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Uplift and denudation history at low-elevation passive margins: Insights from morphostratigraphic analysis in the SE Armorican Massif along the French Atlantic margin

Soulèvement et dénudation sur une marge passive de basse altitude : analyse morpho-stratigraphique appliquée au sud-est du Massif armoricain le long de la marge atlantique française

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ABSTRACT

Like other low-elevation passive margins, the French Atlantic margin is characterized by a gradual topographic transition from the coast to low-altitude interior plains or plateaus. Here we propose a morphostratigraphic analysis to constrain long-term landscape evolution and denudation rates, through the characterization of palaeotopographies and related palaeoweatherings in an area restricted to the southeast Armorican Massif. Two regional-scale palaeosurfaces are recognized: (i) the Infraliassic palaeosurface, the truncated weathering profiles of which are sealed by Liassic marine deposits; (ii) the Eocene palaeosurface, underlain by thick kaolinite- and iron-rich palaeosaprolites and by siliceous duricrusts (silcretes). Quantitative constraints on large-scale tectonic uplift and long-term denudation are obtained from these morphostratigraphic markers. Mean uplift and denudation rates calculated on post-Eocene times range between 0.5 and 2 $m.Ma^{-1}$. These low values imply high landscape stability of the inland margin over most of the Cenozoic.

RÉSUMÉ

Comme d'autres marges passives de faible énergie de relief, la marge atlantique française est caractérisée par une transition topographique progressive, passant de la côte à des plaines et plateaux intérieurs de basse altitude. Nous proposons ici une analyse morphostratigraphique pour caler l'évolution à long terme et les taux de dénudation, à travers la caractérisation des paléotopographies et paléoaltérations associées dans une zone limitée au sud-est du Massif armoricain. Deux paléosurfaces d'extension régionale y sont identifiées : (i) la paléosurface infraliasique, dont les profils d'altération tronqués sont scellés par des dépôts marins liasiques ; (ii) la paléosurface éocène, soulignée par d'épaisses paléoaltérations ferrugineuses et des indurations siliceuses (silcrètes). Des valeurs quantifiées du soulèvement tectonique régional et de l'érosion à long terme sont obtenues à partir de ces surfaces-repères datées. Les taux moyens calculés sur la période post-éocène sont compris entre 0,5 et 2 $m.Ma^{-1}$. Ces faibles valeurs impliquent une grande stabilité des paysages de la marge continentale au cours du Cénozoïque.

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1. Introduction

For two decades, geodynamic and geomorphological studies of passive margins have mainly contributed to the understanding of uplift and erosional histories at high-elevation rifted margins, i.e. continental passive margins characterized by a major scarp or "Great Escarpment" facing the sea, with elevations up to 2000–3000 m above sea level (a.s.l.) on the back slope mountainous uplands (Gilchrist and Summerfield, 1990; Summerfield, 2000). Conversely, low-elevation rifted margins, i.e. whose topography rises gradually from the coast to low-relief interior plains and plateaus ($<$ 500 m a.s.l.), have been poorly characterized in terms of long-term uplift and denudation. This under-representation in the research literature is partly due to the analytical limits of thermochronological methods classically used in passive margin studies, e.g. apatite fission track analysis (Cockburn et al., 2000; Gallagher et al., 1994; Gunnell et al., 2003; Kounov et al., 2009) that do not allow one to detect depths of denudation with a vertical resolution lower than 400–500 m (Gunnell, 2000). Moreover, insights into the factors controlling the uplift and erosional response at passive margins have recently been provided by numerical surface process models (Beaumont et al., 2000; Codilean et al., 2006), but the pertinence and further applicability of such models has often been limited by the lack of data on denudation rates required to calibrate uncertainties in model parameters (Van der Beek and Braun, 1998). Although data from cosmogenic isotope analyses are locally available and document post-rift denudation for a range of passive margin environments, there is a general lack of data for denudation rates at a finer resolution, i.e. to constrain landscape development in low-energy surface environments.

The present investigation focuses on the Southeast Armorican Massif along the French Atlantic margin (Fig. 1), which belongs to the category of mature, low-elevation rifted margins – a direct consequence of the opening of the Bay of Biscay during Cretaceous rifting. Based upon a morphostratigraphic analysis (Peulvast et al., 2009) involving field surveys and geomorphic mapping of weathering formations and surficial deposits, our contribution aims to provide a qualitative and quantitative insight into long-term uplift and denudation at a low-elevation passive margin, and to afford further constraints on numerical landscape evolution models in such settings. To achieve this we propose a coherent morphostratigraphic scheme based on crosscutting relations between regional palaeosurfaces, stratigraphic dips and continental palaeoweatherings that challenge the results recently obtained from numerical modelling experiments (Maurin and

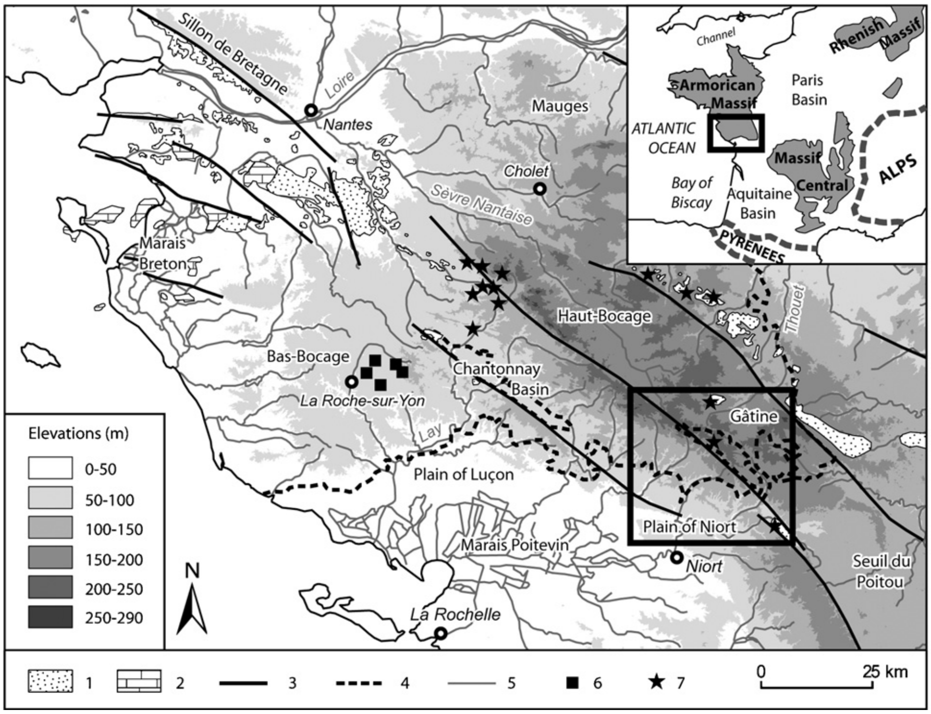

Fig. 1. Orohydrography and distribution of sedimentary formations and Eocene palaeoweatherings along the South Armorican segment of the French Atlantic margin. 1: continental Eocene deposits; 2: marine Eocene deposits; 3: fault; 4: contact between crystalline basement and Liassic cover; 5: river; 6: ferricrete; 7: silcrete. Digital Elevation Model from U.S. Geological Survey SRTM 90 elevation database; geologic contours of Eocene formations modified after (Godard et al., 1994). Rectangle locates Fig. 2.

Fig. 1. Oro-hydrographie et répartition des formations sédimentaires et des paléoaltérations d'âge Eocène le long du segment vendéen de la marge atlantique française. 1 : Eocène continental ; 2 : Eocène marin ; 3 : faille ; 4 : contact socle-couverture liasique ; 5 : rivière ; 6 : ferricrète ; 7 : silcrète. Modèle Numérique d'Altitude d'après les données topographiques SRTM 90 de l'*U.S. Geological Survey* ; localisation des affleurements géologiques éocènes, modifiée d'après (Godard et al., 1994). Le rectangle localise la Fig. 2.

Renaud, 2002). Owing to its richness in palaeolandforms and palaeosaprolites of various ages, the southeast Armorican Massif affords good opportunities for quantifying the magnitude of uplift and depths of denudation, mainly for the Cenozoic, and for providing new focus on factors likely to control landscape evolution at low-elevation rifted margins.

2. Study area: topography and geological setting

The South Armorican segment of the French Atlantic margin (Fig. 1) is a non-volcanic, low-elevation passive margin formed by the rifted opening of the Bay of Biscay in Early Cretaceous times (Guillocheau et al., 2003). Onshore, the topography of the continental margin displays many features that are characteristic of other low-lying rifted margins, such as Southern Australia or Eastern Argentina: (i) an absence of major scarp or "Great Escarpment" parallel to the coastline; and (ii) a gradual topographic transition from the coast to low-altitude interior plains or plateaus, only achieved by possible successive, small scarps. Located ~50 km inland, the selected study area is situated at the limit of two natural regions highlighted by geology (Fig. 1): the 'Gâtine' to the north, which extends the granitic and metamorphic terranes of the Vendean 'Haut-Bocage', and the low-altitude Plain of Niort to the south, underlain by the Jurassic sediments of the Aquitaine Basin. The Gâtine forms a small upland belt exhibiting relatively constant elevations between 200 and 250 m a.s.l.; it overlooks the 'Bas-Bocage' and the Plain of Niort by a semi-continuous, 50-to-100-m-high erosional escarpment. In the study area, an intermediate region called 'Entre-Plaine-et-Gâtine', ~10 km wide, provides topographic contact and geologic transition between the two domains.

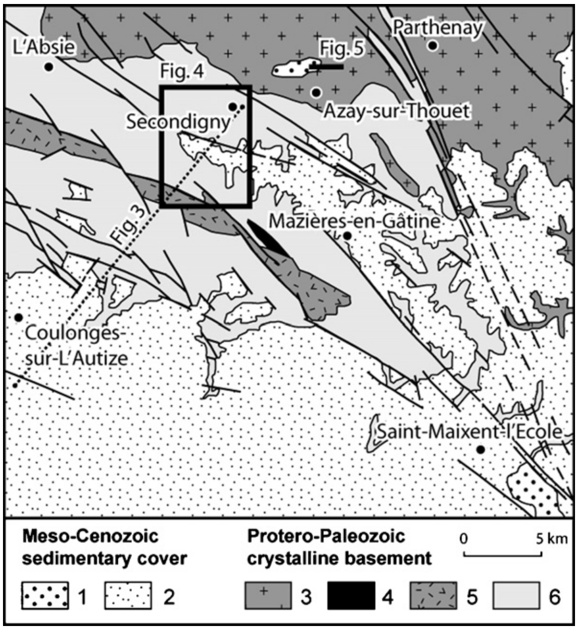

Fig. 2. Geological sketch map of the study area in Southeast Armorican Massif. 1: Cenozoic sediments (Eocene to Rupelian); 2: Mesozoic sediments (Lias and Dogger); 3: granitoids; 4: metabasaltes; 5: rhyolites and ignimbrites; 6: metasedimentary series (schists, micaschists and quartzites). Dotted line outlines the geological cross-section represented on Fig. 3. Location of Figs. 4 and 5 is shown as rectangle and solid black line, respectively. Geologic contours after Bouton and Branger, 2007.

Fig. 2. Esquisse géologique de la région étudiée dans le Sud-Est du Massif armoricain. 1 : sédiments cénozoïques (Eocène à Rupélien) ; 2 : sédiments mésozoïques (Lias et Dogger) ; 3 : granitoïdes ; 4 : métabasaltes ; 5 : rhyolites et ignimbrites ; 6 : séries métasédimentaires (schistes, micaschistes et quartzites). La ligne pointillée souligne le tracé de la coupe géologique représentée en Fig. 3. Le rectangle et le trait noir épais localisent les Fig. 4 et 5, respectivement. Contours géologiques d'après Bouton and Branger, 2007.

Located at the contact between the Armorican Massif and the Aquitaine Basin, the area is geologically divided into a crystalline basement of Protero-Palaeozoic age and a sedimentary cover of Meso-Cenozoic age, respectively (Fig. 2). The basement area belongs to the southeastern extremity of the "South-Armorican Domain" (Ballèvre et al., 2009). It consists of Proterozoic ('Brioverian') and Palaeozoic (Cambrian to Devonian) terranes, the complex structure of which results from tectonics, metamorphism and granitization events related to the superimposition of the Cadomian and Variscan orogenies. This basement is mainly composed of metasedimentary (schists, micaschists and quarztites) and metavolcanic rocks (metabasaltes and metarhyolites), locally intruded by Palaeozoic granites. The major faults of the region have a late-orogenic origin and are globally trending NW-SE – e.g. the Secondigny fault zone, considered as a major branch of the South Armorican Shear Zone (SASZ) (Jégouzo, 1980). The sedimentary cover consists of Jurassic sandstones and limestones (Lias and Dogger) and of residual continental deposits of presumed Eocene age (Coubès et al., 1984) (Fig. 2). This hypothesis for an Eocene age was supported by: (i) palynological and cartographic studies on similar sedimentary formations for the whole Vendean massif (Godard et al., 1994); and (ii) the existence of pedogenic silcretes on the upper part of these sediments, which are typical of Eocene formations in Western France (Guillocheau et al., 2003; Thiry, 1999; Wyns, 1991; Wyns et al., 2003). Despite the existence of faults, the Jurassic sediments underlying the Plain of Niort have a general dip to the south, i.e. towards the Aquitaine Basin. This dip is near zero on the uplands of Gâtine, where Liassic marine deposits have been identified up to an elevation of 250 m a.s.l. (Bouton and Branger, 2007).

3. Morphostratigraphic analysis: identifying palaeosurfaces and related palaeoweatherings

The objective of the morphostratigraphic analysis is to document a long-term record of tectonic uplift and denudation history, through the characterization of existing palaeotopographies and related palaeoweatherings. Two regional-scale palaeosurfaces are recognized in the southeast Armorican Massif: (i) the Infraliassic palaeosurface, the truncated weathering profiles of which are sealed by Liassic marine deposits; (ii) the Eocene palaeosurface, underlain by thick kaolinite- and iron-rich palaeosaprolites and by siliceous duricrusts (silcretes). These two palaeosurfaces were already described to the north, in the eastern Armorican Massif and in Anjou (Wyns, 1991), and to the west, in the 'Bas-Bocage' and around the Chantonnay Basin (Wyns et al., 1988).

3.1. The Infraliassic palaeosurface and related palaeoweatherings

The Infraliassic palaeosurface is the erosion surface on which were deposited unconformably the first Liassic sediments. Directly derived from the post-Variscan surface, it was mainly shaped under a steady-state or acyclic regime during Permo-Triassic times (Guillocheau et al., 2003) and its development (eradication of most of the residual bedrock landforms) continued until the Early or Middle Liassic times. In the study area, this surface is generally sloping southwards and has been locally affected by low-throw faults, probably formed during the opening of the Bay of Biscay in the Early Cretaceous (Fig. 3). Buried or exhumed elements of the Infraliassic palaeosurface are known at high elevations in the Gâtine, around 210 to 220 m a.s.l. in the Secondigny area. At this elevation, when still buried, the palaeosurface beveling the micaschists is sealed by marine deposits dated from the Pliensbachian (calcareous sandstones with crinoids and belemnites, locally silicified) (Bouton and Branger, 2007). In the field, the Pliensbachian deposits often begin with a coarse arkose (0 to 0.30 m) gullying the basement rocks and showing a short sediment transport (the clasts consist of quartz, feldspar and mica grains from the nearby granitic massif of Neuvy-Bouin). The arkosic deposits fill small palaeodepressions or palaeogullies shaped into the micaschist rocks, which are weathered and rubefied on at least ten meters. However, the well-preserved lithological structure (isalterite) and the low intensity of weathering of the micaschists suggest a significant stripping of the upper part of the pre-Liassic weathering mantle, whose remnants known in the French Massif Central correspond to more evolved and thick palaeosaprolites (Triassic albitization facies of southern Massif Central and Morvan) (Ricordel et al., 2007; Wyns et al., 2003). Thus the preserved palaeosurface is interpreted here as a marine abrasion surface of Pliensbachian age, responsible for the stripping of the pre-Liassic palaeoweathering mantle; it could further be defined as an inherited shore platform of etch origin (Twidale et al., 2005). The correlative products of this marine abrasion episode correspond to the arkosic and conglomeratic deposits that fill the palaeodepressions described at the base of Liassic deposits.

Large tracts of the exhumed Infraliassic palaeosurface extend the stratigraphic unconformity between the crystalline basement and the first Liassic deposits, north of the Plain of Niort (the base of the Liassic sediments is represented here by the Hettangian), but also in the Gâtine, north of the Secondigny forest, around 220 m a.s.l. In the latter area, the rocks outcropping in the plane of the exhumed Infraliassic palaeosurface are strongly weathered, both on micaschists and granites (20 to 30 m thick isalterites, locally topped by clayey alloterites: Fig. 4). Here, the high weathering intensity of basement rocks is mainly due to the superimposition of the post-Jurassic weathered landsurface (mainly Cretaceous and Palaeogene in age) on the Infraliassic abrasion surface (Bouton and Branger, 2007). This observation has two important geomorphological implications: (i) it shows that most of the exhumation of the basement from its Mesozoic cover was acquired no later than the Palaeogene, considering the hot and humid palaeoclimatic conditions necessary for the formation of the post-Jurassic weathered landsurface; (ii) it further indicates very low depths of denudation in the Gâtine, given the excellent state of preservation of the exhumed Infraliassic palaeosurface at this location.

3.2. The Eocene palaeosurface and related palaeoweatherings

The Eocene palaeosurface is the erosion surface that bevels the Jurassic sediments in the Plain of Niort, and connects to the Gâtine where it truncates both the basement rocks and the Liassic deposits. In eastern Armorican Massif and in Anjou, it corresponds to the 'Grès à Sabals' surface (Wyns, 1991). Sparse sedimentary formations with residual white sandstone of Eocene age (Coubès et al., 1984) lie in the continuation of the palaeosurface at 220 to 230 m a.s.l. in the Gâtine, north of Azay-sur-Thouet. Their description is that of continental clastic sediments with a sandy-clay texture, rich in inherited kaolinite and iron oxi-hydroxides, and partly

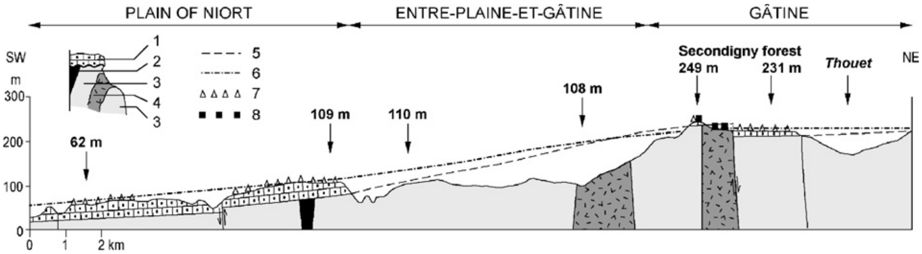

Fig. 3. Geological cross-section from the Plain of Niort to the Gâtine (drawn from the geological map of France at 1:50 000 scale, sheet Coulonges-sur-l'Autize: Bouton and Branger, 2007). 1: limestones (Lias and Dogger); 2: sandstones and limestones (Givetian); 3: metasedimentary formations (Neoproterozoic to Ordovician); 4: rhyolithes and ignimbrites (Tremadoc); 5: Infraliassic palaeosurface; 6: Eocene palaeosurface; 7: flint clays with iron pisolithes; 8: silcrete (Upper Eocene). Location of cross-section is shown on Fig. 2.

Fig. 3. Coupe géologique allant de la Plaine de Niort à la Gâtine parthenaise (réalisée à partir de la carte géologique de la France à 1/50 000, feuille Coulonges-sur-l'Autize : Bouton and Branger, 2007). 1 : calcaires (Lias et Dogger) ; 2 : formations gréso-calcaires (Givétien) ; 3 : formations métasédimentaires (« Briovérien » à Ordovicien) ; 4 : rhyolites et ignimbrites (Trémadoc) ; 5 : paléosurface infraliasique ; 6 : paléosurface éocène ; 7 : argiles à silex et pisolithes de fer ; 8 : silcrète (Eocène supérieur). La localisation de la coupe est indiquée sur la Fig. 2.

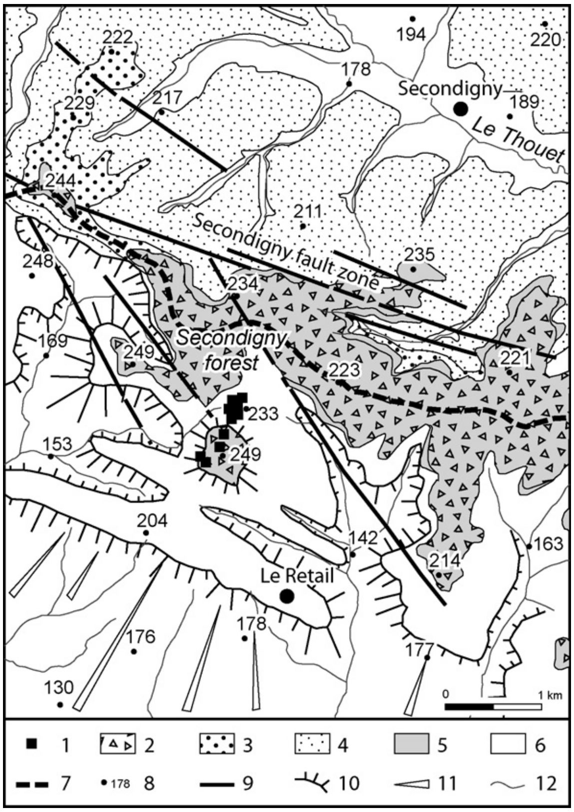

Fig. 4. Simplified geomorphic map of the Secondigny area (Deux-Sèvres, France). 1: silcrete (Upper Eocene); 2: flint clays with iron pisolithes; 3: alloterites on micaschists; 4: isalterites on micaschists; 5: gritty limestones (Pliensbachian); 6: poorly weathered crystalline bedrock; 7: drainage divide; 8: elevation in meters; 9: fault; 10: hillslope; 11: pediment; 12: river. Geologic contours after Bouton and Branger, 2007.

Fig. 4. Carte géomorphologique simplifiée du secteur de Secondigny (Deux-Sèvres, France). 1 : silcrète (Eocène supérieur); 2 : argiles à silex et pisolithes de fer ; 3 : allotérites micaschisteuses ; 4 : isaltérites micaschisteuses ; 5 : calcaires gréseux (Pliensbachien) ; 6 : socle peu altéré ; 7 : ligne de partage des eaux ; 8 : point coté en mètres ; 9 : faille ; 10 : versant ; 11 : glacis ; 12 : rivière. Contours géologiques d'après Bouton and Branger, 2007.

cemented by silica. These sedimentary formations might be interpreted as correlative products of the stripping of pre-Eocene palaeosaprolites, previously developed on crystalline basement and Jurassic carbonate rocks of the Gâtine. As for the Infraliassic palaeosurface, the Eocene surface seems to have recorded a regional-scale updoming, responsible for its flexuration toward the southeast (Fig. 3). Nevertheless, where it is well preserved, the Eocene palaeosurface does not seem to have been fragmented by Oligocene extensional tectonics (Ziegler and Dézès, 2007) – contemporary to the formation of the Saint-Maixent graben to the southeast – nor by a hypothetical neotectonics of Plio-Quaternary age.

Contrary to the Infraliassic palaeosurface stripped of its pre-Liassic regolith, the Eocene palaeosurface has a well-expressed weathering signature, which allows a good reconstruction of its geometry in the absence of sufficient stratigraphic markers. The palaeosurface is underlain by kaolinite- and iron-rich palaeosaprolites (Fig. 4), comparable to laterites currently formed in the humid and sub-humid tropics. Such climates existed in Western France in the Early Cretaceous and the Early and Middle Eocene (Thiry et al., 2006; Wyns et al., 2003). On micaschists and granites, the base of weathering profiles is an isalterite, with weathering intensity increasing toward the soil surface. However, unlike lateritic weathering profiles in the tropics, no summit ferricrete (i.e. iron duricrust) caps the palaeo-profiles observed in the southeast Armorican Massif. Palaeogene ferricretes are known elsewhere in the Armorican Massif and in Vendée, e.g. in La Ferrière near La Roche-sur-Yon (Fig. 1). They probably also existed in the Gâtine, as evidenced by ferricrete fragments found at the top of alloterites developed from Jurassic sediments in the Secondigny forest (Bouton and Branger, 2007). When developed at the expense of Mesozoic sediments, the alloterites correspond to flint clays ("argiles à silex"), extending here the alloterites developed on micaschists in the Secondigny forest area (Fig. 4). Common facies in the region is represented by flint clays with iron pisolithes, generally 10 to 15 m thick. All these weathering formations, well developed and preserved in this part of the Armorican Massif, formed between the Early Cretaceous and the Middle Eocene times (Thiry et al., 2006; Wyns et al., 2003). Together with their correlative products of erosion scattered in the Gâtine and on its northeastern foothills, they correspond to the 'Siderolithic' formations of former authors (Klein, 1961).

In the Upper Eocene, important silicification features of pedogenic origin developed in the region (Guillocheau et al., 2003; Thiry, 1999; Wyns et al., 2003), with silcrete formation either at the expense of Eocene sedimentary deposits (e.g. north of Azay-sur-Thouet: Fig. 5), at the expense of Liassic sediments or directly from weathered basement rocks (Secondigny forest: Fig. 4). These siliceous duricrusts typically formed under arid tropical climate and are equivalent to the residual sandstones ('grès ladères') of Anjou and Vendée. Their preservation in the same plane as the Infraliassic and Eocene palaeosurfaces implies a high stability of the surfaces they have sealed for at least 50 My. Nevertheless, large tracts of the Eocene palaeosurface are degraded by the effects of subsequent erosion and Quaternary dissection, with numerous granitic tors outcropping 20 to 30 m below the level of this surface (Fig. 5). Such irregular topographic surfaces around 200 to 210 m a.s.l. with tors and 'chirons' are interpreted as exhumed or exposed weathering fronts (or etch surfaces: (Goudie, 2004; Twidale and Vidal-Romani, 2004)). Their exhumation by runoff or other erosional processes (solifluction, creeping) implies denudation depths not exceeding 20 to 30 m since 50 My.

4. Implications for uplift history and denudation depths

4.1. Geometry and rates of tectonic uplift

Rates and amplitudes of regional uplift are first estimated in the Gâtine from the elevations of Pliensbachian marine sediments, most of which were deposited in

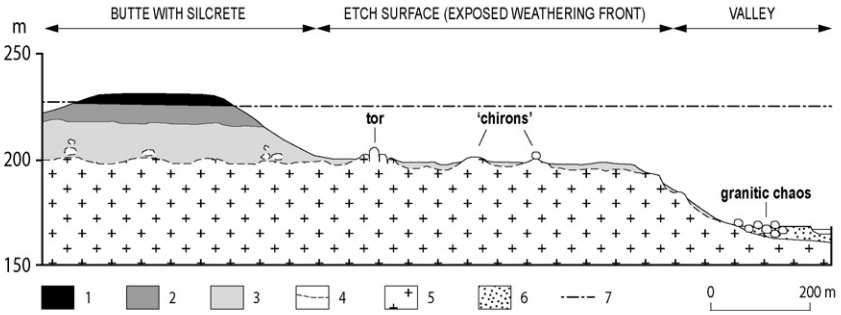

Fig. 5. Synthetic cross-section showing lateritic palaeoweathering profiles (with summit silcrete) and exposed weathering fronts (etch surface) below the Eocene palaeosurface in the Gâtine. 1: Eocene continental sediments with pedogenic silcretes; 2: alloterites (clayey grus); 3: isalterites (sandy grus); 4: weathering front; 5: granitic bedrock; 6: alluvium; 7: Eocene palaeosurface.

Fig. 5. Coupe synthétique montrant les paléoprofils d'altération latéritiques (avec silcrète sommitale) et le front d'altération exhumé (*etch surface*) sous le plan de la paléosurface éocène dans la Gâtine parthenaise. 1 : sédiments continentaux éocènes à silicifications pédologiques ; 2 : allotérites (arènes argileuses) ; 3 : isaltérites (arènes sableuses) ; 4 : front d'altération ; 5 : granite ; 6 : alluvions ; 7 : paléosurface éocène.

shallow subtidal environments. In that area, the base of the Pliensbachian deposits currently occurs up to 249 m a.s.l. (maximal elevation found in the Secondigny forest). According to the recalibrated Exxon curve (Miller et al., 2005), sea-level was at +50 m in Middle Liassic times, so deformation of this stratigraphic marker records a post-Pliensbachian crustal uplift of 200 m at the top of the 'Gâtine', i.e. at a mean rate of 1 m.Ma^{-1} if averaged over the last 200 My. The uplift trend of the Gâtine was probably at work as soon as the Early Liassic times, as suggested by the absence of Hettangian deposits at the base of the Jurassic series of the Gâtine, while marine Hettangian sediments are well represented in the Plain of Niort. In the last area, elevations of the marine Pliensbachian strata gradually decrease southwards (dip between 1 and 2°), from 90 to 100 m a.s.l on its northern border to –50 m to the south in the Niort area (Cariou et al., 1983). Confrontation of the minimal elevation with the Pliensbachian palaeosea level suggests a cumulative subsidence of $\sim$100 m since 190 My. In summary, post-Pliensbachian crustal deformations record a sharp flexure with a half wavelength of $\sim$50 km, embodied by the warping of the Infraliassic palaeosurface (Fig. 3). From the Gâtine to the Plain of Niort, it mimics the geometry of a broad monocline, only chopped by a few faults with low throw (10 to 20 m). Absence of important faulting, e.g. in the right of the Secondigny fault zone sealed by Liassic deposits, suggests, at least locally, discreet tectonic events during the Cretaceous rifted opening of the Bay of Biscay.

The deformations recorded by the younger Eocene palaeosurface also afford opportunities for analysing the regional tectonic behavior since $\sim$50 My. Assuming that the Eocene palaeosurface was near-horizontal in Early Tertiary times, a reconstruction of its geometry would also indicate a sharp flexure and the lack of important faulting, with a cumulative uplift of 150 m at the top of the Gâtine (Fig. 3). This estimate is quite similar to the values of post-Ypresian uplift deduced from the altitudes of deformed Ypresian fluvial sediments in Vendée (Godard et al., 1994). Such a similarity seems to support the hypothesis of an initial geometry close to the horizontal, with the exception of small residual bedrock landforms rising above the Eocene surface, e.g. the quartzitic butte culminating at 249 m a.s.l. in the Secondigny forest (Figs. 3 and 4). Regional updoming might have affected the northern border of the Jurassic plain of Niort, since the Eocene palaeosurface is strongly sloping southwards at this place. Furthermore, the syn- to post-Eocene crustal uplift in the Gâtine is also an estimate of surface uplift since 50 My, where the Eocene palaeosurface is still sealed by pedogenic silcretes. All the data support an acceleration of tectonic uplift during the Tertiary, at a mean rate of 3 m.Ma^{-1}, in probable connection with the Alpine lithospheric buckling (Guillocheau et al., 2003). Uplift could have been caused by compressional intraplate stresses in the Middle and Late Eocene times ("Pyrenean phase"), regionally evidenced by microtectonic studies (north-south subhorizontal styloliths and N00E to N35E senestrial strike-slip movements: Bouton and Branger, 2007). The NNE-SSW-trending, Oligocene extensional tectonics – e.g. responsible for the formation of the Saint-Maixent graben with Rupelian lacustrine infilling – seems to have only a localized impact along a few weakness zones, since it does not seem to affect the Eocene palaeosurface (Fig. 3). Due to the geographic position of the Armorican Massif in the Alpine foreland (Ziegler and Dézès, 2007), the regional uplift may have continued from Late Miocene to the Present, in response to a NW-SE compression corresponding to the later phase of the Alpine lithospheric buckling (Bonnet et al., 2000; Guillocheau et al., 2003; Müller et al., 1997). In all cases, as for a range of other passive margin settings (e.g., the transform margin of Northeast Brazil (Peulvast et al., 2008)), the effects of the Mesozoic rifting have here somewhat faded under the influence of independent, geodynamic and tectonic events that occurred later during the Cenozoic.

4.2. Patterns and rates of long-term denudation

Here we focus on the Cenozoic denudation rates inferred from the analysis of the Eocene palaeosurface, which are the most relevant to understanding the present-day landscape patterns. An apparent contrast in denudation patterns allows us to oppose the uplands of Gâtine, with no significant erosion since Eocene times, and its southeastern foothills ('Entre-Plaine-et-Gâtine') where denudation depths seem to have been greater (Fig. 3).

In the Gâtine, the Infraliassic and Eocene palaeosurfaces are often confused and bear lateritic palaeosaprolites and siliceous duricrusts (silcretes) with an age ranging from Cretaceous to Late Eocene. Thus no significant erosion of the basement and of the Jurassic sediments took place between the Eocene times and the Present. Where the Eocene palaeosurface is degraded and reveals exposed weathering fronts (etch surfaces), the eroded slice of rock does not excess the thickness of the lost palaeoweathering mantle, i.e. 20 to 30 m since ~50 My (Fig. 5). It therefore suggests denudation rates ranging from 0.5 to 1 $m.Ma^{-1}$, e.g. similar to values reported from the Laurentian platform (Eastern Canada) (Degeai and Peulvast, 2006; Peulvast et al., 2009) or the West African craton (Beauvais et al., 2008; Brown et al., 1994; Gunnell, 2003). The post-Eocene denudation estimated here is mostly mechanical (saprolite stripping), but important chemical denudation probably occurred before the stripping phase in pre-Eocene times, considering the rock chemical dissolution necessary to generate the lateritic residuals (palaeosaprolites) covering the Eocene palaeosurface.

In the 'Entre-Plaine-et-Gâtine', denudation depths are more important and, accordingly, the basement rocks do not display any palaeoweathering feature. Field observations show that the rocks in this area are poorly weathered: argillic alteration and reddening of schists and rhyolites reach only a few centimeters. The low intensity of rock weathering and the lack of lateritic palaeosaprolites seem compatible with the development of a younger erosion topography, probably during the Late Tertiary, by comparison with the well-studied Neogene surface in Southern Brittany (Sellier, 1985) and in Anjou (Wyns, 1991). At the foot of the erosional escarpment limiting the Gâtine, glacis or pediments (i.e. gently inclined surfaces truncating the basement rocks: (Goudie, 2004)) connect eroding slopes to the lower surface, slightly dissected by a hydrographical network of dendritic type (Fig. 4). At this location, the maximum denudation depth inferred from the reconstructed Eocene palaeosurface reaches ~100 m, which corresponds to a maximum mean denudation rate of 2 $m.Ma^{-1}$ over the last 50 My. We note that these values are two to four times higher than in the Gâtine or in the Plain of Niort. The slice of removed rock equates to the total denudation (chemical + mechanical) accomplished since Eocene times by downwearing (i.e. surface lowering), implying successive stages of etching and stripping until attaining the present-day topography (Thomas, 1989). Local backwearing or minor scarp retreat could also be involved at the front of glacis or pediments distributed all along the erosional escarpment.

In summary, the maximum denudation recorded in the 'Entre-Plaine-et-Gâtine' since 50 My (~100 m) might be interpreted as the erosional response to the flexural uplift of Tertiary age, probably related to the Alpine lithospheric buckling. It corresponds to a wide, shallow embayment in the southward flank of the flexure, as highlighted by the morphostratigraphic evidence (Fig. 3). This new interpretation has several implications for the mechanisms of regional uplift and long-term erosion: (i) the geometry of the flexure is of downwarp-type, contrary to the hypothesis formulated by Maurin and Renaud (Maurin and Renaud, 2002) in their upwarp-type model of flexural isostasy applied to the 'Seuil du Poitou'; (ii) the cause of flexural uplift is primarily tectonic, and not isostatic, as suggested by the same authors: the eroded slice of rock ($\leq$ 100 m) on a narrow width (~10 km) cannot explain alone the differential uplift of Gâtine by a simple isostatic rebound over a short period of 5 My; (iii) the lower depths of denudation observed to the southeast on limestones, compared to the higher denudation depths on the crystalline bedrock cropping out to the Northwest, directly reflect the amortization of the lithospheric updoming toward the 'Seuil du Poitou'. In no way they could reflect a greater resistance of Jurassic limestone caprock compared to the crystalline basement (antithetical view to that expressed by Maurin and Renaud, 2002). Conversely, differential erosion operates on less resistant, subhorizontal Jurassic sediments to exhume large tracts of the Infraliassic palaeosurface beveling the more resistant Protero-Palaeozoic basement, around the Plain of Niort and in the uplands of Gâtine.

5. Conclusion

This study led to original results and conclusions regarding the long-term landscape evolution and denudation rates at a low-elevation rifted margin, which appears as a geodynamic setting highly favorable to the preservation of ancient landscapes and palaeotopographies. A detailed analysis of palaeolandforms and related weathering formations in the southeast Armorican Massif has clarified the conditions for their development and preservation from the Mesozoic to the Present. The Infraliassic palaeosurface stripped of its Permo-Triassic weathering mantle corresponds to a marine abrasion surface of Pliensbachian age, still buried or exhumed in places. The Eocene palaeosurface corresponds to a weathered landsurface having evolved under hot and humid climates between the Early Cretaceous and the Middle Eocene times; at the time the wet palaeoclimatic conditions were responsible for the development of thick lateritic palaeosaprolites, and were followed by much drier climates in the Late Eocene, causing the formation of extensive siliceous duricrusts (silcretes).

From a methodological viewpoint, our study also points out the valuable contribution of the morphostratigraphic approach (Peulvast et al., 2009) to the understanding of uplift and denudation history in low-energy surface environments, because of the analytical limits of current thermochronological methods. In the study area, calculated uplift and erosion rates are very low, ranging between 0.5 and 2 $m.Ma^{-1}$ during post-Eocene times. The morphostratigraphic analysis used in this study thus provides a potential useful means of constraining numerical surface process models and, possibly, of calibrating physical methods of quantification, e.g. in low-temperature thermochronometry.

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