Major weathering in France related to lithospheric deformation

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Abstract

This article presents the preliminary results of a study concerning the relationships between weathering and instances of vertical deformation of the west European lithosphere in France during the post-Paleozoic period. The continental alterites and associated continental sediments, which developed horizontally along planation surfaces, are considered here to constitute a continuous series, ranging from a subtractive "negative" pole (laterites in the broad sense) to an additive "positive" pole (siliceous crusts, and calcretes, along with lacustrine limestone and evaporites). During the weathering period, the alterite facies often shift from one pole to the other, enabling weathering sequences to be defined. Comparison between the weathering sequences and the timing of vertical deformation of the lithosphere in the Alpine foreland shows that, in spatio-temporal terms, negative weathering coincides with upwarping of the lithosphere (domes), while positive weathering coincides with downwarping of the lithosphere (depressions). Two major periods clearly demonstrate these relationships: (i) the Early Cretaceous, when lateritic profiles developed on the shoulder of the North Biscay rift on the one hand, and on a dome forming part of the southern edge of the North Sea on the other hand; (ii) the Tertiary, when lateritic weathering occurred along the "peri-Alpine ridge" resulting from lithospheric buckling during the compressional phases experienced by the Pyrenees (Palaeocene to Middle Eocene) and the Alps (Late Miocene to present day), while continental carbonates developed from the Late Eocene until the Early Miocene over a depressed surface area near sea level.

Introduction

In western Europe, the Alpine foreland consists of a patchwork of Hercynian basement outcrops and Mesozoic to Cenozoic sedimentary cover. Traces of emergence and paleoweathering are common and are generally linked geometrically to continental planation surfaces. Where they are interstratified within dated series, the weathering profiles can easily be followed and gradually correlated. This is not the case where they are not sealed, whether recent weathering profiles or old exhumed profiles are involved; this is particularly the case with Hercynian massifs and their margins. It is easier to understand the spatio-temporal distribution of weathered paleosurfaces and their geometry by placing them within the geodynamic context of development of the west European lithosphere during the Alpine cycle. After reviewing the principal weathering episodes recorded in France, we endeavour, whenever possible, to place them within the geodynamic context of western Europe.

By the end of the Hercynian times, the western Europe was under tropical latitude (Scotese *et al.*, 1979). During Mesozoic and Cenozoic times, it moves slowly northward up to its present position. The present repartition of the climatic belts around the Earth does not reflect the ancient ones, as it has been forced from the last 10 Ma by polar ice caps. For example, numerous evidences from palynology show that the France area encountered wet and warm conditions during Eocene, at a time when it was at the current latitude of Spain. Although mean paleotemperatures decreased slowly during the northward drift of the Europe and were subject to other variations (due to variations of atmospheric CO_2 content), the temperature and the mean amount of rainfall (Parrish *et al.*, 1982) were probably sufficient to enable weathering during all the Mesozoic and Cenozoic times. We consider that the succession of weathering types ("subtractive" and "additive") during Cretaceous and Cenozoic times cannot fully be explained by the only climatic variations, and we try to explore here a possible link with vertical lithospheric movements.

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Types of weathering and their associated sediments

Weathering is a complex physical and chemical process that leads either to leaching of the substrate's rocks, or to their transformation/epigenesis through the input of dissolved elements. Broadly speaking, most of the continental alterites can be considered to be distributed within a continuous series that shifts between two opposite poles (Fig. 1): a subtractive negative pole, characterised by the net export of material, and an additive positive pole, characterised by a net import of material.

- The negative pole is the domain of laterites in the broad sense to which, for carbonate substrates, can be added clays, the Clay-with-flints and the Clay-with-Jurassic-cherts. During the hydrolysis of primary minerals, the most soluble chemical elements (K, Na, Ca, Mg and, to a lesser extent, Si) are extracted, brought into solution and then exported. The remaining elements reprecipitate in the form of new mineral phases (mainly clays, oxides and hydroxides). The nature of the newly formed phases depends on the quantity of the elements available at the time and place where they are formed. A lateritic weathering profile typically includes (from top to bottom) a bauxitic or ferruginous duricrust (differential concentration of the less mobile elements at the top of the profile), and a unit of loose soil with a dominant clay content (saprolite); on crystalline rocks, there is also a fissured horizon layer (Wyns, 1998; Wyns *et al*., 2003), which develops over tens of metres at the top of the hard substrate in response to the swelling of phyllitic minerals during the early stage of weathering; on granites, the fissures resulting from weathering having a characteristic planar shape.

- The positive pole is characterised by infiltration of the substrate by chemical elements contributed by runoff and groundwater into the low, more or less confined areas subject to evaporation; this infiltration leads to the formation of encrustations with thicknesses of either tenths of metres or several metres. Depending on their predominant chemism, these encrustations are called silcretes, dolocretes, calcretes, or gypcretes.

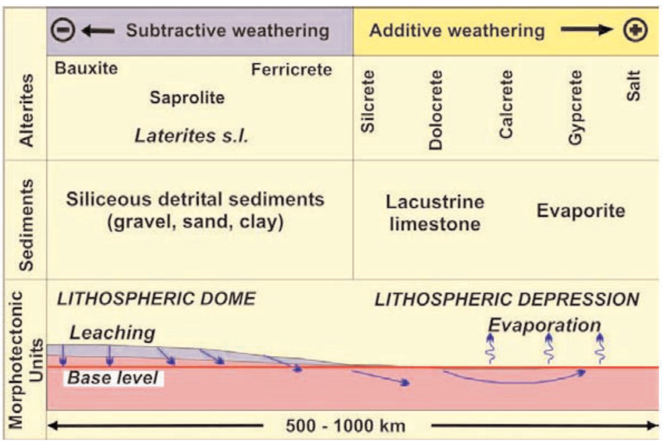

Fig. 1.– Spatial organisation of the various types of weathering and their associated sediments depending on the major intracontinental morphotectonic units.

The continental sediments that are deposited on surfaces undergoing weathering are in balance with the alterites: the sediments associated with 'negative' alterites are generally siliceous detrital sediments originating from the partial reworking of the alterites: siliceous sand and gravel. Likewise, the most common sediments associated with 'positive' alterites are lacustrine or palustrine limestone and evaporites (gypsum, salt).

The type of weathering (negative or positive) is at least partly controlled by the altimetric potential: more often than not, negative weathering is associated with surfaces with a raised topography but with a low average slope, these being the conditions required to allow the water to infiltrate and leach substantial volumes of rock. Likewise, positive weathering is encountered in low areas, for which the most common model is one of broad intracontinental depressions or basins that are more or less endoreic, towards which groundwater and runoff converge. Instances of lithospheric deformation enable the creation of the morphological conditions that allow this weathering to take place: negative weathering is associated with lithospheric upwarping (domes) whereas positive weathering with lithospheric downwarping (depressions). During vertical deformation of the lithosphere, the type of weathering shifts from one pole to the other, depending on the direction this deformation takes (uplift or subsidence), thus creating a record in the form of weathering sequences (Wyns, 2002).

Ancient indicators of lateritic profiles: Carboniferous to Triassic

The geodynamic context

From the Carboniferous onwards, the Hercynian chain was gradually levelled and subjected to peneplanation. This began with subsidence of the chain under the effect of gravity, and then continued with erosion. Gradual cooling of the crust, composed of newly formed metamorphic and plutonic rocks, led to its thermal subsidence (Fig. 2). In the Paris Basin, the accommodation curves show that, from Triassic to Jurassic, the crust's thermal subsidence amounted to about 10 m per 1 million years (Guillocheau *et al*., 2000) (Fig. 3). Depending on the region and during this same period, the upper surface of the Hercynian crust sank beneath sea level 100 to 150 million years after the paroxysm of Hercynian collision, which caused the major post-Hercynian transgression throughout western Europe.

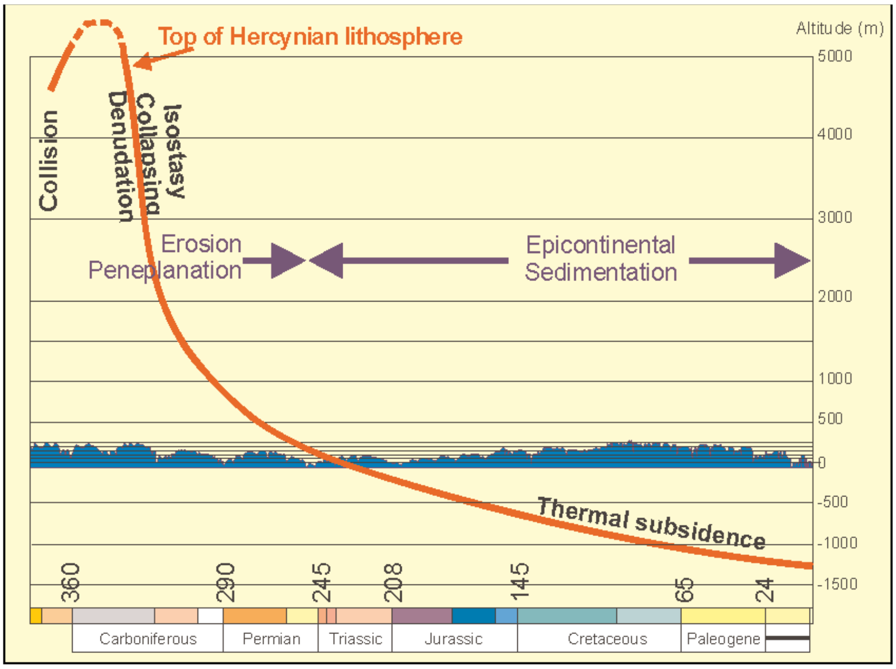

Fig. 2.– Principle of the altimetric variation of the top of the Hercynian crust after collision: the decrease in altitude was firstly the result of tectonic denudation and collapsing under the force of gravity, and then the result of erosion, followed by thermal subsidence. The top of the Hercynian (post-Hercynian peneplain) has been submerged beneath sea level (shown in blue) between the Triassic and the Jurassic (Wyns and Guillocheau, 1999).

The post-orogenic period preceding the Mesozoic transgression was characterised by weathering associated with the various stages of peneplanation. However, the tectonic break-up and burial of these ancient indicators means that it is currently difficult to reconstruct the paleogeography associated with this weathering. Consequently, what we provide here is a provisional inventory of the occurrences identified at the time of writing.

Carboniferous weathering

Some rare evidence of negative weathering profiles has been identified in the Massif Central and the Vosges, interstratified in the Carboniferous series:

- In the Massif Central, a paleosurface established on the granite at Chateauneuf-les-Bains (Aigueperse geological map) has a characteristic negative weathering profile west of Combronde, with a fissured horizon layer overlain by tens of metres of grus. This surface is tilted and the weathering profile is covered by volcano-sedimentary and volcanic formations attributed to the Visean;

- In the Vosges, near Thannenkirch (Colmar-Artolsheim geological map), the discordant Namur-Westphalian coal shales overlie a planation surface and seal a weathering profile derived from the Thannenkirch granite; the weathering profile shows 20 m or so of grus overlying a fissured horizon layer about 50 m thick.

Infra-Permian weathering

The Permian basins partly consist of red continental detrital sediments: clays, sandstones, and conglomerates. Preliminary observations conducted on the western edge of the Saint-Affrique Permian basin (Saint-Sernin-sur-Rance geological map) have shown that beneath the earliest Permian conglomerates, the folded and metamorphosed Cambrian basement shows vestiges of a truncated lateritic profile: only a few metres of weathered clay overlying a fissured horizon layer have been preserved, the rest of the profile having been gullied prior to Permian deposition. It is likely that lateritic weathering provided part of the sedimentary input for the Permian basins, and that lateritic coverage was extensive at the end of the Carboniferous. The infra-Permian weathering profiles and their paleogeography have yet to be identified and studied.

Pre-Triassic weathering

Where the Triassic lies directly on the pre-Permian Hercynian basement, it shows many signs of weathering; two main types are recognised:

- Classic negative weathering, which is marked on granites by the presence of a commonly thick cover of *in situ* grus overlying a well-developed, fissured horizon layer. Such weathering can be particularly well observed in the Cévennes (Liron granite, Mont Lozère granite) and is probably widely present under the Triassic in the ancient internal margin of the Tethys, at the presumed site of the ancient ocean rift shoulder. Indicators of these pre-Triassic profiles are thus to be found around the Morvan and in the Nièvre (the Saint-Saulge horst, Saint-Saulge geological map), in the Vosges (Hohneck, the Schlucht Pass, Lake Blanc), and under the Alsace plain (geothermal borehole at Soultz);

- A particular type of positive weathering - supergene albitisation: This was described for the first time and dated in the Rodez strait (Schmitt, 1986), and is commonly

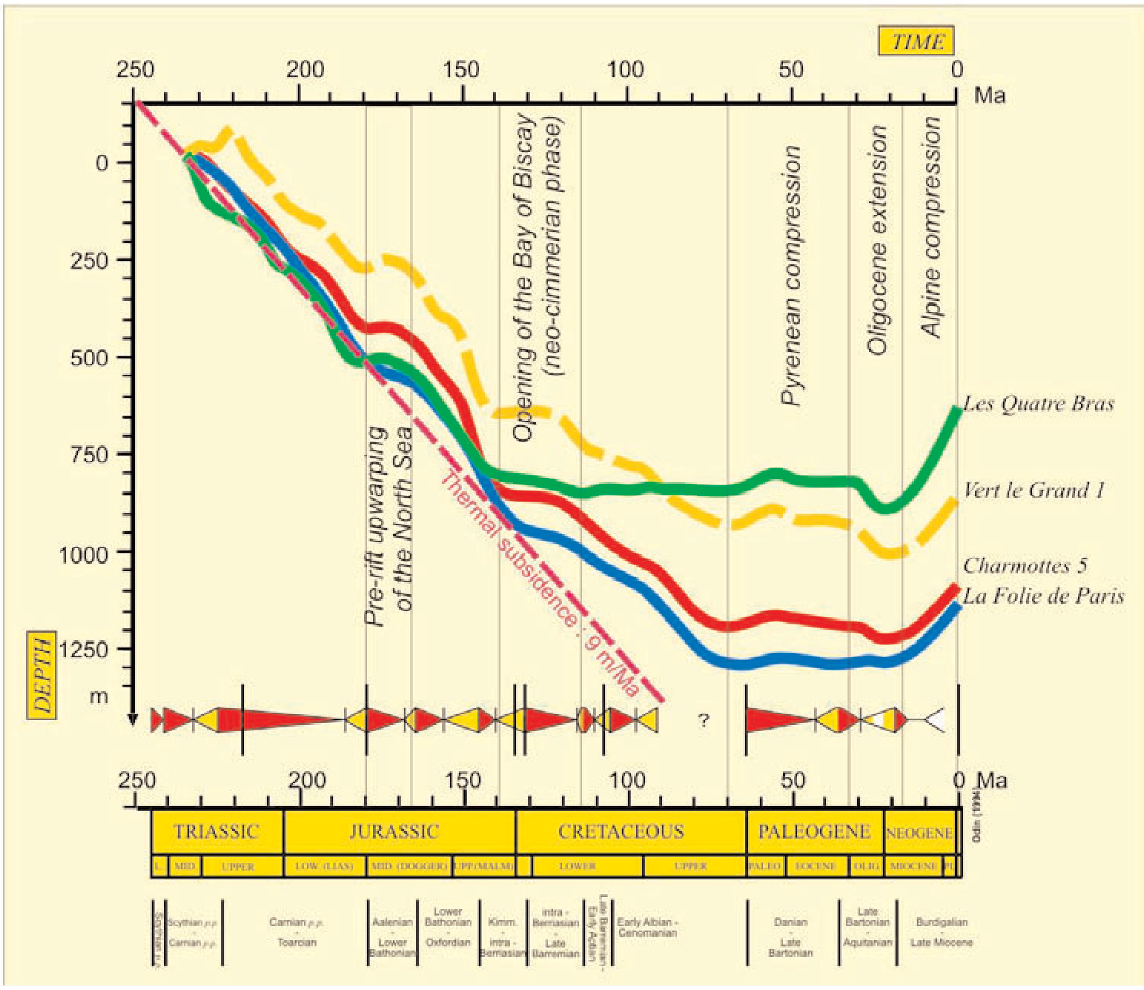

Fig. 3.– Accommodation curves for four boreholes in the Paris Basin, showing the post-Hercynian thermal subsidence of the crust and the uplifting linked to the main geodynamic events in western Europe during the Mesozoic and Cenozoic (modified from Guillocheau et al.*, 2000)*

observed beneath the Triassic of the Tethys margin in various regions of France, as well as in Catalonia (Gomez-Gras and Parcerisa, oral commun.). They have yet to be inventoried and mapped. What happened is that sodic epigenesis affected the rocks in the pre-Triassic substrate over a thickness of tens of metres, giving the rocks a characteristic pink colour. This epigenesis is interpreted as being the result of the circulation of mineralised groundwater in a confined Sebkha-type environment, in a zone where mixing occurred between silica-laden continental water and seawater laden with sodium chloride.

The presence of the two different types of weathering - negative weathering (grus), and positive weathering (albitisation) - beneath the Triassic raises the issue of the relative chronology involved, as it is difficult for these two processes to co-exist at the same time. One working hypothesis would be to envisage a link between negative weathering and the ancient instances of pre-rift upwarping in the Tethys, during a period when there was sufficient altitude to enable effective leaching. Such conditions probably occurred during most of the Permian. Albitisation would have then taken place during a second period when thermal subsidence of the margin brought about its gradual submergence. Much work is still to be done in order to establish this chronology, and to map the true extent of these two types of weathering around the Tethys.

Cretaceous weathering

Geodynamic context

The Early Cretaceous saw the opening of the Bay of Biscay and the beginnings of the opening of the North Atlantic. From the tip of Brittany to the Cévennes, a wide strip of land that was above water at the end of the Jurassic was subsequently eroded during its uplift, thus exposing the Hercynian basement: this was the site of the northern shoulder of the Bay of Biscay, which was probably 1 to 2 km high judging from present-day examples of rift shoulders. In the North Sea, an incipient oceanic opening took place. On its southern edge, the Rhenish shield and most of what is now Belgium were uplifted (Quesnel, in this volume), forming a promontory that became connected with the promontory of the eastern coast of England. Apatite fission-tracks evidence (Van den Haute and Vercoutere, 1989) indicates that the land was uplifted 2 to 3 km. Between these two lines of relief, which were mainly NW-SE oriented, the “Wealden” trough was established that drained continental detrital sediments into the Tethys, from the London Basin to Burgundy, via the Paris Basin. Thermal subsidence of these shoulders allowed a renewed marine transgression during the Cenomanian on both sides of Poitou, and then later, during the Senonian, up to the Causses and the Cévennes related to the scissor-like opening of the Bay of Biscay. On the northern European promontory, transgression was also late, occurring during the Turonian or the Senonian, depending on the area (Yans, in this volume).

Alterites - distribution and typology

At the former site of the shoulder of the North Biscay rift, transgressive marine formations dating from the Late Cretaceous sealed lateritic weathering profiles. In Anjou, Poitou and the Vendée, the basement has a classic lateritic profile, which is generally truncated due to the erosion linked to the Cenomanian transgression. The preserved saprolite is commonly 10 to 15 m thick: the Thouarcé and Montreuil-Bellay map areas, and the Viennay pre-Cenomanian profile in the Parthenay map area (Steinberg, 1967). Where weathering of Jurassic limestone occurred, the weathering sequence is generally more complete: more or less complete silicification of the limestone several metres beneath the paleosurface, followed by a brecciation/karstification phase contemporaneous with laterisation. Such cases of silicification have been observed over Bathonian limestone in Lower Normandy (Bayeux-Courseulles geological map), and in Anjou (Montreuil-Bellay geological map). In the Poitou region (Bélâbre geological map), Bajocian limestone was dolomitised before being silicified to a depth of 5 to 6 m, and then subjected to brecciation. In the Causses region, a full weathering sequence can be reconstructed, with it being particularly clearly observable on the Larzac plateau (Millau geological map): along the plateau’s surface, dolomitisation developed that encroached sideways onto the various Jurassic formations, and which is consequently post-diagenetic. This dolomitisation, commonly spathic, has a tower-like appearance in many places (the chaotic formations at Montpellier-le-Vieux and Nîmes-le-Vieux). Silicification then occurred over the same surface, generally at the expense of the spathic dolomite, followed by karstification contemporaneous with the formation of alterites (“Terre du Causse”). The fill of this ancient karst contains silicified spathic dolomite pebbles. In the large karst depressions (Le Luc, Nant geological map), the remains of a bauxitic duricrust can be observed above the weathered clays, overlain by Late Cretaceous marine limestone (Turonian to Campanian, Bruxelles, 2001). Farther north, in the Mende map area, a paleosurface that truncates the Liassic series, and which connects northwards with the Massif Central’s basement and southwards with the Causses plateaus, is dotted with silicification (jaspers). It is possible that this silicification marks the infra-Cretaceous surface, although no Late Cretaceous sediments have been reported in that area.

In northern France and Belgium, on the other side of the Wealden trough, the transgressive and discordant Late Cretaceous deposits also sealed weathering profiles showing the same development as those of the North Biscay shoulder (Quesnel, in this volume).

Tertiary weathering

The geodynamic context

Following a change in Africa’s trajectory during the Late Cretaceous, the convergence of Africa and Europe led to western Europe being subject to compression from the Santonian onwards, accompanied by the first signs of tectonic compressional deformation of the platform (Ziegler, 1988). This N-S compression increased from the Palaeocene onwards and led to the formation of folds from the Palaeocene to the Bartonian. Traditionally, this period is referred to as the “Pyrenean compression”. At regional level, the accommodation curves established for the Paris Basin (Guillocheau *et al.*, 2000) show that the substrate was completely uplifted during this period. This uplifting, also highlighted by the modelling of continental paleosurfaces (Wyns, 1991, 1996b and 1997; Quesnel, 1997; Thomas, 1999; Brault, 2002), is interpreted as being the result of buckling of the west European lithosphere in the Alpine arc foreland.

A period characterised by extensional deformation began in the Priabonian and continued throughout the Oligocene (known as “Oligocene extension”). It was particularly marked by the active subsidence of the west European intracontinental grabens. This generalised E-W extension, while Africa and Europe were still undergoing N-S convergence, can be explained by a slower rate of expansion of the North Atlantic in relation to the Central Atlantic during this period. This in turn led to sinistral displacement in the African-Arabian block in relation to Europe (Bergerat, 1987; Ziegler, 1988), with this strike-slip component dominating the N-S convergence component. In the Paris Basin, the accommodation curves show a resumption of subsidence.

During the Miocene, the expansion differential at the ridges decreased (Dercourt *et al.*, 1986) and compression resumed and intensified with Alpine collision, the culminating phase of which occurred from the end of the Miocene onwards (thrusting of the Jura over the Bresse and over the molasse basin) and continues to this day. The accommodation curves for the Paris Basin show a renewed uplifting since the Late Miocene, which correlates with the formation of the peri-Alpine lithospheric ridge running from the Massif Central as far as Bohemia.

Alterites - distribution and typology

During the Palaeocene and the Eocene, two thirds of France was above water: the marine realm had been pushed back to the north of the Seine where it connected with the North Sea, and to the south of the Garonne where it joined with the Bay of Biscay. This whole region was then subjected to leaching weathering (Fig. 4), the indicators of which are generally well preserved in the form of weathering profiles that were identified many years ago as lateritic profiles (Milon, 1932; Durand, 1960; Estéoule-Choux, 1967; Simon-Coinçon, 1989; Simon-Coinçon *et al.*, 1995). This weathering also affected both the basement, where the alterites attain an average thickness of 20 to 30 m (clays and sands, Armorican Massif and the Massif Central), and the sedimentary cover: kaolinitic clays on Liassic marls (Vendée, Poitou, Charentes, Morvan), Clay-with-cherts on Jurassic limestone (Poitou, Berry, Morvan, Bourgogne, Jura), Clay-with-flints on the Chalk in Normandy and the Perche (Quesnel, 1997), and sand-with-flints on "Tuffeau" -sandy Chalk- in the Touraine and Anjou regions (Wyns, 1996a). The initiation of these profiles, which followed a peneplanation episode that truncated all the sedimentary series, was at least post-Campanian in the greatest part of the area, and was post-Maastrichtian in Normandy (Quesnel *et al.*, 1996) as well as on the north Aquitaine platform. Continental detrital sediments were transported over the surface subjected to weathering. They consisted of sand, clays and gravels, and are referred to as "Siderolithic". These deposits are seldom thick (generally less than 10 m), except in isolated subsident areas such as the Brenne Basin, and on the southern edge of the Aquitaine platform (in the region of Coutras, Dubreuilh, 1987; Wyns, 1996b). They are nowhere carbonated and are generally azoic, except for a few clays that have locally provided pollens, particularly from the Early Eocene (Brenne Basin, Chateauneuf 1977).

At the end of this lateritic episode, the top of the profiles, and particularly the continental, more porous sediments, were infiltrated by illuvial clays. The grains of sand from the siderolithic sediments thus appear to be floating in a clay matrix, providing a material known as "puddled clay" (a mixture of coarse sand and clay used in traditional buildings made out of soil).

Illuviation processes were gradually taken over by silicification, forming discontinuous, indurated slabs on the ancient planar surface. This silicification has been described and compared to Australian silcretes by Thiry (1981, 1999); where developed on sand of the puddled-clay type, they produce characteristic quartzites containing detrital quartz grains floating in a beige siliceous matrix consisting of silicified clay. Where developed on gravels, and Clay-with-flints (or cherts), we commonly observe finely zoned cap rock resulting from the illuviation of clay and the precipitation of titanium oxides (Thiry, 1981). The Ladères sandstones and the Sabals sandstones, which overlie or grade laterally into silcretes and that contain flora dated as Bartonian in Anjou, are probably contemporaneous with this widespread silicification episode. Although they can seldom be observed *in situ* due to a lack of outcrops, these silcretes covered the whole area affected by lateritic weathering, and they are generally found as relict stones throughout the southern half of the Paris Basin, in Normandy, Brittany, Vendée, the Poitou region, the north Aquitaine platform, the Massif Central, the Morvan, as well as in Lorraine and Belgium ("Pierre de Stonne", Quesnel, in this volume).

After this silicification episode, the continental landscape was infiltrated by carbonates: calcretes, then lacustrine and palustrine limestone. These continental carbonates, the appearance of which is diachronous, became generalised from the Priabonian (40 Ma) and

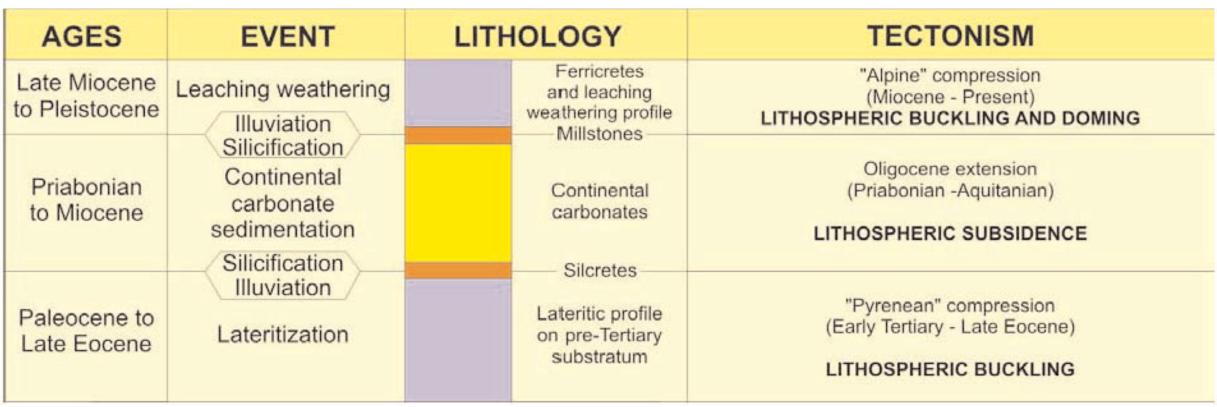

Fig. 4.- Sequential organisation of weathering types in France during the Tertiary

persisted during the Oligocene and until the earliest Miocene (Aquitanian): limestones of Château-Landon, Champigny, Brie, Beauce, Étampes, Anjou and Touraine, Poitou, Berry, and of the Orléanais. In Aquitaine, where detrital sedimentation continued due to thermal subsidence of the North Biscay margin, carbonates locally appeared in the form of carbonate cement in sand, whereas clay minerals, dominated by kaolinite during the leaching weathering episode, changed into smectites. Carbonate continental sedimentation also affected the active grabens during the Priabonian and Oligocene in the Massif Central, Poitou, Brittany, Sarthe, Bresse, and the Rhine graben.

The Miocene to Pleistocene period is less well known due to the discontinuity of stratigraphic markers. Nevertheless, a new widespread silicification episode after carbonate sedimentation can be distinguished: millstone ("Meulières") of Montmorency, Hurepoix, Brie, and Beauce. Similar deposits have also been identified capping the carbonates in Touraine, Anjou, Poitou, and the Quercy region, as well as the carbonate series in the grabens of the Massif Central. Ménillet (1993) described millstone clays as alterites resulting from a succession of processes, amongst which we recognise: an early silicification phase, a clay illuviation phase, and a phase of silica dissolution and its redistribution towards the bottom of the profile. The best developed facies is cavernous millstone, the cells of which are filled with kaolinitic clay. Karstification of the carbonate substrate accompanied the millstone formation. According to Ménillet (1993), most of the millstone in the Paris Basin was formed from the Pliocene (Hurepoix) to Pleistocene (Brie), with the millstone of Brie being less developed than that of the Hurepoix. In Île de France, Touraine and Poitou, discrete ferruginisation in the form of ferruginous pisolites accompanied millstone formation; in the Poitou region, however, ferruginisation generated accumulations several metres thick above the millstone.

Conclusions

Based on the inventory of post-Hercynian weathering, two periods -the Cretaceous and the Tertiary- show sufficiently extensive and well preserved remains to propose a link between the type of weathering and the geodynamic development of western Europe. In both cases, negative weathering coincided with lithospheric upwarping (domes), while positive weathering and the associated continental carbonate sedimentation coincided with lithospheric downwarping (depressions). The order in which the types of weathering occurred, shifting between a negative pole and a positive pole, constitutes a weathering sequence whose direction reflects vertical movements of the lithosphere.

Thus, for continental development during the Tertiary, the shift from Pyrenean compression to Oligocene extension was marked by a change in surface processes from a negative pole (laterisation) to a positive pole (continental carbonate sedimentation): inversion of the type of weathering coincided with tectonic inversion, the inflection point being emphasised by capped silicified rock (silcretes): as silica is the less soluble element, it precipitates before the carbonates. Deformation of the lithosphere controls the ground's altitude in relation to the base level, thus controlling the type of weathering: when the ground surface falls and approaches that of the base level, the progression of the lateritic profile comes to a halt; the piezometric surface approaches ground level, thus slowing rainwater infiltration; the sediments transported at the surface, carried by increasingly frequent periodic floods, become predominantly clay and steadily infiltrate, causing illuviation of the top of the underlying formations. Later, when the water table is generally close to ground level, evaporation leads to a steady concentration of solutions: silica, which can no longer combine with alumina because it is completely trapped by the clays, precipitates first to produce silcretes; then carbonates precipitate in turn, and eventually dominate the landscape.

The paroxysm of Alpine collision probably started at the end of the Miocene and increased during the Pliocene-Quaternary. Weathering conditions shifted from a positive pole (Oligocene and earliest Miocene continental carbonates) to a negative pole (karstification, ferrugination, and renewed formation of the Clay-with-flints in Normandy: Cavelier and Kuntz, 1974; Quesnel, 1997). The inversion was marked by a new silicification episode and millstone formation: compared to the Eocene silcretes, the characteristic of the millstone is that silicification preceded clay illuviation, which itself preceded dissolution: this explains why the millstone is everywhere contained within a clay mass that is now kaolinised, with the final dissolution explaining the cavernous appearance typical of the upper part of the profiles.

Post-Hercynian weathering in France appears to be controlled at least partly by vertical movements of the lithosphere. The episodes of widespread silicification constitute topographic inversion markers. Leaching weathering → clay illuviation → silicification (silcrete) → continental carbonate sedimentation is a sequence indicative of subsidence of the lithosphere, while the inverse sequence, entailing continental carbonate sedimentation → silicification (millstone) → clay illuviation → leaching weathering, is indicative of uplifting of the lithosphere.

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