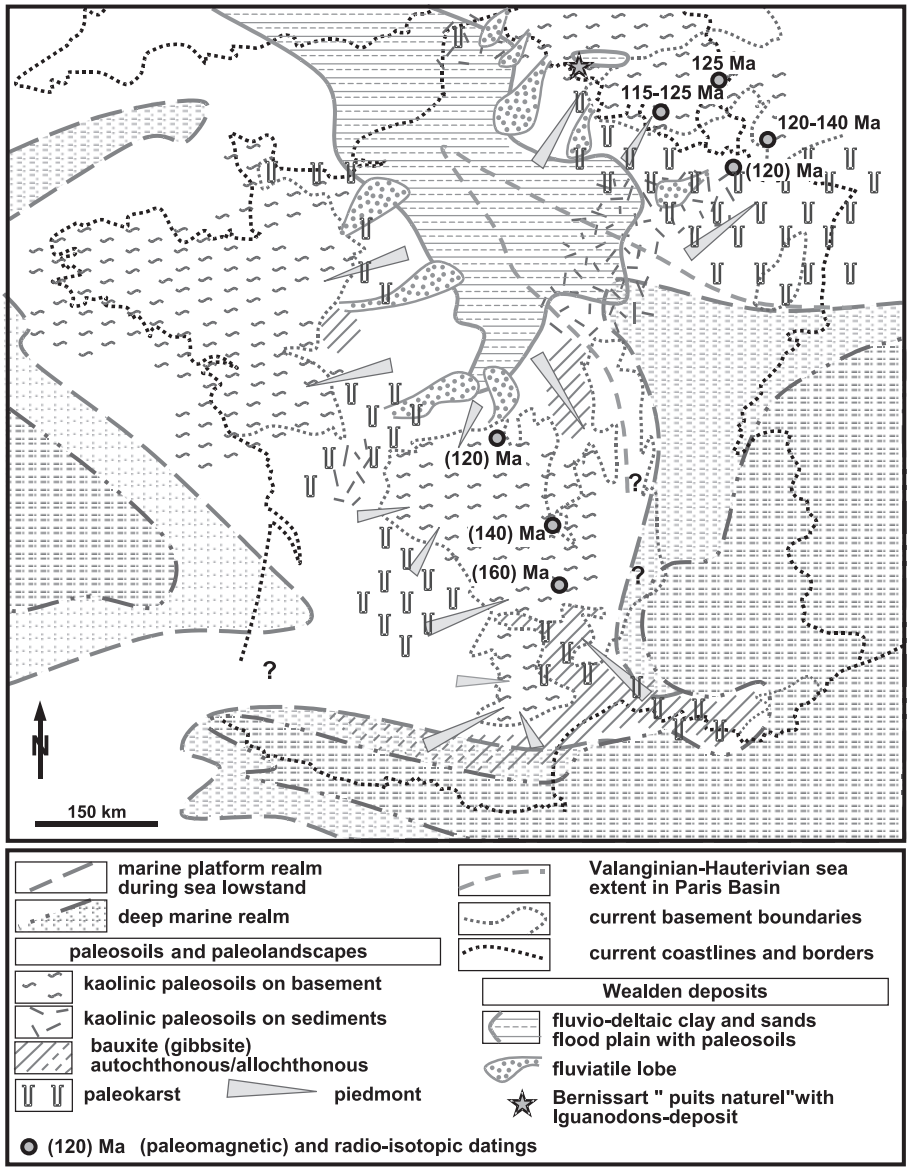


FIG. 12. – Lower Cretaceous paleoweathering occurrences synthesis as drawn on the paleogeographic map of France and Belgium from Berriasian to Barremian. The paleogeographic frame of marine realms has been compiled and modified after the Tethys Atlas maps [Masse *et al.*, 1993] and the Paris Basin synthesis [Magniez *et al.*, 1980]. Marine realms have been drawn upon the Morvan Massif and the eastern Massif Central during Valanginian-Hauterivian in order to agree with geological data [Rat, 1968] and apatite fission tracks thermochronology [Barbarand, 1999], although placing precisely the coastlines remains difficult because of the subsequent erosions. The major feature of the continental paleogeography is the Wealden gutter, individualized between deeply weathered basement areas. The detrital supplies from tributaries well distinguished in some areas, and accumulated in a vast flood plain behind the Burgundy threshold. Wide basement areas were cropping out and covered by thick kaolinitic paleosoils, as shown by recent datings. Vast karstic landscapes developed upon all the cropping out Jurassic platforms. Bauxites covered almost the whole South of France, their extent seems to have been more limited in the Paris Basin : nevertheless bauxites are probably only residual there, many surfaces might have been resilicified during the Tertiary.

FIG. 12. – *Synthèse des occurrences de paléoaltérations crétacées inférieures reportées sur la carte paléogéographique de la France et de la Belgique pour la période du Berriasien au Barrémien. Le cadre paléogéographique des domaines marins a été compilé et modifié d'après l'Atlas de la Téthys [Masse* et al.*, 1993] et la synthèse du bassin de Paris [Magniez* et al.*, 1980]. Les domaines marins ont été tracés chevauchant le Morvan et l'est du Massif central au Valanginien-Hautérivien pour rendre compte des données géologiques [Rat, 1968] et thermochrologiques des traces de fission dans les apatites [Barbarand, 1999], bien qu'il soit difficile de replacer précisément les rivages en raison des érosions ultérieures. Le trait majeur de la paléogéographie continentale est constitué par la gouttière wealdienne, individualisée entre des zones de socle profondément altéré. Les apports détritiques y affluent par des tributaires bien individualisés dans certains secteurs, et s'accumulent dans une vaste plaine d'inondation en arrière du seuil de Bourgogne. De larges zones de socle étaient à l'affleurement et couvertes d'épais paléosols kaoliniques, comme l'ont montré les récentes datations. D'amples paysages karstiques sont développés sur toutes les plates-formes jurassiques à l'affleurement. Les bauxites sont omniprésentes dans le Sud de la France, leur extension semble plus limitée dans le bassin de Paris, mais elle n'y sont vraisemblablement que résiduelles, d'importantes surfaces ayant pu être resilicifiées au cours du Tertiaire.*

Downloaded from http://pubs.geoscienceworld.org/sgf/bsgf/article-pdf/177/3/155/2966832/155.pdf
by BRGM user

of Lower Cretaceous paleoweathering mantle seem to support this idea. Thus, thick paleosoils are encountered in Paleozoic massifs and along the edges of the Wealden gutter while they are less abundant and thinner in the centre of the gutter. This situation may be explained by topographical control but also by time exposure. Indeed, the gutter flanks had a stronger susceptibility to aerial exposure by sea-level fall than the centre as they formed topographical "heights", whatever the cause of the emersions, namely eustatism or epirogenic oscillations.

Anyway, the distribution of paleosoils and saprolites during the early Cretaceous in France and Belgium indicates that hills and plateaus underwent more intense weathering processes than lowlands (coastal plains). Therefore, on the first order, large wavelength tectonics appear to control weathering intensity and distribution in continental environments [Wyns, 1991, 2002; Quesnel, 1997] as it controls the accomodation distribution in the basins [Robin *et al*., 1998]. During the early Cretaceous, this tectonic activity mainly proceeded as uplifts along rift shoulders, respectively the Gascogne rift for the area between the Bretagne tip and the Provence [Wyns, 1999; Wyns *et al*., 2003], and the rift associated with the North Sea for the Brabant and Ardenne massifs [Quesnel *et al*., 2002].

Lower Cretaceous kaolinitic paleosoils, although they have been enhanced by hot and wet climatic conditions as well as by high CO_2 concentration in the atmosphere, are also indicators of uplifted areas. It is likely that during this period, the overall trend for all old basements in Europe was to be located at higher elevation than peripheral Jurassic platforms. The thick weathering profiles covering these elevated basements areas supplied detrital materials to the adjacent basins, passing on the Jurassic platforms where continental deposits were occasionally trapped in the karsts. However, based on the state of knowledge and available techniques it is not possible today to decipher the respective elevations of basement areas and Jurassic platforms. If compared with modern rift shoulders, such as those of Africa, elevations between 1000 and 3000 m are possible, but extrapolating these values to the Lower Cretaceous paleoelevations remains speculative.

CONCLUSION

Recent works on paleoweathering in France and Belgium, especially dating data collected from paleoprofiles in different geological settings, have deeply renewed our knowledge of the Lower Cretaceous continent. Among the findings listed and discussed in this contribution, it should be highlighted that:

– based on new geochronological data, early Cretaceous ages obtained on several formations that were up to now widely attributed to the Siderolithic *s.l.*, mainly to the late Eocene-Oligocene period, lead to greatly revise the importance of the post-Cretaceous weathering relative to its Lower Cretaceous counterpart which is contemporaneous with bauxite development;

– deciphering the informations from the paleomorphologies linked to these paleosoils also enables to list diverse paleolandscapes with scarps, wide plateaus, inselbergs, paleovalleys on crystalline basement, karstic landscapes on the limestone plateaus, also cuestas and fluvial channels, and finally connection of these paleomorphologies to the flood plain established in the Wealden gutter;

– the mapping of the paleoweathering-related data gives the basis for a paleogeographic map of the continental realm, providing additional information for classical paleogeographic maps which mainly concern marine realms;

– the inventory and the mapping of these powerful extensive kaolinitic paleosoils enables to discuss the processes at play in their development, the respective role of atmosphere geochemistry, of climate, tectonics and duration.

This rough inventory of the Lower Cretaceous paleosoils and saprolites shows the great complexity of continental history during this period but also general trends all over the studied area. The preserved paleoweathering mantles may be envisioned as "snapshots" of a longlasting continental evolution, the aspects concerning erosion phases being more difficult to handle and quantifiy. In this research area, data such as apatite fission-track thermochronology may provide an order of magnitude of the denudation amplitude [Barbarand *et al*., 2001; Barbarand, 2003] and vertical movements may be interpreted using global geodynamics [Wyns, 1991, 2002; Wyns *et al*., 2003]. Relative elevations can be assessed from both the residual testimonies and subsequent transgressions. In contrast, there are no reliable tools, which can be used to evaluate absolute paleoelevations whereas such tools exist for paleobathymetry assessment in the marine realm.

The next challenge is to make substantial progress in paleoweathering profiles dating, especially to improve time resolution which is a necessary step before attempting efficient correlation between the continental records, i.e. the paleoweatherings, and the diverse processes involved in their development (eustatism, climate, global and regional tectonics). Another challenge is to draw paleogeographic maps showing the paleoweathering features and the differentiated paleolandscapes, in the same way as marine paleogeographic maps show depositional environments, paleobathymetry, etc. Our goal is also to set up a "continental stratigraphy of climatic and geodynamic events" which is expected to be compared to the "sequence stratigraphy" used in marine realm.

Acknowledgements. – This work was supported financially by the ANDRA, the Service de la Carte Géologique de France, the ONDRAF/NIRAS, the FNRS, the Heidelbergcement-CBR group and the Communauté Française de Belgique. The continental paleogeographic map presented in this paper is inspired from a number of different researches that ran for the past 20 years on paleoweathering– and paleosurface-related topics: first the program R.C.P. 706 of CNRS "Paléoaltérations superficielles et profondes" (1983-1987), then the IGCP 317 of UNESCO "Paleoweathering Records and Paleosurfaces" (1990-1995) and finally diverse BRGM projects (Sedimor, Reliefs, CANEV). Space is lacking to list here all the colleagues and friends who have contributed to this work by mentioning sections in the field, providing sample analysis, or simply by exchanging ideas. Their help is greatly appreciated even if they are not cited here. Without these people, the paleogeographic map would not appear as presented here.

Downloaded from http://pubs.geoscienceworld.org/sgf/bsgf/article-pdf/177/3/155/2966832/155.pdf
by BRGM user

References

ALLEN P. (1989). – Wealden research – ways ahead – *Proc. Geol. Ass.*, **100**, 529-564.

ASTRUC J.G. (1988). – Le paléokarst quercynois au Paléogène: altérations et sédimentations associées. – *Doc. BRGM*, **133**, 135 p.

BARBARAND J. (1999). – Cinétique de cicatrisation des traces de fission dans les cristaux d'apatite et histoire thermique de la bordure Sud-Est du Massif central. – Thèse doctorat, géochimie, Université Henri Poincaré, Nancy I, 323 p. + VII annexes (169 p.).

BARBARAND J. (2003). – Apatite fission-track thermochronology in western Europe: search for weathered/eroded cover rocks on the Hercynian basement (method, results, limitations and perspectives). – *Géol. France*, **1**, 91-93.

BARBARAND J., CARTER A. & PAGEL M. (2003). – La recherche de l'extension des formations crétacées aujourd'hui érodées. – Réunion SGF-AGBP-CFC: *Bassins crétacés de France et d'Europe occidentale*, Paris, 6-7 Novembre 2003, 1 p.

BARBARAND J., LUCAZEAU F., PAGEL M. & SÉRANNE M. (2001). – Burial and exhumation history of the southeastern Massif Central (France) constrained by apatite fission track thermochronology. – *Tectonophysics*, **335**, 3-4, 275-290.

BARDOSSY G. & COMBES P.-J. (1999). – Karst bauxites: interfingering of deposition and palaeoweathering. *In*: M. THIRY & R. SIMON-COINÇON, Eds., Palaeoweathering, palaeosurfaces and related continental deposits. – *Spec. Publ. Intern. Ass. Sediment.*, **27**, 189-206.

BELLION G. (1979). – Contribution à l'étude du gisement de kaolin de Ploëmeur (Morbihan): caractères, origine. – Thèse 3ème cycle, Univ. Rennes, 189 p.

BERNER R.A. (1994). – GEOCARB II: A revised model of atmospheric CO_2 over Phanerozoic time. – *Am. J. Sci.*, **294**, 56-91.

BERTHIER P. (1821). – Analyses de l'alumine hydratée des Baux, département des Bouches-du-Rhône. – *Ann. des Mines*, Paris, **VI**, 531-534.

BESSE J. & COURTILLOT V. (2002). – Apparent and true polar wander and the geometry of the geomagnetic field over the last 200 m.y. – *J. Geophys. Res.*, **107**, (B11) 2300, doi: 10.1029/2000JB000050.

BIGOT A. (1939). – Cavités karstiques dans les calcaires du Jurassique inférieur du Calvados. – *Bull. Soc. Linn. Normandie*, **9**, I, p. 54.

BLAVIER E. (1842). – Etudes géologiques sur le département de l'Orne. – *Annuaire de l'Orne*, 95 p.

BLESS M.J.M. & FELDER P.J. (1989). – Note on the late Cretaceous of Hockai (Hautes Fagnes, NE Belgium). – *Ann. Soc. Géol. Belgique*, **112**, 1, 47-56.

BONNISSENT P. (1870). – Essai géologique sur le département de la Manche. – *Mém. Soc. Sc. Nat. & Math. Cherbourg*, 430 p.

BONTE A. (1955). – Sables verts et poches de dissolution dans le Bathonien moyen de l'Aisne et des Ardennes. – *Ann. Soc. géol. Nord*, **75**, 72-83.

BONTE A. (1965). – Sur la formation en deux temps des bauxites sur mur calcaire. – *C.R. Acad. Sci.*, Paris, **26**, D, 5076-5078.

BONTE A. & GODFRIAUX Y. (1958). – Le Wealdien du Boulonnais (feuilles de Marquise et de Boulogne à 1/50 000). – *Bull. Serv. Carte Géol. France*, **255**, 20-28.

BOULANGER M.C. (1844). – Statistique géologique et minéralurgique du département de l'Allier. – Imp. P.A. Desrosiers, Moulins, 482 p.

BOULVAIS P., VALLET J.-M., ESTÉOULE-CHOUX J., FOURCADE S. & MARTINEAU F. (2000). – Origin of kaolinisation in Brittany (NW France) with emphasis on deposits over granites: stable isotope (O, H) constraints. – *Chem. Geol.*, **168**, 211-223.

BRAULT N. (2002). – Ressources du sous-sol et environnement en Bretagne. Genèse, géométrie et propriétés des différents types d'aquifères. – Thèse Doct., Géosciences Rennes, Univ. Rennes 1, 193 p. + annexes

BRUXELLES L. (2001). – Dépôts et altérites des plateaux du Larzac central: causses de l'Hospitalet et de Campestre (Aveyron, Gard, Hérault). Evolution morphogénique, conséquences géologiques et implications pour l'aménagement. – Thèse doct., Université de Provence, Aix-en-Provence, 266 p. + 5 cartes couleur.

BRUXELLES L. (2003). – La doline du Luc-Bas (Campestre-et-Luc, Gard): témoin des paléoaltérations successives des Grands Causses et de leur morphogenèse. – *9ème Congrès Français de Sédimentologi*e, Livre des résumés, 2003, n° **38**, 94-95.

BRUXELLES L., AMBERT P., GUENDON J.-L. & TRONCHETTI G. (1999). – Les affleurements du Crétacé supérieur sur les Grands Causses méridionaux (France). – *C.R. Acad. Sci.*, Paris, *Sciences de la Terre et des Planètes*, **329**, 1, 705-712.

CANTINOLLE P., DIDIER P., MEUNIER J.-D., PARRON C., GUENDON J.-L., BOCQUIER G. & NAHON D. (1984). – Kaolinites ferrifères et oxy-hydroxydes de fer et d'alumine dans les bauxites des Canonnettes (S.E. de la France). – *Clay Minerals*, **19**, 125-135.

CARPENTIER A. (1926). – Sur l'extension du Wealdien dans le Nord de la France. – *C.R. Acad. Sci.*, Paris, **183**, 667-669.

CASANOVA J., GIOT D., QUESNEL, F., NÉGREL PH., ROBELIN C., ROGER J. & WYNS R. (2001). – Projet Sedimor, apports de l'histoire géologique des argilites sur les interactions fluides-roches, rapport d'avancement au 31/01/2001. – *Rap. BRGM/RP-50660-Fr*, 91 p.

CASIER E. (1960). – Les iguanodons de Bernissart. – Edit. du patrimoine de l'Institut Royal des Sciences Naturelles de Belgique, 134 p.

CAUMONT A. (de) (1828). – Essai sur la topographie géognostique du département du Calvados. – *Mém. Soc. Linn. Normandie*, **IV**, 56-236.

COMBES P.J. (1990). – Typologie, cadre géodynamique et genèse des bauxites françaises. – *Geodin. Acta*, **4**, 2, 91-109.

COMBES P-J. & PEYBERNÈS B. (1991). – Rôle de l'eustatisme dans la genèse des bauxites de type Ariège (Pyrénées centrales). – *C. R. Acad. Sci.*, Paris, **313**, II, 669-676.

CORROY G. (1925). – Le Néocomien de la bordure orientale du bassin de Paris. – Thèse Nancy, 334 p.

COYLE D. A., WAGNER G. A., HEJL E., BROWN R. & VAN DEN HAUTE P. (1997). – The Cretaceous and younger thermal history of the KTB site (Germany): apatite fission track data from the Vorbohrung. – *Geol. Rundsch.*, **86**, 203-209.

DANGEARD L. (1936). – Observations sur la feuille géologique de Mortagne. – *Bull. Soc. Linn. Normandie*, 8, **IX**, 145-148.

DANGEARD L. (1944). – Poches de décalcification remplies d'argiles et de galets entre Caen et la mer. – *Bull. Soc. Linn. Normandie*, 9, **III**, 87-88.

DELÉPINE G. (1925). – Pierre de Stonne, Caillou de Beaumont et dépôts wealdiens sur la feuille de Mézières. – *Ann. Soc. géol. Nord*, **1924**, 30-148.

DEMOULIN A. (1995). – Les surfaces d'érosion méso-cénozoïques en Ardenne-Eifel. – *Bull. Soc. géol. Fr.*, **166**, 5, 573-585.

DERCOURT J., GAETANI M., VRIELYNCK B., BARRIER E., BIJU-DUVAL B., BRUNET M.-F., CADET J.-P., CRASQUIN S. & SANDULESCU M., Eds., (2000). – Atlas Peri-Tethys, palaeogeographical maps. – CCGM/CGMW, Paris, 24 maps and explanatory notes, I-XX, 269 p.

DERCOURT J., RICOU L.-E. & VRIELYNCK B., Eds (1993). – Atlas Tethys palaeoenvironmental maps. – Gauthier-Villars, Paris, 14 maps + 1 plate, 307 p.

DESCHAMPS M. (1973). – Etude géologique du Sidérolithique du Nord-Est, du centre du Massif central français et des terrains qui lui sont associés. – Thèse Doct.-ès-Sci., Univ. Paris IV, 1270 p.

DUFAY D. (1955). – Etude stratigraphique et pétrographique du Cénomanien inférieur et moyen du Perche septentrional. – *Bull. Soc. Linn. Normandie*, 9, **VIII**, 70-86.

DUPUIS C. (1992). – Mesozoic kaolinised giant regoliths and Neogene halloysitic cryptokarst: two striking paleoweathering types in Belgium. *In*: J.-M. SCHMITT & Q. GALL, Eds, Mineralogical and geochemical records of paleoweathering. – *Mém. Sci. de la Terre*, ENSMP, **18**, 61-68.

DUPUIS C., CHARLET J.-M., DEJONGHE & THOREZ J. (1996). – Reconnaissance par carottage des paléoaltérations kaolinisées mésozoïques de la Haute Ardenne (Belgique). Le sondage de Transinne (194E-495): premiers résultats. – *Ann. Soc. Géol. Belgique*, **2**, 91-109.

DUPUIS C. & VANDYCKE S. (1989). – Tectonique et karstification profonde: un modèle de subsidence original pour le bassin de Mons. – *Ann. Soc. Géol. Belg.*, **112**, 2, 479-489.

Downloaded from http://pubs.geoscienceworld.org/sgf/bsgf/article-pdf/177/3/155/2966832/155.pdf
by BRGM user

DURAND S. (1960). – Le Tertiaire de Bretagne. Etude stratigraphique, sédimentaire et tectonique. – *Mém. Soc. Géol. Min. de Bretagne*, **XII**, 389 p.

DURAND S. & MILON Y. (1959). – Sédimentation et évolution continentale au Crétacé et au Tertiaire au sud du Massif armoricain et en Bretagne. – *Bull. Soc. Géol. Minéral. Bretagne*, **I,** 67-77.

EKART D.D., CERLING T.E., MONTANEZ I.P. & TABOR N.J. (1999). – A 400 million year carbon isotope record of pedogenic carbonate: implications for paleoatmospheric carbon dioxide. – *Am. J. Sci.*, **299**, 805-827.

ELHAÏ H. (1963). – La Normandie occidentale entre la Seine et le golfe normand-breton. Etude morphologique. – Thèse Doc. ès lettres, Paris, Imp. Brière, Bordeaux, 675 p.

ESTÉOULE-CHOUX J. (1967). – Contribution à l'étude des argiles du Massif armoricain. Argiles des altérations et des bassins sédimentaires tertiaires. – *Mém. Soc. Géol. Min. de Bretagne*, **XIV**, 319 p.

ESTÉOULE-CHOUX J. (1983). – Altérations et silicifications au Tertiaire dans le Massif armoricain. – *Géol. France*, **4**, 345-352.

ESTÉOULE-CHOUX J., ESTÉOULE J. & LOUAIL J. (1969). – Sur la présence d'un dépôt à kaolinite et à gibbsite entre le Bajocien et le Cénomanien en Maine-et-Loire. – *C.R. Acad. Sci.*, Paris, série D, **268**, 891-893.

ESTÉOULE-CHOUX J., ESTÉOULE J. & LOUAIL J. (1971). – Etude géologique et minéralogique des "argiles à silex" surmontant le Bajocien du Touveil (Maine-et Loire). Mise en évidence d'évolutions successives. – *93ème Congrès National des Sociétés Savantes*, Tours, 1968, Sciences, t. I, 215-231.

FABER A., GAMEZ P., HANZO M. & MIRAMBET F. (1999). – Le fer. *In*: HANZO M. (coord.), Mines de Lorraine et du Luxembourg. Journée d'étude d'automne (1-3 octobre 1998). – *Bull. Inf. Géol. Bass. Paris*, **36**/1, 27-34.

FERRY S., KAELIN J.-L., ELION P., COURTINAT B., BUSNARDO R. & CLAVEL B. (2001). – Révision stratigraphique du Crétacé inférieur du bassin de Paris à la lumière des travaux de l'ANDRA sur le site de l'Aube. – *8ème Congrès ASF*, Orléans, Livre des résumés. – *Publ. ASF*, Paris, 36, p. 135.

GALLAGHER K., BROWN R. & JOHNSON C. (1998). – Fission track analysis and its applications to geological problems. – *Annu. Rev. Earth Planet. Sci.*, **26**, 519-572.

GIGOT P., DUPRÉ L., LE GALL J., COUTARD J.-P., OZOUF J.-C., PAY T., LECOINTE A., DESLOGES J. & DEROIN J.-P. (1999). – Carte géologique de la France à 1/50 000, feuille Falaise, n°176. – BRGM, Orléans, et Notice explicative, 154 p.

GILG H.A. (2000). – D-H evidence for the timing of kaolinitization in Northeast Bavaria, Germany. – *Chem. Geol.*, **170**, 5-18.

GIOT D., QUESNEL F., WYNS R., ROGER J., ROBELIN C., CASANOVA J., NÉGREL P. & BRULHET J. (2003). – La paléoaltération anté-albienne au forage de Villers-le-Tourneur (feuille Rethel, Ardennes, France): un témoin décisif dans la reconstruction des paléosurfaces au NE du bassin de Paris, ASF 2003 – *9ème Congrès ASF*, Bordeaux, Livre des résumés. – *Publ. ASF*, Paris, **38**, 232 – 233.

GIRAUD J. (1902). – Etudes géologiques sur la Limagne (Auvergne). – *Bull. Serv. Carte Géol. Fr.*, **13**, 87, 410 p.

GLASMACHER U., ZENTILLI M. & GRIST A.M. (1998). – Apatite fission-track thermochronology of Paleozoic sandstones and the Hill-intrusion, northern Linksrheinisches Schiefergerbirge, Germany. *In*: P. VAN DEN HAUTE and F. de CORTE, Eds., Advances in fission-track geochronology. – Kluwer Academic Publishers, p. 151-172.

GOSSELET J. (1888). – L'Ardenne. – *Mém. Serv. expl. Carte géol. dét. Fr.*, 881 p.

GOSSELET J. (1911). – Les assises crétaciques et tertiaires dans les fosses et sondages du Nord de la France – fasc. 3. Région de Béthune. – Etude des Gîtes et Minéraux de la France, Paris, 178 p.

GOSSELET J. (1913). – Les assises crétaciques et tertiaires dans les fosses et sondages du Nord de la France – fasc. 4. Région de Valenciennes. – Etude des Gîtes et Minéraux de la France, Paris, 222 p.

GROSSOUVRE A. (de) (1886). – Etude sur les gisements de fer du centre de la France. – *Ann. Mines*, sér. 8, **10**, 311-418.

GROULT J. (1959). – Sables séquaniens et sables albiens des environs de Lisieux. – *Mem. Sci. Nat. & Math. Cherbourg*, sér. 5, **9**, 69-152.

GUENDON J.-L. & PARRON C. (1985). – Les phénomènes karstiques dans les processus de bauxitisation sur substrat carbonaté. – *Ann. Soc. géol. Belgique*, **108**, 85-92.

GUENDON J.-L., PARRON C. & TRIAT J.-M. (1983). – Incidences des altérations crétacées sur la notion de Sidérolithique dans le Sud-Est de la France. – *Bull. Soc. géol. France*, série 2, **XXV**, 1, 41-50.

GUILLOCHEAU F., BRAULT N., THOMAS E., BARBARAND J., BONNET S., BOURQUIN S., ESTÉOULE-CHOUX J., GUENNOC P., MENIER D., NÉRAUDEAU D., PROUST J.N. & WYNS R. (2003). – Histoire géologique du Massif armoricain depuis 140 Ma (Crétacé-Actuel). – *Bull. Inf. Géol. Bass. Paris*, **40**, 1, 13-28.

GUILLOCHEAU F., ROBIN C., ALLEMAND P., BOURQUIN S., BRAULT N., DROMART G., FRIEDENBERG R., GARCIA J.-P., GAULIER J.-M., GAUMET F., GROSDOY B., HANOT F., LE STRAT P., METTRAUX M., NALPAS T., PRIJAC C., RIGOLLET C., SERRANO O., VAIRON J. & GRANDJEAN G. (2000). – Meso-Cenozoic geodynamic evolution of the Paris Basin: 3D stratigraphic constraints. – *Geodin. Acta*, **13**, 198-246.

JACQUOT E. (1849). – Mémoire sur les mines et les minières de la partie occidentale du département de la Moselle. – *Ann. Mines*, **16**, 427-494.

JUIGNET P. (1965). – Analyse minéralogique des sédiments arénacés de l'Oxfordien supérieur, de l'Albien et d'une formation intermédiaire dans la région de Lisieux (Calvados). – *Bull. Soc. géol. France*, 7, **VII**, 327-333.

JUIGNET P. (1971). – Modalité du contrôle de la sédimentation sur la marge armoricaine du bassin de Paris à l'Aptien-Albien-Cénomanien. – *Bull. Bur. Rech. Géol. Min.*, (2), **1**, 3, 113-126.

JUIGNET P. (1974). – La transgression crétacée sur la bordure orientale du Massif armoricain. Aptien, Albien, Cénomanien de Normandie et du Maine. Le stratotype du Cénomanien. – Thèse Doct. ès Sci., Univ. Caen, 786 p.

LAJOINIE J.P. & LAVILLE P. (1979). – Les formations bauxitiques de la Provence et du Languedoc. Dimensions et distribution des gisements. – *Mém. BRGM*, **100**, 142 p.

LAPPARENT (de) J. (1930). – Les bauxites de la France méridionale. – *Mém. carte géol. détaillée de la France*, 205 p.

LAUNAY L. (de) (1892-93). – Etude sur le plateau central. I. La vallée du Cher dans la région de Montluçon. – *Bull. Serv. Carte Géol. Fr.*, **30**, IV, 289-328.

LAVILLE P. (1981). – La formation bauxitique provençale (France). Séquence des faciès chimiques et paléomorphologie crétacée. – *Chron. Rech. minière*, **461**, 51-68.

LECLERCQ V. (1980). – Le sondage de Douvrain. – Publication du Service Géologique de Belgique, Ministère des Affaires Economiques, *Professional Paper* 1980/3, **170**, Bruxelles, 51 p.

LEGRAND R. (1968). – Le massif du Brabant. – *Mem. Expl. Cartes géol. et min. Belg.*, **9**, 148 p.

LIDMAR-BERGSTRÖM K., OLSSON S. & ROALDSET E. (1999). – Relief features and palaeoweathering remnants in formerly glaciated Scandinavian basement areas. *In*: M. THIRY R. & SIMON-COINÇON, Eds., Palaeoweathering, palaeosurfaces and related continental deposits. – *Spec. Publ. Int. Ass. Sediment.*, **27**, 275-301.

LIPPOLT H. J., BRANDER T. & MANKOPF N. R. (1998). – An attempt to determine formation ages of goethites and limonites by (U + Th)-^{4}He dating. – *N. Jb. Miner. Mh.*, Stuttgart, **11**, 505-528.

LOUAIL J. (1984). – La transgression crétacée au sud du Massif armoricain. Cénomanian de l'Anjou et du Poitou, Crétacé supérieur de Vendée. Etude stratigraphique, sédimentologique et minéralogique. – *Mém. Soc. Géol. Minéral. Bretagne*, Rennes, **25**, 333 p.

MAGNIEZ F., MÉDIONI R. MÉGNIEN C., MÉGNIEN F., AMÉDRO F., DESTOMBES P., FAUVEL P.J., JUIGNET P. MANIVIT J., ROBAZYNSKI F. & SORNAY J. (1980). – Crétacé Inférieur. *In*: CL. MÉGNIEN & F. MÉGNIEN, Eds., Synthèse géologique du bassin de Paris – Stratigraphie et paléogéographie. – *Mém. BRGM*, **101**, 255-287.

MANSY J.-L., LAMARCHE J., AUFFRET J.-P., GUENNOC P., VIDIER J.-P., AMEDRO F., ROBASZYNSKI F., LEFEVRE D., SOMME J., DENISE B., MISTIAEN B., PRUD'HOMME A. & VACHARD D. (2006). – Carte géologique de la France à 1/50 000, feuille Marquise, seconde édition, n°5, + Notice explicative, Orléans: BRGM.

MASSE J.-P., BELLION Y., BENKHELIL J., BOULIN J., CORNÉE J.-J., DERCOURT J., GUIRAUD R., MASCLE G., POISSON A., RICOU L.-E. & SANDULESCU M. (1993). – Lower Aptian palaeoenvironments (114-112 Ma). I*n*: J. DERCOURT, L.E. RICOU & B. VRIELYNCK, (eds), Atlas Tethys palaeoenvironmental maps. – Gauthier-Villars, Paris, 14 maps + 1 plate, 307 p.

Downloaded from http://pubs.geoscienceworld.org/sgf/bsgf/article-pdf/177/3/155/2966832/155.pdf
by BRGM user

MASSE J.-P. & PHILIP J. (1976). – Paléogéographie et tectonique du Crétacé moyen en Provence: révision du concept d'isthme durancien. – *Revue Géogr. Phys. Géol. Dyn., (2)*, **18**, 1, 49-66.

MAURIZOT P., AUFFRET J.-P., BAIZE S., DEROIN, J.-P., DUGUÉ O., FILY G., LE GALL J., LELIEPAULT F., MAZENC B. & PELLERIN J. (2000). – Carte géologique de la France à 1/50 000, feuille Bayeux-Courseulles, n°119. – BRGM, Orléans, et notice explicative.

MÉDIONI R. & ROBASZINSKI F. (1980). – Les faciès wealdiens. *In*: CL. MÉGNIEN & F. MÉGNIEN, Eds., Synthèse géologique du bassin de Paris – Stratigraphie et paléogéographie. – *Mém. BRGM*, **101**, 275-279.

MEES F. & STOOPS G. (1999). – Palaeoweathering of Lower Palaeozoic rock of the Brabant Massif, Belgium: a mineralogical and petrological analysis. – *Geol. J.*, **34**, 349-367.

MÉNILLET F., GÉRARD J., KUNTZ G., LETURCQ T., PELLERIN F. & QUESNEL F. (1997). – Carte géologique de la France à 1/50 000, feuille Sées, n°213, BRGM: Orléans. Notice explicative par MÉNILLET F., GÉRARD J., LANGEVIN C., LEMOINE B., LETURCQ T., PELLERIN J. & QUESNEL F.

MEYER R. (1976). – Continental sedimentation, soil genesis and marine transgression in the basal beds of the Cretaceous in the East of the Paris Basin. – *Sedimentology*, **23**, 235-253.

MIGON P. & LIDMAR-BERGSTRÖM K. (2001). – Weathering mantles and their significance for geomorphological evolution of central and northern Europe since the Mesozoic. – *Earth-Sci. Rev.*, **56**, 285-324.

MILON Y. (1932). – L'extension des formations sidérolithiques éocènes dans le centre de la Bretagne. – *C. R. Acad. Sci*., Paris, **194**, 1360-1361.

NICOLAS J. (1968). – Nouvelles données sur la genèse des bauxites à mur karstique du sud-est de la France. – *Mineral. Deposita*, **3**, 18-33.

PAGEL M., BRAUN J.-J., DISNAR J.-R., MARTINEZ L., RENAC C. & VASSEUR G. (1997). – Thermal history constraints from studies of organic matter, clay minerals, fluid inclusions and apatite fission-track at the Ardèche paleo-margin (BA1 drillhole, GPF program), France. – *J. Sed. Res.*, **67**, 235-245.

PELLERIN J. (1967). – Premiers résultats d'une étude des argiles d'altération à silex jurassiques de la campagne de Caen. – *Mém. hors-sér. Soc. géol. Fr.*, **4**, 60-64.

PELLERIN J. (1968). – La campagne de Caen ; plateaux jurassiques et bordure du Massif ancien. – Thèse 3ème cycle, Univ. Caen, 343 p.

PEYAUD J.-B., BARBARAND J., CARTER A. & PAGEL M. (2005). – Mid-Cretaceous uplift and erosion on the northern margin of the Ligurian Tethys deduced from thermal history reconstruction. – *Internat. J. Earth Sci.*, 94/3, p. 462-474. DOI: 10.1007/s00531-005-0486-z

PIRRIE D., MARSHALL J.D., DOYLE P. & RICCARDI A.C. (2004). – Cool early Albian climates; new data from Argentina. – *Cret. Res.*, **25**, 27-33.

PRICE G.D. (1999). – The evidence and implications of polar ice during the Mesozoic. – *Earth-Science Rev.*, **48**, 3, 183-210.

QUESNEL F. (1997). – Cartographie numérique en géologie de surface. Application aux altérites à silex de l'ouest du bassin de Paris. – Thèse, Univ. Rouen, 256 p, annexes 162 p.

QUESNEL F. (2003). – Paleoweathering and paleosurfaces from northern and eastern France to Belgium and Luxembourg: geometry, dating and geodynamic implications. *In*: Paleoweathering and paleosurfaces in the Ardennes-Eifel region – Preizerdaul, Luxembourg, 14-17 mai 2003. – *Géol. France*, **1**, 95-104.

QUESNEL F., DUGUÉ O., RÉMONDOT R.-C., COUEFFE R., LE GALL J., VERNHET Y., OTT D'ESTEVOU P., AUFFRET J.-P., DEROIN J.-P., POUPINET N., OZOUF J.-C., LAUTRIDOU J.-P., COUTARD J.-P., CLET M. & FRESLON M., *unpublished*, Carte géologique de la France à 1/50 000, feuille Sainte-Mère-Eglise, n° 94. – BRGM, Orléans, et notice explicative.

QUESNEL F., GIOT D., ROBELIN C., ROGER J., WYNS R. & CASANOVA J. (2002). – Apports des paléoaltérations et des paléosurfaces à la reconstitution de l'histoire hydrogéologique de l'est de la France (projet SEDIMOR). – Journée du Partenariat de Recherche et Développement entre le BRGM et l'ANDRA, Orléans, France, 5 mars 2002, Programme et résumés, p. 57-62.

QUESNEL F., PROST A.E., LABLANCHE G., THIRY M., SIMON-COINÇON R., THÉVENIAUT H., AVEC LA COLLABORATION DE : GUERROT C., THIÉBLEMONT D., JEZEQUEL P., CHÈVREMONT P., ROSSI P., MAGET P., CRIBELLIER M., LAUSANNE S., BONNEMAISON M., BOURDILLON C., FARJANEL G. & FAUCONNIER D. (2006). – Notice explicative de la Carte géologique de la France à 1/50 000, feuille Châteaumeillant, n°595. – BRGM, Orléans.

QUESNEL F., THIRY M., SIMON-COINÇON R., THÉVENIAUT H. & WYNS R. (2003). – Paléopaysages sidérolithiques au nord du Massif Central. – 9ème Congrès Français de Sédimentologie, Bordeaux, 14 au 16 oct., Livre des résumés. – *Publ. ASF*, Paris, **38**, 416-417.

QUESNEL F., YANS J., DUPUIS C., WYNS R., THÉVENIAUT H., FARJANEL G., VOISIN L., GIOT D., DEMOULIN A., VERGARI A., BAELE J.-M., SPAGNA P., DE PUTTER T., COLBACH R., MULLER A., LACQUEMENT F., VANDYCKE S. & BRULHET J. (2006). – Les paléoaltérations et paléosurfaces méso-cénozoïques au NE de la France, en Belgique et au Luxembourg: Synthèse des connaissances, nouvelles données et implications géodynamiques. – *Géol. France* (in press).

QUINIF Y., VANDYCKE S. & VERGARI A. (1997). – Chronologie et causalité entre tectonique et karstification. L'example des paléokarsts crétacés du Hainaut (Belgique). – *Bull. Soc. géol. France*, **168**, 4, 463-472.

RAT P. (1968). – Sur le comportement du futur seuil de Bourgogne au Crétacé. – *Bull. Soc. géol. Fr.*, ser. 7, **X**, 393-402.

RIOULT M. & JUIGNET P. (1965). – Prolongement de l'affleurement du Cénomanien au nord de Fresville, Manche. – *Bull. Soc. Linn. Normandie*, **10**, 6, 30-37.

RIOULT M., PELLERIN J. & JUIGNET P. (1966). – Témoins résiduels d'Albien en Basse Normandie et spécialement sur la campagne de Caen. – *Bull. Soc. Linn. Normandie*, **10**, 7, 19-44.

ROBASZYNSKI F. (1981). – Moderation of Cretaceous transgression by block tectonics. An example from the north and north-west of the Paris Basin. – *Cret. Res.*, **2**, 197-213.

ROBIN C., GUILLOCHEAU F. & GAULIER J.-M. (1998). – Discriminating between tectonic and eustatic controls on the stratigraphic record of the Paris basin. – *Terra Nova*, **10**, 323-329.

ROBINSON S.A., ANDREWS J.E., HESSELBO S.P., RADLEY J.D., DENNIS P.F., HARDING I.C. & ALLEN P. (2002). – Atmospheric pCO_2 and depositional environment from stable-isotope geochemistry of calcrete nodules (Barremian, Lower Cretaceous, Wealden Beds, England). – *J. Geol. Soc. London*, **159**, 2, 215-224.

ROUSSET C. (1969). – Le bombement varois; relations entre la bauxitisation au Crétacé moyen, en Provence, et l'évolution originale de la région en régime karstique. – *C.R. Acad. Sci.*, Paris, **268**, série D, 2331-2334.

ROUSSET C. (1975). – Apports de la méthode rétro-tectonique à la connaissance de la paléogéographie régionale: l'exemple des bauxites de Provence. – *C.R. Acad. Sci.*, Paris, **281**, D, 375-378.

RUELLAN P.-Y., MOREAU M.-G., SIMON-COINÇON R. & THIRY M. (2003). – Formations "sidérolithiques" du Lembron (Massif central): paléoaltérations, paléoreliefs et datation. – 9ème Congrès Français de Sédimentologie, Bordeaux, 14 au 16 oct., Livre des résumés. – *Publ. ASF*, Paris, **38**, 446-447.

RUFFEL A. (1995). – Evolution and hydrocarbon prospectivity of the Brittany Basin, (Western approach trough), offshore north-west France. – *Mar. Petrol. Geol.*, **12**, 387-407.

RUSCIADELLI G. (1996). – Stratigraphie séquentielle et quantification de l'espace disponible du remplissage du Jurassique supérieur et du Crétacé inférieur du bassin de Paris. – Thèse, Univ. Paris Sud, Orsay, 178 p.

SCHMITT J.-M. (1999). – Weathering, rainwater and atmosphere chemistry: example and modelling of granite weathering in present conditions, in a CO_2-rich, and in an anoxic palaeoatmosphere. *In*: M. THIRY & R. SIMON-COINÇON, Eds., Palaeoweathering, palaeosurfaces and related continental deposits. – *Spec. Publ. Int. Ass. Sediment.*, **27**, 21-41.

SÉRANNE M., CAMUS H., LUCAZEAU F., BARBARAND J. & QUINIF Y. (2002). – Surrection polyphasée de la bordure cévenole. Un exemple de morphogenèse lente. – *Bull. Soc. géol. Fr.*, **173**, 2, 97-112.

SIDDALL R., CARTER A. & HURFORD A.J. (1996). – Doming, denudation and the Tertiary evolution of the Massif Central, France. – *International Workshop on Fission-Track Dating*, Gent, Belgium, August 26-30, livre des résumés p. 105.

Downloaded from http://pubs.geoscienceworld.org/sgf/bsgf/article-pdf/177/3/155/2966832/155.pdf
by BRGM user

SIMON-COINÇON R. (1989). – Le rôle des paléoaltérations et des paléoformes dans les socles: l'exemple du Rouergue (Massif central français). – *Mém. Sc. de la Terre, E.N.S.M.P.*, **9**, 290 p.

SIMON-COINÇON R. & ASTRUC J.G. (1991). – Les pièges karstiques en Quercy: rôle et signification dans l'évolution des paysages. – *Bull. Soc. géol. Fr.*, **162**, p. 595-605.

SIMON-COINÇON R., THIRY M. & QUESNEL F. (2000). – Paléopaysages et paléoenvironnements sidérolithiques du nord du Massif central (France). – *C.R. Acad. Sci.*, Paris, *Sciences de la terre et des planètes*, **330**, 10, 693-700.

STEINBERG M. (1967). – Contribution à l'étude des formations continentales du Poitou. – Thèse Doct. ès Sci., Univ. Paris XI, 415 p.

STOOPS G. (1992). – Micromorphological study of Pre-Cretaceous weathering in the Brabant Massif (Belgium). *In*: J.-M. SCHMITT & Q. GALL, Eds, Mineralogical and geochemical records of paleoweathering. – ENSMP, *Mém. Sci. de la Terre*, **18**, 69-75.

TAPSOBA P. (1967). – Les sols ferrugineux du Lembron. – Thèse 3è cycle, Fac. Sciences, Univ. Clermont Ferrand, 130 p. + carte hors-texte.

THÉVENIAUT H. (2003). – Paleomagnetism as an indirect dating tool of lateritic weathering profiles (saprolite, bauxite and ferricrete): theoretical bases, method, results in French Guiana, Africa and Europe. *In*: Paleoweathering and paleosurfaces in the Ardennes-Eifel region – Preizerdaul, Luxembourg, 14-17 mai 2003. – *Géol. France*, **1**, 89-90.

THÉVENIAUT H., WYNS R. & QUESNEL F. (2002). – Etude paléomagnétique de la borne de fer. – Journée du Partenariat de Recherche et Développement entre le BRGM et l'ANDRA, Orléans, France, 5 mars 2002, Programme et résumés, p. 63-65.

THIRY M. (1999). – Diversity of continental silicification features: Examples from the Cenozoic deposits in the Paris Basin and neighbouring basement. *In*: M. THIRY & R. SIMON-COINÇON, Eds., Palaeoweathering, palaeosurfaces and related continental deposits. – *Spec. Publ. Intern. Ass. Sediment.*, **27**, 87-128.

THIRY M. (2000). – Palaeoclimatic interpretation of clay minerals in marine deposits: an outlook from the continental origin. – *Earth Sci. Rev.*, **49**, 1-4, 201-221.

THIRY M., MOREAU M.-G., SIMON-COINÇON R. & RUELLAN. P.-Y. (2004). – Datation des paléoaltérations et des événements géodynamiques continentaux – II – paléoaltérations, paléoreliefs et datation des formations "sidérolithiques'' du Lembron. – Rapport Armines/Ecole des Mines, LHM/RD/2004/03, 76 p.

THIRY M., SIMON-COINÇON R., QUESNEL F. & WYNS R. (2005). – Altération bauxitique associée aux argiles à chailles sur la bordure sud-est du bassin de Paris. – *Bull. Soc. géol Fr.*, **176**, 2, 199-214.

THIRY M. & TURLAND M. (1985). – Paléoséquences de sols ferrugineux et de cuirassements siliceux dans le Sidérolitique du nord du Massif central (bassin de Montluçon-Domérat). – *Géol. France*, **2**, 175-192.

THOMAS E. (1999). – Evolution cénozoïque d'un domaine de socle: le Massif armoricain. Apport de la cartographie des formations superficielles. – Thèse Doct., Géosciences Rennes, Univ. Rennes 1, 126 p. + annexes

VALETON I. (1966). – Sur la genèse des gisements de bauxite du Sud-Est de la France. – *Bull. Soc. géol. Fr.*, (7), **VIII**, 685-701.

VÉRAGUE J. (1974). – La transgression cénomanienne et les témoins anté-cénomaniens d'altération entre Sées et Alençon (Orne). – *Norois*, **84**, 541-562.

VÉRAGUE J. (1996). – Altération des granites et géomorphologie: l'exemple des massifs de Basse Normandie et du Maine. – Thèse Doct. Etat, Paris I, 2 tomes, 683 p.

VERCOUTERE C. & VAN DEN HAUTE P. (1993). – Post-Palaezoic cooling and uplift of the Brabant Massif as revealed by apatite fission track analysis. – *Geol. Mag.*, **130**, 5, 639-646.

VERGARI A. (1998). – Nouveau regard sur la spéléogenèse: le "pseudo-endokarst" du Tournaisis (Hainaut, Belgique). – *Karstologia*, **31**, 1, 12-18.

VERGARI A. & QUINIF Y. (1997). – Les paléokarsts du Hainaut (Belgique). – *Geodin. Acta*, **10**, 4, p. 175-187.

VERNHET Y., MAURIZOT P., LE GALL J., GIGOT P., DUPRET L., BARBIER G., LEROUGE G., BESOMBES J.-C. & PELLERIN J. (2002). – Carte géologique de la France à 1/50 000, feuille Villers-Bocage, nº145. – BRGM, Orléans, et Notice explicative, 232 p.

VOISIN L. (1978). – La sablière de Prez – Ardennes, observations récentes 1976-1978. – *Bull. Soc. Hist. Nat. Ardennes*, **68**, 33-36.

VOISIN L. (1981). – Les silicifications en Thiérarche ardennaise. Implications paléogéographiques. – *Rev. géogr. Est*, **4**, 265-276.

WAGNER G.A., COYLE D.A., DUYSTER J., HENJES-KUNST F., PETEREK A., SCHÖDER B., STÖCKERT B., WEMMER K., ZULAUF G., AHRENDT H., BISCHOFF R., HEJL E., JACOBS J., MENZEL B., NAND LAL, VAN DEN HAUTE P., VERCOUTERE C. & WELZEL B. (1997). – Post-Variscan thermal and tectonic evolution of the KTB site and its surroundings. – *J. Geophys. Res.*, **102**, B8, 18221-18232.

WEHMANN M. (1911). – La Borne de Fer près d'Aumetz. – *Lothringer Zeitung*, Metz, 134 p.

WYNS R. (1991). – Evolution tectonique du bâti armoricain oriental au Cénozoïque d'après l'analyse des paléosurfaces continentales et des formations géologiques associées. – *Géol. France*, **3**, 11-42.

WYNS R. (1996). – Essai de quantification de la composante verticale de la déformation finie au Cénozoïque en Poitou, Limousin occidental et dans la plate-forme nord-aquitaine d'après l'analyse des paléosurfaces continentales et des sédiments associés. – Rapport BRGM Nº2238, 83 p.

WYNS R. (1999). – Contraintes géologiques et géomorphologiques à l'histoire de la mobilité verticale de la lithosphère continentale en Europe de l'ouest depuis le Crétacé: Relations avec la genèse des grabens et du volcanisme tertiaires. *In*: P. NEHLIG, Coord., Colloque "Volcanismes, sédimentations et tectoniques cénozoïques périalpins", Aurillac, sept. 1999. – *Doc. BRGM*, **291**, 46-47.

WYNS R. (2002). – Climat, eustatisme, tectonique: quels contrôles pour l'altération continentale? Exemples des séquences d'altération cénozoïques en France. – *Inf. Géol. Bass. Paris*, **39**, 5-16.

WYNS R., QUESNEL F., SIMON-COÏNÇON R., GUILLOCHEAU F. & LACQUEMENT F. (2003). – Major weathering in France related to lithospheric deformation, *In*: Paleoweathering and paleosurfaces in the Ardennes-Eifel region – Preizerdaul, Luxembourg, 14-17 mai 2003. – *Géol. France*, **1**, 79-97.

YANS J. (2003). – Chronologie des sédiments kaoliniques faciès wealdiens (Barrémien moyen Albien supérieur ; bassin de Mons) et de la saprolite polyphasée (Crétacé inférieur et Miocène inférieur) de la Haute-Lesse (Belgique). Implications géodynamiques et paléoclimatiques. – Thèse de doctorat inédite, Faculté Polytechnique de Mons & Université de Paris-Sud Orsay, 316 p.

YANS J., SPAGNA P., VANNESTE C., HENNEBERT M., VANDYCKE S., BAELE J.-M., TSHIBANGU J.-P., BULTYNCK P., STREEL M. & DUPUIS C. (2005). – Description et implications géologiques préliminaires d'un forage carotté dans le "Cran aux Iguanodons" de Bernissart. – *Geol. Belgica*, **8**, 43-49.

YANS J., DEJAX J., PONS D., DUPUIS C. & TAQUET P. (2005). – Paleontologic and geodynamic implications of the palynological dating of the Bernissart wealden facies sediments (Mons basin, Belgium). – *C.R. Palevol*, **4**, 135-150.

Downloaded from http://pubs.geoscienceworld.org/sgf/bsgf/article-pdf/177/3/155/2966832/155.pdf
by BRGM user