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To cite this version:

Paul Bessin, François Guillocheau, Cécile Robin, Jean-Michel Schrötter, Hugues Bauer. Planation surfaces of the Armorican Massif (western France): denudation chronology of a Mesozoic land surface twice exhumed in response to relative crustal movements between Iberia and Eurasia. Geomorphology, 2015, 233, pp.75-91. 10.1016/j.geomorph.2014.09.026 . insu-01116939

HAL Id: insu-01116939

https://insu.hal.science/insu-01116939v1

Submitted on 16 Feb 2015

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Abstract

The Armorican Massif, an extensive outcrop of Variscan basement in western France, is shaped by several planation surfaces of debated origin and age. We propose an evolution model for these landforms and their deformation based on detailed mapping of the planation surfaces, their relative chronology and their relationships with dated outcrops of sediments and weathering products. The Armorican landscape consists of six stepped planation surfaces (labelled PS1 to PS6) later incised by two successive river networks. These landforms are pediments and pediplains or polygenic landforms (Armorican Planation Surface – PS5) resulting from two periods of etchplanation. These planation surfaces are mostly pre-Late Cretaceous in age, based on the age of the sediments overlapping these pediments. The three older ones (PS1 to PS3) are pre-Pliensbachian (191–183 Ma); PS4 is pre-Bajocian (170-168 Ma), PS5 (here called the "Armorican planation surface") is polygenic and ranges from the base of the Early Cretaceous to the base of the Bartonian (140–40 Ma); and the youngest (PS6), which is poorly constrained, is older than 40 Ma (base of the Bartonian) or 15 Ma (base of the Middle Miocene). Most of these "old" landforms are exhumed, i.e. they were buried by sediments and later re-exposed by denudation. At least two phases of burial and exhumation have been identified: (1) burial in Jurassic time followed by denudation during the early Cretaceous and (2) burial in late Cretaceous time followed by denudation during the latest Cretaceous to early Eocene. The depth of burial is unknown but is probably low due to the small amount of coeval siliciclastic sediments in the surrounding basins. The two periods of exhumation correspond to critical periods in the plate movements between Africa, Iberia and Eurasia. The first is probably related to the initiation and break-up of the rift between Iberia and Eurasia and the second to the convergence between these two plates.

Keywords: Armorican Massif; exhumation; planation surface; pediment; Mesozoic; Cenozoic

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1. Introduction

The geology of north-western Europe is a complex pattern of sedimentary basins (North Sea, Western Approaches, London and Paris basins, etc.) and outcrops of Proterozoic to Paleozoic basement (Cornwall, Armorican Massif, Ardennes–Eifel, Vosges–Black Forest, French Massif Central, etc.).

The relief of these basement outcrops has been extensively shaped into a succession of planation surfaces. These nearly flat topographic surfaces range from x10 km^2 to x1000 km^2 and bevel the underlying bedrock structures despite residual hills (Brown, 1968; Migoń, 2004a; Huggett, 2011). Although their relative spatial extent and age are still debated (Widdowson, 1997), several types of planation surfaces have been described in Europe:

(1) peneplains (British Isles: Wooldridge and Linton, 1955; Brunsden, 1963; Scandinavia: Elvhage and Lidmar-Bergström, 1987; Lidmar-Bergström, 1989; 1995; 1999; Lidmar-Bergström et al., 1997; Johansson et al., 2001).

(2) pediplains and pediments (Hungary: Pécsi, 1970; Pinczés, 1970 - Germany: Rosenkranz, 1970 - British Isles: Dury, 1972 - Scandinavia: Lidmar-Bergström, 1995; Lidmar-Bergström et al., 1997; Johansson et al., 2001).

(3) etchplains, which are either mantled (Sudetes: Migoń, 1997; 1999 - Western Europe: Migoń and Lidmar-Bergström, 2001) or stripped (British Isles: Jones, 1999 - Scandinavia: Lidmar-Bergström, 1999; Johansson et al., 2001 - Western Europe: Migoń and Lidmar-Bergström, 2001).

(4) wave-cut platforms (British Isles: Ramsay, 1846; Wooldridge and Linton, 1955; Brunsden, 1963).

Planation surfaces in the Armorican Massif, have been mapped by de Martonne (1906), Musset (1922), Guilcher (1948; 1949) and Klein (1975). In these classic studies, most authors agreed on the existence of several planation surfaces with ages ranging from the Mesozoic for the most elevated, to the Cenozoic for the closest to sea-level. Some scholars have also discussed the nature of the planation surfaces: Meynier (1951, 1952), Klein (1975, 1990), Sellier (1985) and Wyns (1991) suggested that many surfaces were pediments, but based on the occurrence of rounded pebbles at some locations, Klein (1975) also advocated wave-cut platforms. At the same time, numerous

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occurrences of deep weathering products such as laterites and silcretes were described by a number of geologists (Ferronnière, 1921; Kerforne, 1921; Milon, 1932; see Estéoule-Choux, 1983 for a review). These weathering mantles suggest that some Armorican landforms were shaped in a different climatic setting (hot semi-arid or hot and very humid) from the present, as suggested long ago by Jessen (1938) for Germany. The present-day network of valleys has incised these planation surfaces. Fluvial incision started at the transition between the early and middle Pleistocene. The timing is related to the Africa/Apulia/Eurasia convergence regime and was enhanced by major early to middle Pleistocene climate change (Bonnet et al., 2000).

The aim of this paper is (1) to characterize the different types of pre-incision landforms (incised valleys were previously studied by Bonnet, 1997 and Bonnet et al., 2000), their relative chronology, their links with dated sediments and weathering mantles and (2) to propose a model of evolution for these landforms at the scale of the entire Armorican Massif.

2. Regional setting

2.1. Geology

The Armorican Massif is a Variscan (Hercynian) basement (late Devonian to Carboniferous deformations) with some remnants of Cadomian (late Neoproterozoic) deformations (Chantraine et al., 2001; Ballèvre et al., 2009). This basement outcrop is surrounded by three main sedimentary basins: the Western Approaches Basin to the north, the Armorican and Celtic Margins to the west and south, and the Paris Basin to the east.

The Armorican Massif is made up of three main Variscan units (Ballèvre et al., 2009) bounded by major N110E shear faults: the North Armorican Shear Zone (NASZ) and the two branches of the South Armorican Shear Zone (SASZ). The basement consists of metamorphic rocks (micaschist and gneiss, dominant south of the SASZ), sedimentary rocks (schist, sandstone and quartzite, dominant between the NASZ and the SASZ), and plutonic rocks (granites are widespread). The bedrock was densely fractured by N140E faults at the time of the Permian–Triassic extension (aborted pre-Atlantic rifting episode; Ziegler, 1990).

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The Western Approaches Basin is a long-lived, complex depocentre (Ziegler, 1987; Ruffell, 1995). It was initiated at the time of the Permian extension (rift 1), reactivated during the early Cretaceous North-Atlantic extension (rift 2), and inverted during late Paleogene times (Le Roy et al., 2011).

The Paris Basin (Perrodon and Zabek, 1990; Guillocheau et al., 2000) is an intracratonic basin floored by Lower Triassic strata. It underwent moderate inversions during early Cretaceous time and buckled under a compressive stress regime during Cenozoic times.

The Armorican and Celtic continental margins were initiated at the time of the first oceanic accretion in the Bay of Biscay, i.e. during the uppermost Aptian (early Cretaceous) (Montadert et al., 1979; Thinon et al., 2003). The Armorican passive margin is a starved continental margin, whereas the Celtic margin has been more abundantly supplied with sediment by the (English) Channel since the Neogene (Bourillet et al., 2003).

These basins were controlled by plate movements between Iberia (Africa) and Eurasia at the time of early rifting in the North Atlantic and Bay of Biscay (early Cretaceous) and later during the peak of Pyrenees compression (latest Cretaceous to Eocene, see Vissers and Meijer, 2012a; 2012b for a review).

Detailed Jurassic and Cretaceous palaeogeographic maps (Enay et al., 1980; Hancock and Rawson, 1992; Lasseur, 2007) indicate (1) that facies lines can be traced across the modern boundaries of the Armorican Massif, meaning that the present-day limits of the basins are erosional; and (2) that the Armorican Massif was partly (or totally) covered by sediments.

2.2. Geomorphology and landscape evolution since the Mesozoic

The present-day topography of the Armorican Massif is structured around three main upland areas: the Western Brittany Plateau, the Vendée High and the Lower Normandy Plateau (Fig. 1). The mean elevation of the study area is 150 to 220 m, the highest summit is 417 m, and low areas (Eastern Brittany Low, Ligerian Low and Maine Low) range between 30 m and 100 m. The SASZ is an important structure to the south and defines the boundary with a low-lying flat domain hereafter called the Vannes Platform (Fig. 1). All of these physiographic units are incised by rivers to various depths.

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De Martonne (1906) was the first to recognize a planation surface (defined as a peneplain) of regional importance, extending everywhere around the Western Brittany Plateau and deformed after its planation. Musset (1917; 1922; 1928) identified two other deformed planation surfaces, both more elevated than the one described by de Martonne. Meynier (1940), Gautier (1947), Guilcher (1948; 1949), and Klein (1975) argued for a pre-Eocene age for de Martonne's regional lower planation surface based on the occurrence of dated Eocene silicified deposits in the eastern part of the Armorican Massif, and ascribed a Mesozoic age to the two upper surfaces.

Some scattered vestiges of Mesozoic and Cenozoic sediments are preserved on the weathered basement of the Armorican Massif. The oldest sediments, of early (Pliensbachian–Toarcian) and middle (Bajocian–Bathonian) Jurassic age, occur on the Lower Normandy Plateau (Rioult, 1968; Dugué, 2007). Remnants of Upper Cretaceous marine sediments are more widely distributed (Durand et al., 1973; Juignet, 1974; see compilation below). After a period of lateritic weathering, attested by kaolinite reworking in various Eocene deposits (Estéoule-Choux and Ollivier-Pierre, 1973; Ollivier-Pierre, 1980), the Armorican Massif was flooded at least six times by rising sea-levels (Guillocheau et al., 2003) during (1) the early Eocene (Ypresian), along the southern part of the Armorican Massif, (2) the base of the late Eocene (Bartonian), (3) the early Oligocene (Rupelian), (4) the middle Miocene, (5) the uppermost Miocene (Messinian?) and the early Pleistocene (Gelasian). Between the Bartonian and Rupelian sea-level rises, lacustrine aggradation occurred, preserved in N150E grabens (Rennes, Landéan, Saffré) mostly located in the Eastern Brittany Low. The middle Miocene flood and associated marine bioclastic limestones (mainly located along the Carentan Flat, the Eastern Brittany Low and the Lower Loire Platform: Durand, 1959; Lécuyer et al., 1996; Courville and Bongrain, 2003; Dugué et al., 2005) are clearly of eustatic origin. The basement and these previous deposits were later incised by (1) a first drainage network during the late Miocene, forming valleys that became later filled by the continental to estuarine Upper Miocene to Pliocene "Red Sands" (Brault et al., 2004; Dugué et al., 2007); and (2) a second generation of rivers, which form the modern drainage and were emplaced around the early to middle Pleistocene boundary (Bonnet et al., 2000).

2.3. Palaeoclimate

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The world-scale Cenozoic temperature curve has been quite well known since the works of Miller (Miller et al., 1977) and Zachos (Zachos et al., 2001; 2008). The cool latest Cretaceous was followed by global warming during the early Eocene and then by overall cooling since the Eocene–Oligocene transition. The palaeoprecipitation curve, however, which is key to the interpretation of past landforms, is poorly known. The only available constraints are palaeobotanical data (mainly pollens and spores) and palaeosols. At the European scale, the Middle Jurassic was very hot and humid, evolving to drier conditions at the Jurassic–Cretaceous boundary. The early Cretaceous was again very humid, with the formation of lateritic profiles (Lower Cretaceous laterites — Ardennes: Yans, 2003; French Massif Central: Théveniaut et al., 2007; Ricordel-Prognon et al., 2010). Cenozoic Armorican deposits record tropical humid (Paleocene to early Eocene) to semi-arid (late Eocene to Oligocene) conditions (Durand and Ollivier-Pierre, 1969; Châteauneuf, 1980; Ollivier-Pierre, 1980; Ollivier-Pierre et al., 1987) until the Miocene–Pliocene boundary, a period during which the present-day climatic conditions prevailed across Europe (Mosbrugger et al., 2005; Roche et al., 2008; Utescher et al., 2009).

3. Material and methods

This study is based on planation surface mapping in the Armorican Massif and aims to establish the relative chronology, age and formative processes of the different generations of land surfaces identified. After completion, a planation surface can be (1) tilted or updomed on a wavelength of at least x10 km, and/or (2) bevelled in response to a local fall in base level, resulting in two surfaces with the older step occurring at a higher elevation and the younger at a lower elevation. Given that a planation surface can be deformed by crustal movements, it follows that its elevation can vary across the regional landscape. An erosion surface can also be shaped by different erosional processes due to relative base-level changes and thus become a polygenetic surface (Peulvast and Claudino Sales, 2005), i.e. a surface shaped by more than one deformation event or one climatic regime.

The characterization and relative chronology of these planation surfaces was obtained by combining Digital Elevation Model (DEM) analysis (IGN, 2011; Jarvis et al., 2008) under ArcGIS 10© with field controls. The characterization and mapping (at the scale of 1:80,000) of the planation surfaces are based on a combination of three different GIS analysis methods:

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1- 3D visualization of the DEM (using ArcScene™) with a vertical exaggeration of x15, in order to emphasize the continuity of the inclined planation surfaces (primary or tilted by deformation) at a local scale, which is one of the limits of the approach but provides an innovation over the previous classic monographs dealing with the region (e.g. Klein, 1975).

2- Slope, shading and curvature analysis from the DEM (Smith and Pain, 2011), which are effective techniques for mapping the dissection of planation surfaces by valley networks as well as the contours of scarps forming the upper boundaries of planation surfaces.

3- Landform classifications from the DEM analysis performed in a Geographical Information System (GIS). Several classification methods were tested such as the Hammond (1964) landform typology, later automated (Dikau et al., 1991; Morgan and Lesh, 2005), which is based on a combination of slope, local relief and curvature parameters for a chosen number of neighbourhood cells. However, the Topographic Position Index (TPI) Landform Classification (Weiss, 2001; De Reu et al., 2013) has lately been preferred due to an empirical best fit with observed landforms. This method is based on the measurement of the TPI (difference between the elevation of a cell and the elevation of cells in a given neighbourhood radius) classified into discrete slope-position classes using the TPI standard deviation and slope values to identify ridges, upper slopes, middle slopes, flats, lower slopes and valleys. The parameters from two neighbourhood radii (best fits used in this study: 500 m/2000 m; 1000 m/4000 m) are combined to produce the final classification in order to reveal more complex landscape information. The TPI Landform Classification combined with previous methods (3D visualization and classical DEM analysis) provides great accuracy when mapping planation surfaces, scarps and incised valleys.

The relative chronology and dating of the planation surfaces were based on the geometric relationships between these surfaces and sediments and weathering mantles of known age. To date these surfaces, a GIS mapping project was elaborated using (1) different landform maps published since ~1950; (2) geological maps of France at 1:50,000 scale (source data provided by the Bureau des Recherches Géologiques et Minières) for lithology, weathering mantles and Mesozoic to Cenozoic sedimentary rocks; and (3) dated outcrops (mainly Cenozoic sediments) culled from the literature. Numerous topographic profiles were drawn from the DEM (see sections 4.4 and 4.5) at two scales, i.e. for each plateau or high and for the whole Armorican Massif, each time integrating all of the

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aforementioned information layers. Most of the ages provided by fossils (biostratigraphy) were re-evaluated and are reported in the current international stratigraphic chart (ISC 13) reference frame.

4. Armorican landforms

4.1 The Lower Normandy Plateau showcase

Most landforms of the Lower Normandy plateau show uniform morphological characteristics which can be summarized as follows (see Fig. 2):

(1) The land surface exhibits flat or gentle gradients (minimum: 0.01%; maximum: 2%; mean: 0.5%), with concave-up profiles that sharply truncate the underlying heterogeneous bedrock (Figs. 2A, 2B and 2C, underlined in red). These surfaces are 10 km in width (minimum: 3 km, maximum: 8.5 km) and x10 km long (minimum: 11 km, maximum: 29 km). These land surfaces cover areas ranging from 26 km^2 (Fig. 2B) to 195 km^2 (Fig. 2C) i.e. x10 km^2 to x100 km^2 in magnitude. In addition, these surfaces are slightly dissected by the present-day river network. The incisions are underlined by 0.3 km to 3.4 km wide and 8 m to 70 m deep valleys with depth/width ratios ranging from 12 to 136.

(2) The flat or dipping surfaces are bounded by steeper slopes from around 6% (3.4°) to scarps with slopes of 25% (14°), which separate these surfaces from the older and higher planation surfaces (landform boundaries outlined in red in Fig. 2, 3D views). These steeper slopes or scarps are, in map view, continuous, straight or slightly sinuous and are not dissected by an incised channel network coeval with the lower flat surface to which they (steeper slopes or scarps) are linked. The flat surfaces bounded by the steeper slopes/scarps define large flat-bottomed valleys into which the incised Pleistocene valley network cuts randomly. These incised valleys are found to either, (1) flow across rather than along the flat surfaces, (2) be superimposed only on the downstream part of the gently dipping surfaces, or (3) be incised into upslope part rather than into the downslope part of the surfaces. This suggests that the incised river network bears no connection with the formation of the flat to gently dipping surfaces, i.e. the incised valleys are young and were superimposed onto these low-gradient landforms.

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(3) No alluvial sediments (alluvial fans, low preservation fluvial channels) are preserved on these surfaces, but the Lower to Middle Jurassic marine sediments fossilized these landforms (pediment in Fig. 2B: flooded by Middle Jurassic open marine shallow carbonates which onlap Paleozoic quartzites, Doré et al., 1977; Fily, 1989; Gigot et al., 1999; Dugué, 2007; pediment in Fig. 2C: coastal Lower Jurassic deposits, Rioult, 1968; Kuntz et al., 1989; Dugué, 2007). These sediments fill, flood and fossilize the flat to gently dipping surface, shown here by sketches in Figure 2.B'.

These characteristics fit the definition of a specific type of planation surface, namely pediments, which involve (Whitaker, 1979; Dohrenwend and Parsons, 2009):

- a nearly flat erosional surface (Brown, 1968; Whitaker, 1979; White, 2004) truncating a heterogeneous mosaic of rock outcrops;
- an upslope scarp connecting with upstanding landforms (Cooke, 1970; Dohrenwend and Parsons, 2009);
- no cogenetic river channels (whether erosional or depositional) — only shallow-incision migrating streams (x1 m deep, x0.1 to x1 km wide: Strudley et al., 2006; Dohrenwend and Parsons, 2009);
- concave-up longitudinal profiles (Tator, 1952; 1953; Brown, 1968).

Pediments had been previously recognized by researchers across the Lower Normandy Plateau (Klein, 1975, 1990) or across the western and southern parts of the Armorican Massif (Meynier, 1951; 1952; Sellier, 1985; Wyns, 1991), although in a less systematic way than allowed here by GIS analysis. Some pediments are controlled by lithology, mainly by quartzite of Paleozoic age (Early Ordovician Armorican Quarzite, Late Ordovician and base Devonian quarztitic sandstones of the Western Brittany and Lower Normandy plateaus). Elsewhere in the Armorican Massif, other lithological contrasts, such as between metamorphic and plutonic rocks, do not control the location of the first-order planar landscape units such as the Léon–Trégor and Vannes Platform areas.

4.2 Planation surfaces in other parts of the Armorican Massif

The Western Brittany Plateau displays planation surfaces with similar characteristics to the Lower Normandy Plateau, i.e. pediments. North of the Loire River, a large and nearly flat surface

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extends from the Léon–Trégor Platform (W) to the Eastern Brittany Low (E) and to the Vannes Platform (S), between and around the Lower Normandy and Western Brittany Plateaus. This surface, hereafter called the Armorican Surface, is large: it covers an area of approximately 25,000 km^2, and is bounded by scarps or steeper slopes around its upper rim. This Armorican Surface answers to the definition of a pediplain, i.e. a planation surface made up of coalescent pediments (King, 1953). Locally (Léon and Vannes Platforms), the Armorican Surface is covered by undated conglomerate beds containing rounded pebbles of possible marine origin, cropping out at an elevation between 130 m and 210 m (Bourcart et al., 1950; Guilcher and Saint-Réquier, 1969; Hallégouët, 1972; 1976; Plusquellec et al., 1999). This feature suggests that parts of the Armorican Surface might have been shaped by marine wave processes and evolved as a wave-cut platform.

4.3 Planation surfaces and weathering mantles

As shown by a compilation (Fig. 3) of the most recent 1:50,000 scale geological maps of France, where “surficial” formations (soft rock outcrops sometimes up to 30-50 m deep) have been mapped, most of the basement rocks of the Armorican Massif are weathered. Three types of weathering mantle have been characterized in the study area.

(1) Laterites. Complete lateritic profiles in tropical regions can exhibit a thick saprolite (approximately 40 m, maximum 90 m) capped by an iron duricrust. Such occurrences are well preserved in the Eastern Brittany Low and on the low-elevation planation surfaces of the Western Brittany Plateau (see Estéoule-Choux, 1983 for a review). Most of these profiles have been stripped so that only the lower part of the saprolite is preserved: in the field, they appear as kaolinized schist/micaschist, feldspar-rich granite or gneiss.

(2) Grus. These weathered layers occur mainly on feldspar-poor granite. Most researchers have agreed in the past that grus forms under temperate weathering conditions (e.g. Lageat, 2014). Recent drillholes and geophysical investigations for water resources in the grus-dominated areas (Wyns et al., 2003; Lachassagne et al., 2011) indicate instead (i) thicker deposits than expected (40–85 m) and (ii) a location of the grus at the base of large lateritic profiles. For these authors, grus is thus none other than the weathering front of stripped lateritic profiles.

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(3) Silcretes. Presumed silcretes were identified over most of the Armorican Massif. Nevertheless, the use of this term is confusing because most of the silicified sandstones have been labelled as silcrete (Estéoule-Choux, 1983). The two varieties of silicified sandstones recognised by Thiry (1988; 1997) and Thiry et al. (1988a; 1988b) in the Paris Basin have been found in the Armorican Massif: (1) true silcretes involving illuviation structures overprinted on alluvial deposits, and (2) groundwater silicifications of alluvial sediments.

All these weathering materials cover the different pediment or pediplain levels. True lateritic-type weathering profiles (type (1) with kaolinite; not type (2), which is more debatable) are widely distributed. This implies that the pediments and pediplains are older than the silcretes and that they are older than or coeval with the laterites (Fig. 3). These weathered planation surfaces might be stripped etchplains by virtue of pedimentation processes. Two main types of etchplain have been defined in the literature (Migoń, 2004b): (1) mantled etchplains, which correspond to flat weathering surfaces by laterites (Millot, 1980) and (2) stripped etchplains, which are mantled etchplains dissected by rivers or retouched by pedimentation (Büdel, 1957; Thomas, 1989a, 1989b; Bremer, 1993; Twidale and Bourne, 2013).

Some of these planation surfaces, e.g. the Armorican Surface, are polygenetic surfaces with evidence of weathering (etchplanation?), coalescent pediments (collectively forming pediplains) and local reworking by waves (wave-cut platforms).

4.4 Relative chronology of the planation surfaces

At least six stepped planation surfaces, bounded by steeper slopes or scarps but not faults, were mapped (Figs. 4 and 5) at the scale of the Armorican Massif, north of the Loire River. The major planation surface, hereafter called the Armorican Planation Surface (PS5, Figs. 4 and 5), extends from western Brittany to the Paris Basin. This surface is physically continuous over the entire Armorican Massif, meaning that this surface can be traced and mapped, with no main break in slope. Consequently, this surface is not flat and occurs at different elevations (minimum: 30 m, maximum: 110 m). At any given location, specimens of the Armorican Planation Surface occur one step down from the two major plateaus (Western Brittany and Lower Normandy) and are bounded by scarps or by steeper slopes that are traceable in the upslope region of the pediments. Below this major surface,

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only one generation of pediments has been detected (labelled PS6, Fig. 6). PS6 is itself incised by the present-day valley network. The Armorican Surface can be dissected and degraded by these youngest pediments and valleys, and has been accordingly mapped as PS5d (for “degraded”).

For planation surfaces older than the PS5, a relative chronology was established for both plateaus. On the Lower Normandy plateau (PS1 to PS4, Fig. 4), at least four generations of pediments can be mapped below some residual hills. A certain amount of reactivation of the basement faults (Mayenne and Merlerault Faults, SASZ) has locally disrupted this leitmotiv. On the Western Brittany Plateau, which is geographically isolated from the Lower Normandy Plateau, the same number of stepped pediments has been identified.

4.5 Dating the planation surfaces: towards an age model

On the Lower Normandy Plateau, pediments PS1 and PS2 (Fig. 4) are sealed by Aalenian to Bathonian silicified marine oolithic limestones (Doré et al., 1977; Kuntz et al., 1989) and specimens of pediment population PS3 (Fig. 4) are sealed by Pliensbachian transgressive sandstones and claystones (Kuntz et al., 1989). Overlapping of the youngest pediment by the older sediments implies a pre-Pliensbachian age for the pediment generations labelled PS1 to PS3 (Fig. 4).

Specimens of pediment PS4 (Fig. 4) are flooded by Bajocian shallow marine carbonates (Kuntz et al., 1989) lapping onto the pediment scarp ("Ecueils", Ménillet et al., 1994, 1997; Peulvast and Claudino Sales, 2005).

The Armorican Surface (PS5), is covered by late Cretaceous (Cenomanian to Campanian) deposits (Figs. 4 and 6). These occur in various forms (see Fig. 6 caption for references), including (1) thin fossiliferous claystones at the base of transgressive siliciclastic deposits, (2) marine carbonates (chalk) preserved in situ, (3) marine sediments collapsed into karstic cavities, (4) chalk flints or silicified late Cretaceous fossils preserved as undissolved components of a weathering profile (Clay-with-Flints) or (5) reworked late Cretaceous clasts at the base of younger Cenozoic sediment (Bartonian to Pliocene – reworking of the microfossils) or in Pleistocene coastal deposits (Pre-Holocene – flints and chalk). Weathered surface PS5 is also covered by (1) Eocene to Oligocene sediments (La Trinité-Porhoët, Saffré, Céaucé, Rennes among other locations, see Durand, 1959; Estéoule-Choux, 1970; Ollivier-Pierre, 1980; Ollivier-Pierre et al., 1988 for reviews), (2) complete

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lateritic profiles (Estéoule-Choux, 1983), (3) numerous silcretes (see Brault, 2002 for a compilation), and (4) undated conglomerates (sometimes intensely ferruginised) with rounded pebbles of possible marine origin, cropping out at elevations between 150 m and 210 m (Bourcart et al., 1950; Guilcher and Saint-Réquier, 1969; Hallégouët, 1972; 1976; Plusquellec et al., 1999). The Cretaceous sediments are mainly marine, whereas the Eocene to Oligocene deposits are mostly continental. This means that the first planation of surface PS5 occurred after the middle Jurassic (age of the PS4 pediments) and before the late Cretaceous.

Pediments PS6 bear some late Eocene to early Oligocene sediments. However, because these deposits are preserved in grabens (e.g. Ollivier-Pierre et al., 1988; 1993) and the timing of the fault is still being discussed (syn- or post-depositional, Guillocheau et al., 2003), they cannot provide a precise constraint on the age of PS6.

Silcretes can be found capping landforms from PS3 to PS6. Some of them contain leaves of *Sabalites andegavensis* (over PS5) that have been dated as Eocene (Ypresian–Bartonian) in the surroundings of Le Mans (Crié, 1878) and in Brittany (Durand, 1959; Estéoule-Choux, 1970; see Klein, 1975 for a review). The evidence has been confirmed by pollen studies (Châteauneuf, 1980; Juignet et al., 1984).

The remaining question is the age of the planation surfaces of the Western Brittany Plateau. Due to the absence of dated sediments, the only argument currently available is the analogy with the Lower Normandy Plateau, which displays the same number of terraced pediment levels.

Planation surface extent and age (preserved and degraded) are summarized in Figure 5. This document also provides information about land surface deformation by major faults. For example, the SASZ divides the Armorican Surface (PS6) into two domains, the Vannes Platform (southward) and the Eastern Brittany Low (northward), with different elevations but with the same weathering materials and stratigraphic age brackets. Similar patterns were encountered on either side of the Domfront and Mayenne Faults.

5. Discussion

5.1. The Armorican Massif: an exhumed land surface

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Our results suggest Mesozoic ages for most of the planation surfaces of the Armorican Massif (PS1 to PS4, main planation of polygenetic PS5), and thus great antiquity of the land surface. Ancient landforms on other continents have been discussed (e.g. in Australia, Twidale, 1997) but it is often argued that preservation is only possible in cases where the topography was buried by younger sedimentary rocks and later exhumed (e.g. Lidmar-Bergström et al., 2013). Here, some of the tell-tale cover rocks have been preserved as discrete outcrop patches (Figs. 4 and 6) and provide age brackets to two main periods of burial: (1) the early to middle Jurassic (for planation surfaces PS1 to PS4) and (2) the late Cretaceous (for the Armorican Surface – PS5).

The accumulation of Jurassic and Upper Cretaceous marine sediments on the Armorican Massif is in agreement with the palaeogeographic reconstructions proposed from studies of the sedimentary basins. Since the Bathonian, the most authoritative compilation provided by the French Jurassic Research Group (Enay et al., 1980) shows evidence of marine deepening toward the present-day eastern border of the Armorican Massif (i.e. the western edge of the Paris Basin), suggesting marine flooding of this part of the Armorican Massif during the middle Jurassic and part of the late Jurassic. Similarly, along the NW side of the massif, in the Western Approaches Basin, industrial wells show open marine conditions 50 km WNW of Ushant Island (well Lizenn 1) for most of the Jurassic (except the Tithonian). Palaeogeographic maps of the Paris Basin (Lasseur, 2007) and of the Western Approaches (Hancock and Rawson, 1992), and industrial wells along the southern Armorican margin (Penma 1, in Paquet et al., 2010) and in the Western Approaches (Ruffell, 1995) suggest major deepening of these basins during the Campanian peak of chalk deposition (presence of ocean-floor current deposits occurring between the Proto-Atlantic and the Tethys oceans; Esmerode and Surlyk, 2009), followed by a relative sea-level rise that flooded the Armorican Massif.

The denudation periods can be deduced from the siliciclastic sediment inputs into the surrounding basins. This occurred twice after the Jurassic period of deposition, namely during the early Cretaceous (Wealden Group: Berriasian to Barremian, and Lower Greensand Group: Aptian to early Albian facies) and the early Cenozoic (mainly Ypresian). It follows that sedimentation occurred before (Jurassic) or in between (late Cretaceous chalk) these two episodes of clastic input. Denudation of the Armorican Massif thus occurred in two stages, first during the early Cretaceous and subsequently during the early Cenozoic.

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This scenario fits with the record of two periods of weathering during the early Cretaceous and earliest Cenozoic. Lateritic profiles preserved below onlapping Cenomanian sediments on the Paris Basin side of the Armorican Massif (Rioult et al., 1966; Steinberg, 1967; Estéoule-Choux et al., 1969; Vérague, 1974; Wyns et al., 2003) indicate a first Cretaceous period of laterite formation, confirmed by palaeomagnetic dating of lateritic duricrusts on the north side of the French Massif Central (Ricordel, 2007; Théveniaut in Quesnel et al., 2009a; Ricordel-Prognon et al., 2010). The second period of laterization peaked during the early Cenozoic (red beds, or "siderolithic" facies, Estéoule-Choux, 1983). The warm climate that promoted the formation of these laterites probably also explains the deep chemical denudation of Jurassic and late Cretaceous carbonate platforms that buried and preserved these ancient land surfaces.

These elements indicate that the Armorican relief is mostly an exhumed landscape. Exhumation occurred on at least three successive occasions (during the Triassic, i.e. the terminal planation of the Variscan orogenic belt; the early Cretaceous; and the Cenozoic), and was interrupted by two periods of burial (the Jurassic and the late Cretaceous).

Other exhumed landforms and land surfaces have been reported in continental Europe. In Poland, the Sudetic landforms were buried under Neogene sedimentary sequences (Migoń, 1999). In Sweden, Lidmar-Bergström (1996) described a similar setting to the Armorican Massif with old relief buried by Jurassic and Cretaceous cover rocks. Based on the currently estimated extent of late Cretaceous marine flooding and the widespread distribution of open marine chalk, other basement massifs (e.g. the Ardennes) could also have become partly exhumed after the late Cretaceous (see section 5.5).

5.2. Depths of denudation and burial of the exhumed topography

The preservation of old (Mesozoic) landforms and patches of Jurassic and Cretaceous sediments (Figs. 4 and 6) implies that total denudation depths have been low. Few thermochronological data are available for the Armorican Massif (Siddall, 1993). Siddall studied apatite fission-track samples located along the coast from the eastern Lower Normandy Plateau to Vendée. The fission-track ages record three peaks at 150–160 Ma, 190–200 Ma and 210–230 Ma. Fully published data are not available and the reliability of these results is debatable. However, these

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late Triassic to Jurassic ages mean that the amount of post-Jurassic denudation is quite low. The amount of denudation can also be discussed from the volumes of siliciclastic sediments supplied during the early Cretaceous and Cenozoic and currently preserved in the surrounding basins.

The most important period of erosion was the early Cretaceous, with the influx of the Wealden Group siliciclastic deposits all around the Armorican Massif. In the Bay of Biscay and the Western Approaches, these sequences filled rifts (Ziegler, 1987; Ruffell, 1995; Thinon et al., 2001), mainly supplied by the local topographic highs, i.e. the rift shoulders. In the intracratonic Paris Basin, the maximum thickness of early Cretaceous siliciclastic sediments is 500 m (deposited over a period of 45 Ma), which is rather low (Guillocheau et al., 2000).

The Paleogene sediments around the Armorican Massif are mainly carbonates. In the Paris Basin (Guillocheau et al., 2000), English Channel and Western Approaches (Evans, 1990), the maximum thickness of Paleogene rocks is 200 m (deposited over a period of 35 Ma). During the Cenozoic, the Armorican and Celtic Margins behaved as sediment-starved margins (Bourillet et al., 2003), with a maximum total sediment thickness below the shelf break of 2000 m on the Celtic Margin (Evans, 1990) and 1200 m on the Armorican Margin (Paquet et al., 2010).

Even though detailed, three-dimensional measurements of the siliciclastic sediment volumes are not available, available evidence supports a low denudation rate since Jurassic time, except along the borders of the two early Cretaceous rifts: Bay of Biscay and Western Approaches.

Burial depths are rather difficult to estimate in the absence of thermochronological data. Based on Jurassic and late Cretaceous sediment isopach maps available for the Paris Basin (Guillocheau et al., 2000; Lasseur, 2007) and on wells and seismic lines of the Western Approaches Basin (Evans, 1990; Ruffell, 1995), the amount of Mesozoic burial (estimated by an extrapolation of the thickness variations in the surrounding basins) is probably less than 1 km (certainly less than 400 m for the Jurassic) on the Paris Basin side; and is probably greater (1–1.5 km) on the Western Approaches Basin side.

5.3. Nature of the Armorican planation surfaces

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Pre- and syn-Jurassic landforms (PS1 to PS4) are typical pediments, with upstream scarps organized in large flat-floored, valley-like structures reminiscent of the Namibian 'pedivalleys' mentioned by Dauteuil et al. (this volume).

The Armorican Surface (PS5) is a polygenetic planation surface. As mentioned above, its first stage of planation could have occurred at the time of deposition of the Wealden Group siliciclastic sediments (Berriasian–Barremian) and followed by lateritic weathering. The corresponding weathering materials are preserved within the Upper Barremian sediments of the Paris Basin ("Argiles et sables rouges panachés" – Meyer, 1976), confirming the occurrence of an early Cretaceous lateritic episode in northern France. During the late Cretaceous, this surface was covered by chalk. The earliest Cenozoic was a time of a widespread emersion of northern France, which involved a second period of intense weathering evidenced by the Clays-with-Flints (which can be in situ weathering profiles but also reworked deposits; see Quesnel, 2003 for discussions) with flints coming from the Late Cretaceous Chalk (Fig. 6). This surface was also bevelled by waves on its western Atlantic side, with evidence provided by occurrences of lag deposits consisting of rounded pebbles (see section 4.5). The exact age of the conglomerates, however, remains unknown. These facts imply that this polygenic surface was initially an etchplain, which was stripped twice by pediment-forming denudational processes and evolved more locally as a wave-cut surface. Landforms labelled as PS6 are pediments that could be responsible for the partial stripping of the early Cenozoic weathering profiles superimposed onto PS5 (stripped etchplain).

Direct constraints on the post-exhumation denudation depths of Mesozoic land surfaces PS1 to PS6 are difficult to acquire. The best available evidence is provided by preserved Cenozoic sedimentary sequences on the Armorican Massif (Durand, 1959; Guillocheau et al., 2003) and in its surrounding offshore basins (Evans, 1990; Guillocheau et al., 2000; Paquet et al., 2010). The Paleocene to middle Miocene stratigraphy is roughly half carbonate, half siliciclastic sediments. On the Armorican Massif, the Paleogene siliciclastic sediments are mostly claystones and siltstones, except for the silicified quartz-rich sandstones (so-called silcretes), which are of Ypresian to Bartonian age by analogy with those of the Paris Basin (Thiry et al., 1983; Thiry, 1999). The main change in the siliciclastic sedimentation record occurred during the late Miocene with the deposition of the "Red Sands" (Brault et al., 2004), which are coarse-grained estuarine sands filling a network of incised valleys distinct from the present-day one (Bonnet et al., 2000).

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These constraints suggest that, after stripping of the chalk, the amount of mechanical erosion until the late Miocene was low. The only evidence of alluvial deposits is the occurrence of silicified quartz-rich sands widely distributed throughout the Armorican Massif (from PS3 to PS6). As mentioned before, the climatic environment from the Paleocene to the middle Eocene was conducive to lateritic weathering. However, despite the widespread occurrence of its products (Fig. 3) the denudation attributable to chemical erosion is impossible to estimate. During the late Miocene, a major environmental change in base level and/or palaeoprecipitation promoted a shift away from the more diffuse regime of denudation towards more focused fluvial erosion. The pediment surfaces were abandoned in favour of the formation of a network of incised valleys involving two different successive systems: a late Miocene to Pliocene (Red Sands) network, which itself was overprinted by a middle to late Pleistocene valley network (Bonnet et al., 2000; Brault et al., 2004).

The low amount of mechanical erosion during Paleogene times, the widely distributed products of chemical erosion with no major base-level fall, and the focused erosion along incising rivers channels after the late Miocene probably explains the preservation of these Mesozoic exhumed landforms.

5.4. Patterns of landscape exhumation in response to crustal deformation

Both the early Cretaceous and Paleogene denudational intervals coincided with a relative base-level fall. This was due either to eustatic events or to tectonic deformations with uplift. Eustatic falls are insufficient to explain either of the land stripping events (1) because the resulting planation surface, i.e. the Armorican Surface (PS5), is currently deformed, and (2) because, according to the reference sea-level curve of Haq et al. (1987), the long-term sea level was higher during the early Cretaceous than during the Jurassic or slightly lower during the Paleogene than in the late Cretaceous — but still quite high in absolute terms (+200–250 m).

The two periods of early Cretaceous and earliest Cenozoic exhumation correspond instead to major periods of deformation of the surrounding basins. These have been reported by Ziegler (e.g. 1990) and affected much of West Europe. Early Cretaceous times record two deformation “events”, the Neo-Cimmerian (intra-Berriasian: Jacquin and de Graciansky, 1998) and the Austrian (~Aptian–Albian boundary), which are respectively coeval with the early stages of the Biscay Rift and with the onset of

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oceanic accretion in that same geodynamic province (Montadert et al., 1979; Thinon et al., 2003). The latest Cretaceous to Oligocene is the period of convergence between Africa–Iberia and Eurasia and of the resulting Pyrenean orogeny. In the eastern Pyrenees, Vergés et al. (1995) estimated that the maximum rate of crustal shortening occurred during Ypresian and Early Lutetian times. Along the Celtic and Armorican Margins, the ocean–continent boundaries underwent two spectacular tectonic inversions (Thinon et al., 2001): first during the latest Cretaceous, followed by a major but less precisely constrained event during the Eocene. In the Western Approaches Basin, a two-stage Eocene and Oligocene basin inversion has been documented (Le Roy et al., 2011). In the Paris Basin, two major periods of deformation occurred during the Maastrichtian and Selandian, with complete emersion of the basin and a sharp decrease in subsidence (Guillocheau et al., 2000). Likewise, the British Isles basins were deformed (inversion) and exhumed (Holford et al., 2005; Hillis et al., 2008) during the early Cretaceous (St-Georges Channel and East Irish Sea Basins) and early Cenozoic (Wessex–Weald Basin, East Irish Sea). The cause of this deformation remains debated, being either due to uplift as a result of the relative movements between Africa, Iberia and Eurasia (Hillis et al., 2008), or to the Paleocene–Eocene Icelandic plume (Davis et al., 2012). In conclusion, the two periods of exhumation (early Cretaceous and earliest Cenozoic) are chiefly linked to the relative movements between Africa, Iberia and Eurasia, first under a regime of plate divergence, and subsequently under a regime of convergence.

5.5. Is the geomorphological evolution of the Armorican Massif unique in western Europe?

Ages recently obtained for palaeoweathering mantles using isotopic geochemistry or palaeomagnetism (Gilg and Frei, 1997; Lippolt et al., 1998; Théveniaut et al., 2007; Ricordel-Prognon et al., 2010) have substantially modified our understanding of the long-term landscape evolution of continental Europe. These new data, summarized below, have provided Mesozoic and Cenozoic ages for most of the weathering materials (mainly laterites) and shed new light on the age of their associated landforms.

(1) Triassic: the albitization of bedrock outcrops is widely reported from the Variscan basement uplands of Europe (French Massif Central: Schmitt and Simon-Coincon, 1985; Ricordel et al., 2007, Parcerisa et al., 2010a; Bohemian Massif: Franke et al., 2009; Yao et al., 2010; Iberia:

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Franke et al., 2009; Parcerisa et al., 2010b). The dating of this event is based on their location beneath the Jurassic sedimentary cover (Schmitt and Simon-Coincon, 1985; Ricordel et al., 2007; Parcerisa et al., 2010a) and the early Triassic magnetic overprints (95% reference pole confidence cone between 235 Ma and 255 Ma, Ricordel et al., 2007).

(2) Late Jurassic to early Cretaceous: lateritic weathering profiles (including bauxites) and "Clays-with-Jurassic-Cherts" ("argiles à chailles": see Thiry et al., 2006 for a review) were dated (1) by their location below dated late Cretaceous sediments (Rioult et al., 1966; Estéoule-Choux et al., 1969; Vérague, 1974; 1977; Thiry et al., 2005; Théveniaut et al., 2007); (2) by radiometric methods (Lippolt et al., 1998; Yans et al., 2003); and (3) by palaeomagnetism (Théveniaut in Yans et al., 2003; Ricordel, 2007; Théveniaut et al., 2007; Quesnel et al., 2009a; Ricordel-Prognon et al., 2010). Palaeomagnetic data have been obtained from the French Massif Central (north: 120–130 Ma, Théveniaut in Quesnel et al., 2009a; south: 140 ± 10 Ma to 160 Ma with the pole overlapped by the 95% confidence ellipse, Ricordel-Prognon et al., 2010); from the Ardennes (top of the profile: 120–110 Ma and 131 ± 10 Ma to 126 ± 10 Ma, intermediate part of the profile: 88–94 Ma, i.e. before the Campanian–Maastrichtian transgression, Yans et al., 2003); from the borders of the Ardennes with the Paris Basin (130 ± 10 Ma, Théveniaut et al., 2007); and from Saarland (142–120 Ma, Lippolt et al., 1998).

(3) Paleocene to Eocene: lateritic weathering profiles and "Clay-with-Flints" (developed on late Cretaceous chalk) have been dated in the French Massif Central (1) by their location below the dated Cenozoic sediments (see Klein, 1975 for a review), (2) by radiometric dating methods (45.5 ± 1.2 Ma to 40.8 ± 1.8 Ma: Gilg and Frei, 1997) and (3) by palaeomagnetism (50 ± 10 Ma, Théveniaut in Quesnel et al., 2009a; tentatively ca. 50 Ma, Ricordel, 2007). Widespread pedogenic silicifications (silcretes) have formed caprock on continental deposits that range in age from Paleocene to Eocene (Crié, 1878; Quesnel, 2003; Wyns et al., 2003; Quesnel et al., 2009b) or that are overlapped by Ypresian (northern France, Belgium, England; see Quesnel, 2003 for a review) to Bartonian (Châteauneuf, 1980; Quesnel, 2003; Quesnel et al., 2009b) strata.

Given their antiquity, these extant weathering profiles support the view that ancient landforms still exist on the uplands of western Europe. The fossil planation surfaces in the French Massif Central and in the Ardennes–Eifel massifs, where thermochronological and stratigraphic data are also

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available as constraints on the long-term denudation chronology, can serve here as relevant analogues to the Armorican Massif. In the Morvan (north-eastern French Massif Central), stratigraphic data (Lorenz, 1968; 1971) have indicated an occurrence of dated Sinemurian (base of the Jurassic) sediments on the top of the Morvan Plateau (Saint-Agnan area). In the same area, apatite fission-track data (Barbarand et al., 2013) suggest burial under late Cretaceous cover rocks followed by exhumation during the early Paleogene. Despite the relatively large uncertainty in the data (modelled thickness of late Cretaceous chalk cover: 400 ± 300 m), it follows that the topography preserved at the base of the Jurassic corresponding to the top of the Morvan Plateau was buried at least during the early Jurassic and the late Cretaceous, and exhumed at least during Paleocene to Eocene times.

In the Ardennes Massif, the High Ardennes Plateau (500 to 650 m) displays (1) dated lateritic profiles (Dupuis et al., 1996) that indicate weathering periods ca. 130 Ma (Hauterivian–Barremian, i.e. Lower Cretaceous; Yans and Dupuis, 2007), ca. 93 Ma (Cenomanian–Turonian, i.e. base of the Upper Cretaceous) and 21 Ma (Lower Miocene); and (2) some late Cretaceous deposits (open marine chalk; Bless and Felder, 1989), while the lowest Condroz Plateau (200–350 m) is overlain by numerous early Cretaceous cover rocks (Wealden Group; Bless and Felder, 1989). Thermochronological data (Xu et al., 2009) suggest a final exhumation event occurring after 45 Ma (middle Eocene) involving denudation depths of approximately 900 to 1300 m. Again, the preservation on the Ardennes High Plateau of early Cretaceous weathering profiles and basal chalk deposits involving the later exhumation of approximately 1 km of rock indicate that this region is an exhumed topographic system at least early Cretaceous in age, which was buried by late Cretaceous chalk and exhumed at the time of the Cenozoic tectonic inversions of NW Europe.

Landscape evolution in both the northern part of the French Massif Central and the Ardennes is in most ways similar to the denudation chronology presented here for the Armorican Massif. Further landform studies are nonetheless required for these two massifs in order to refine our understanding of Jurassic burial in the Morvan, late Cretaceous chalk burial in the Massif Central and Ardennes, early Cretaceous laterite formation in the Ardennes and Massif Central, and early Paleogene exhumation of all these corresponding land surfaces.

6. The main stages of Armorican landscape evolution

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Even though some points still need to be confirmed by further studies, the evolution of the Armorican relief can be summarized by the following chronology.

1. 250–190 Ma (Pre-Pliensbachian–Triassic ?): elaboration of pediments and pediplains PS1 to PS3 (Fig. 7). These land systems could be a legacy of the final stages of the eroding Triassic topography that supplied the Triassic sediments to the Paris and Wessex basins ("Buntsandstein" = Induan–Anisian, and "Keuper" = Carnian–Norian siliciclastic sediments, Warrington and Ivimey-Cook, 1992; Bourquin and Guillocheau, 1996; McKie and Williams, 2009; Bourquin et al., 2011).
2. 183–170 Ma (Pre-Bajocian to Toarcian–Aalenian): development of pediment population PS4. This might be related to a base-level fall caused by middle-Cimmerian crustal deformations, which have been well recorded in the Paris Basin (Jacquin and de Graciansky, 1998; Guillocheau et al., 2000).
3. 140–40 (?) Ma (base of the Lower Cretaceous to pre-Bartonian?): first growth of the polygenetic Armorican Surface (PS5, Fig. 7). This surface records two events of the European-scale intraplate deformations (Neo-Cimmerian and Austrian events for the early Cretaceous, and Pyrenean deformations for the Paleogene), with a subsidence phase (late Cretaceous) in between. This surface experienced two periods of intense weathering under a hot and humid climate (Barremian and early Eocene). The first period of deformation generated the relief that supplied the Wealden Group siliciclastic sediments of the Paris Basin and possibly of the Western Approaches and Bay of Biscay rifts (Fig. 7).
4. 40(?)–6 Ma (Pre-Bartonian–Messinian): development of pediment population PS6 (Fig. 7). This period is still poorly understood, due to limited tectonic constraints on the formation of the so-called late Eocene to Oligocene rifts of Brittany.
5. 6–0 Ma (Messinian–Present): incision of two networks of V-shaped valleys. These incisions result from crustal uplift of the Armorican Massif — a trend shared with most of the north-western European basement uplands — in response to the convergence between Africa–Apulia and Eurasia, and consequently to the Alpine collision.

7. Conclusions

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(1) The landscape of the Armorican Massif is an assemblage of six stepped planation surfaces (labelled PS1 to PS6) that were later incised by two successive networks of rivers. These mappable land surfaces have been deformed by epeirogenic movements, sometimes displaced by faults, so that each generation of land surface will not display uniform elevation bands across the regional landscape. A regional surface (PS5), previously recognized by de Martonne (1906), is here called the Armorican Planation Surface.

(2) These planation surfaces correspond to pediments and pediplains, i.e. nearly flat erosional surfaces with no concurrent depositional or erosional channelized rivers. The upslope boundary of any given pediment is typically a scarp or the steeper slope in the landscape. The regional Armorican Surface (PS5) is polygenetic and probably underwent two periods of etchplanation in humid, tropical climatic conditions.

(3) These planation surfaces are mostly pre-late Cretaceous, based on the age of existing pediment cover rocks. The three oldest (PS1 to PS3) are older than the Pliensbachian (191–183 Ma); PS4 is older than the Bajocian (170–168 Ma); being polygenetic, PS5 (the Armorican Surface) ranges from the base of the early Cretaceous to the base of the Bartonian (?) (140–40 Ma); and the youngest (PS6) is poorly constrained. The latter formed either before 40 Ma (base of the Bartonian) or before 15 Ma (base of the middle Miocene).

(4) Most of these “old” landforms are exhumed land surfaces, i.e. they were buried by sediments and later exhumed by denudation. At least two cycles of burial and exhumation have been identified: (1) Jurassic burial followed by denudation during the early Cretaceous; and (2) late Cretaceous burial followed by denudation during latest Cretaceous to early Eocene times. The depths of burial are unknown, but were probably low given the small amount of siliciclastic sediment accumulations that were generated by subsequent denudation in the surrounding basins. Other Variscan basement uplands of western Europe such as the French Massif Central and the Ardennes Massif are also partly exhumed land systems which were buried by the Chalk sea during the late Cretaceous, i.e. at least once.

(5) The two periods of exhumation correspond to critical periods in the relative plate movements between Africa, Iberia and Eurasia. The first event is probably related to the birth and break-up of the rift between Iberia and Eurasia (Bay of Biscay), and the second to the convergence between these two plates (Pyrenean orogeny).

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Acknowledgments

We are grateful to the Région Bretagne for funding the Paul Bessin's Ph.D. thesis. We thank the BRGM (Bureau de Recherches Géologiques et Minières) for providing additional field funding, numerical geological maps and unpublished data for research well CDB1 (CINERGY project). We are thankful to the IGN (Institut Géographique National) for providing numerical DEM data. We also thank Dr. Sara Mullin and guest editor Yanni Gunnell for post-editing the English, and two anonymous reviewers for their constructive comments.

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FIGURE CAPTIONS

Figure 1: Main topographic units of the Armorican Massif and surrounding basins on a shaded-colour elevation map (3 arc-second resolution, NASA Shuttle Radar Topography Mission; projection: RGF Lambert 1993). Thick white line: limit between the Armorican Massif (Variscan basement) and the Paris Basin. Grey lines: main faults (NASZ: North Armorican Shear Zone; SASZ: South Armorican Shear Zone; MLT: Merlerault Fault; MA: Mayenne Fault; HUI: Huisne Fault).

Figure 2: 3D geometry (topography and geology), longitudinal and transverse cross-sections of three Armorican pediments of the Lower Normandy Plateau. A: Sélune Pediment; B: Falaise Pediment; C: Briouze Pediment. Geologic data from vectorized 1:50,000 geological maps of France (Sheets No. : 176–Gigot et al., 1999, 209–Langevin et al., 1984, 210–Ménillet et al., 1987, 211–Bambier et al., 1983, 212–Kuntz et al., 1989, 247–Dadet et al., 1984, 248–Vernhet et al., 1997, 249–Vernhet et al., 1995). Sketch B' represents the infill geometry of the Argentan Pediment by marine Middle Jurassic sediments coloured in blue (onlaps: thin white arrows).

Figure 3: Distribution of mappable weathering materials on the Armorican Massif, compiled from the 1:50,000 geological maps of France (BRGM; projection: RGF Lambert 1993). Maps with no data (empty boxes) correspond to pre-1990 geological maps, a time when surficial deposits were ignored by field geologists. Light grey hillshade: paleo-Proterozoic and Paleozoic cover rocks (dominated by shales) reported to illustrate the relationship between weathering and lithology. Weathering products on shale are mainly kaolinite. Thin grey line: limit between the Armorican Massif (Variscan basement) and the Paris Basin.

Figure 4: Detailed chronology and mapping of planation surfaces in the southern part of the Lower Normandy Plateau (see Fig. 5 for location; projection: RGF Lambert 1993). 4a: detailed map of the planation surfaces (PS1 to PS5); 4b: transverse and longitudinal cross-sections showing (1) the landform staircase, (2) the relative pediment chronology (from PS1: the oldest and most elevated surface, to PS5d: the youngest and least elevated surface); and (3) an age model derived from the preserved sedimentary rocks.

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Figure 5: Synthetic map of the Armorican Massif planation surfaces and their ages, compiled from a set of more detailed maps (projection: RGF Lambert 1993).

Figure 6: Map of late Cretaceous cover-rock vestiges on the Armorican Massif. Data from (1) Bauer et al., 2011; (2) Bigot, 1905; (3) Bonissent, 1870; (4) Borne et al., 1989; (5) Bourcart, 1950; (6) Brabant, 1965; (7) Chevalier and Borne, 1989; (8) Dangeard, 1928; (9) Deunff, 1953; (10) Durand, 1958; (11) Durand and Louail, 1971; (12) Durand et al., 1973; (13) Fleury et al., 1989; (14) Graindor, 1958; (15) Graindor and Marie, 1959; (16) Juignet, 1974; (17) Lautridou in Baize, 1998; (18) Lebesconte, 1882; (19) Noury, 1886; (20) Poncet, 1961; (21) Thinon et al., 2009; (22) Vernhet et al., 2009 (projection: RGF Lambert 1993).

Figure 7: Long-term landscape evolution of the Armorican Massif from Triassic to Oligocene time, emphasizing the main burial and exhumation phases. Here the evolution is summarized on a highly synthetic section showing only one plateau (Lower Normandy / Western Brittany) and the Paris border on the left-hand side and the Western Approaches on the right hand-side. The pre-Bajocian period of denudation (pediments PS4) has not been depicted.

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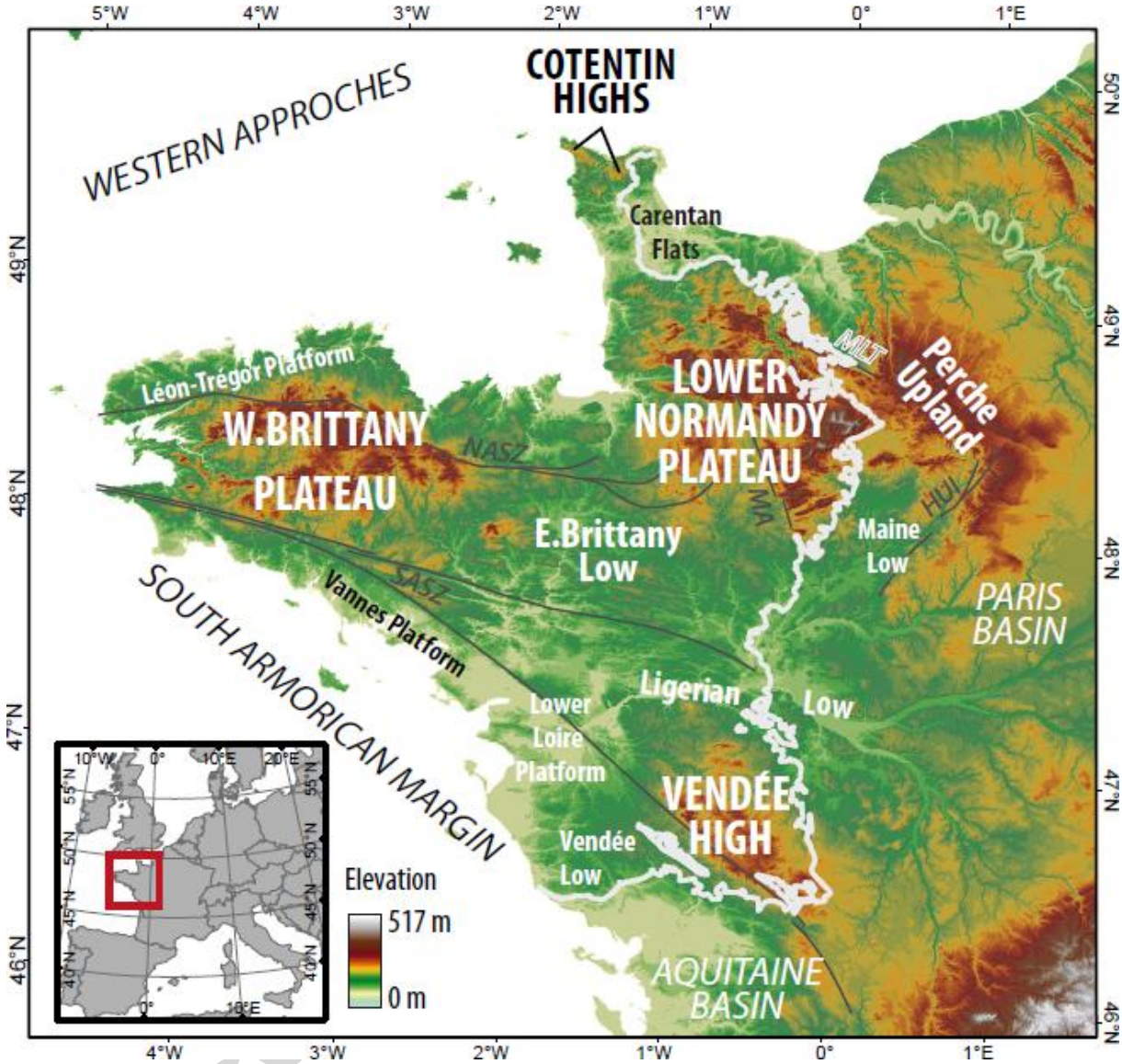

Figure 1

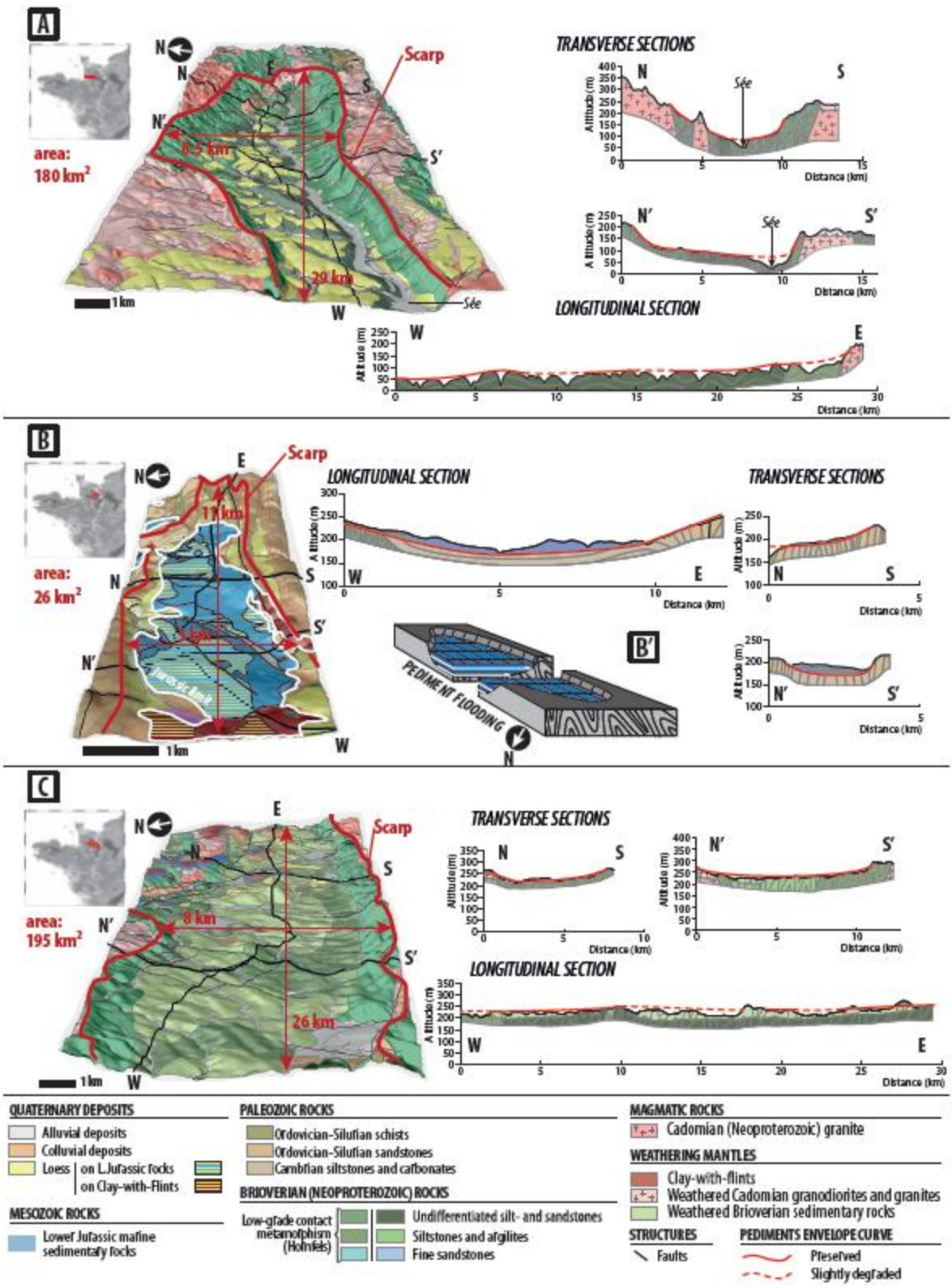
A
area: 180 km²
Scarp
8.5 km
29 km
1 km
Sée
TRANSVERSE SECTIONS
LONGITUDINAL SECTION
Altitude (m)
Distance (km)
B
area: 26 km²
17 km
5 km
Jurassic limit
PEDIMENT FLOODING
B'
C
area: 195 km²
8 km
26 km
QUATERNARY DEPOSITS
Alluvial deposits
Colluvial deposits
Loess
on L.Jurassic rocks
on Clay-with-Flints
MESOZOIC ROCKS
Lower Jurassic marine sedimentary rocks
PALEOZOIC ROCKS
Ordovician-Silurian schists
Ordovician-Silurian sandstones
Cambrian siltstones and carbonates
BRIOVERIAN (NEOPROTEROZOIC) ROCKS
Low-grade contact metamorphism (Hornfels)
Undifferentiated silt- and sandstones
Siltstones and argilites
Fine sandstones
MAGMATIC ROCKS
Cadomian (Neoproterozoic) granite
WEATHERING MANTLES
Clay-with-flints
Weathered Cadomian granodiorites and granites
Weathered Brioverian sedimentary rocks
STRUCTURES
Faults
PEDIMENTS ENVELOPE CURVE
Preserved
Slightly degraded

Figure 2

ACCEPTED MANUSCRIPT

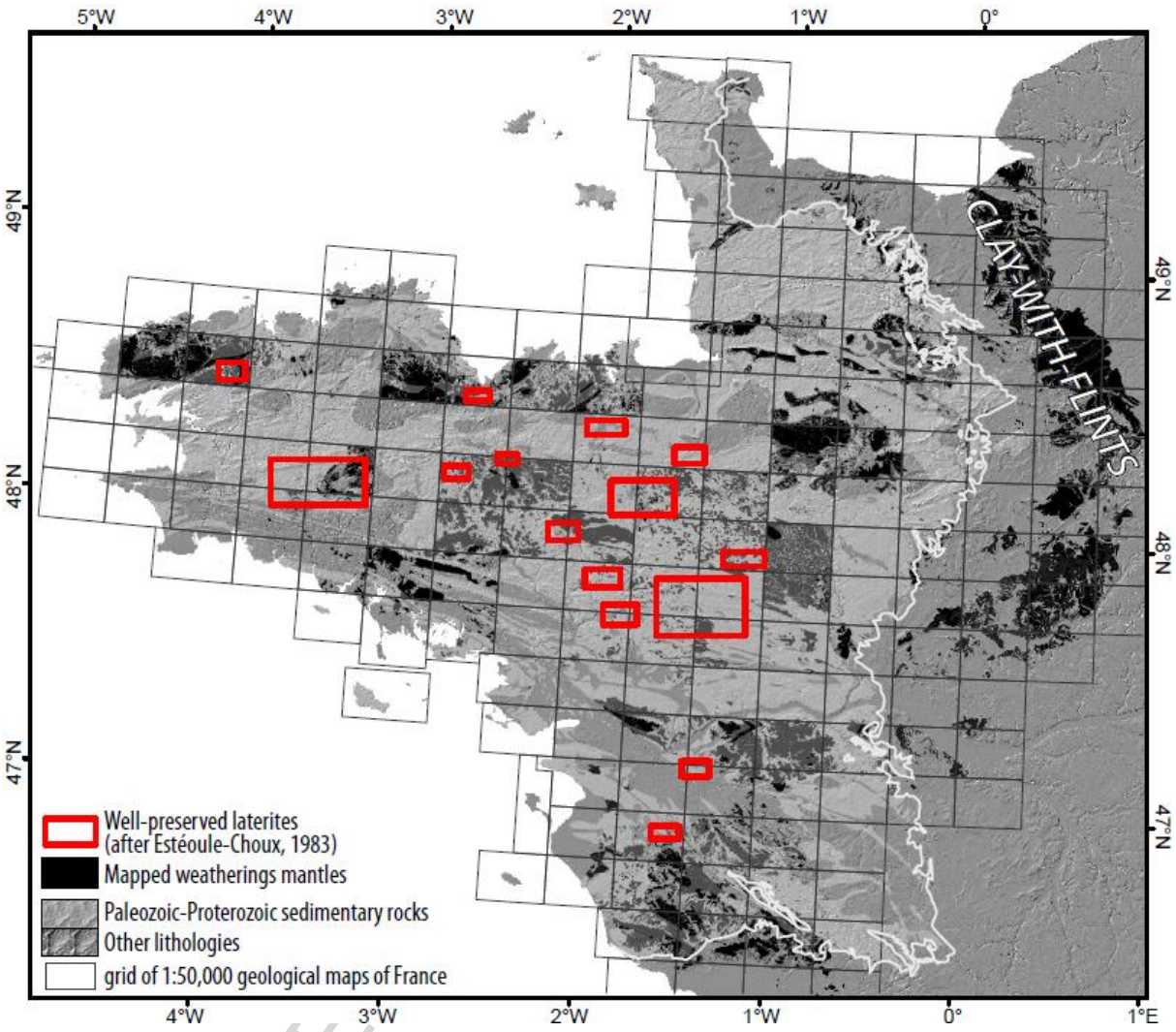

Figure 3

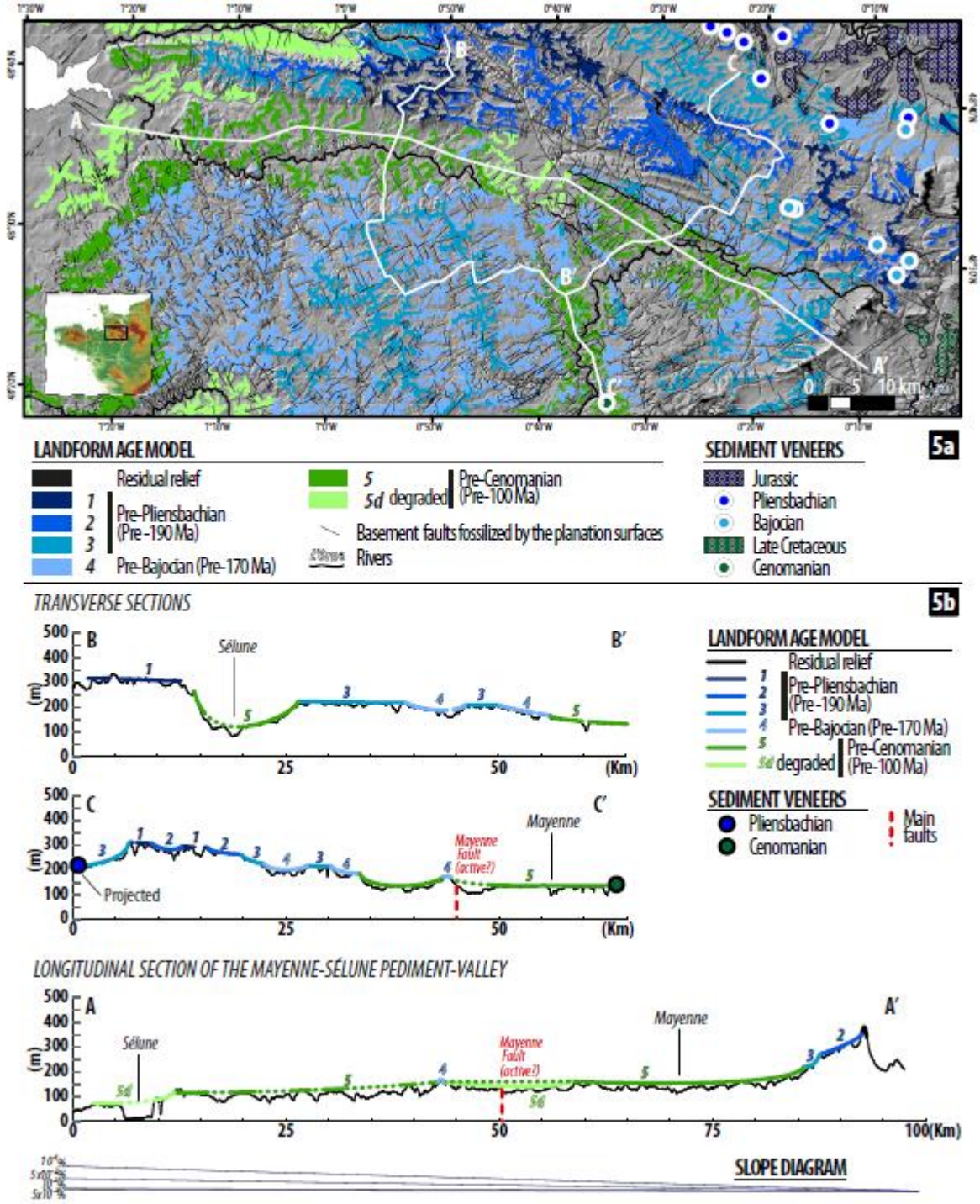
LANDFORM AGE MODEL
Residual relief
1
2
3
4
Pre-Pliensbachian (Pre-190 Ma)
Pre-Bajocian (Pre-170 Ma)
5
5d degraded
Pre-Cenomanian (Pre-100 Ma)
Basement faults fossilized by the planation surfaces
Rivers
SEDIMENT VENEERS
Jurassic
Pliensbachian
Bajocian
Late Cretaceous
Cenomanian
5a
TRANSVERSE SECTIONS
5b
Sélune
Mayenne
Mayenne Fault (active?)
Projected
(Km)
LANDFORM AGE MODEL
SEDIMENT VENEERS
Pliensbachian
Cenomanian
Majn faults
LONGITUDINAL SECTION OF THE MAYENNE-SÉLUNE PEDIMENT-VALLEY
SLOPE DIAGRAM

Figure 4

ACCEPTED MANUSCRIPT

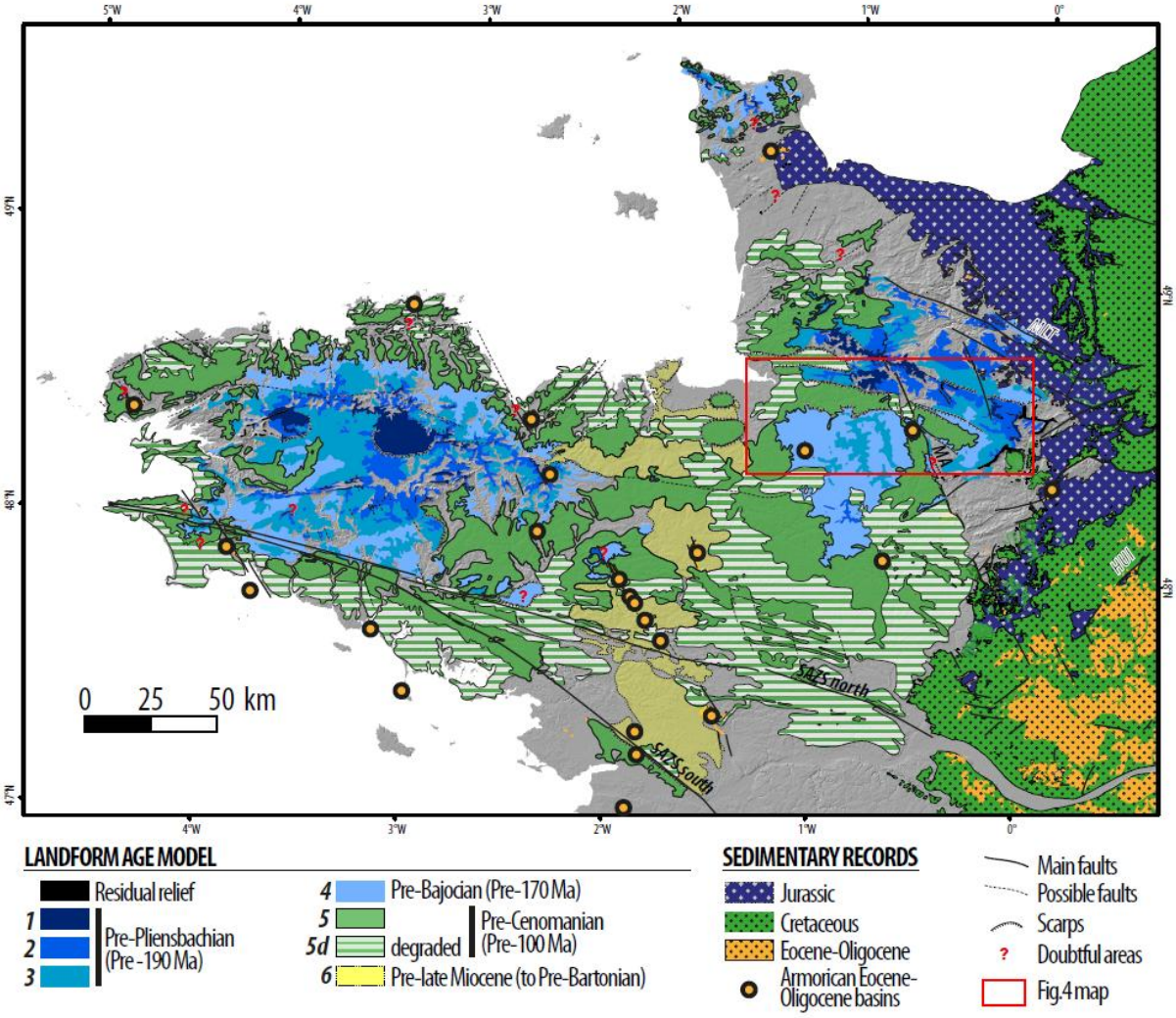

Figure 5

ACCEPTED MANUSCRIPT

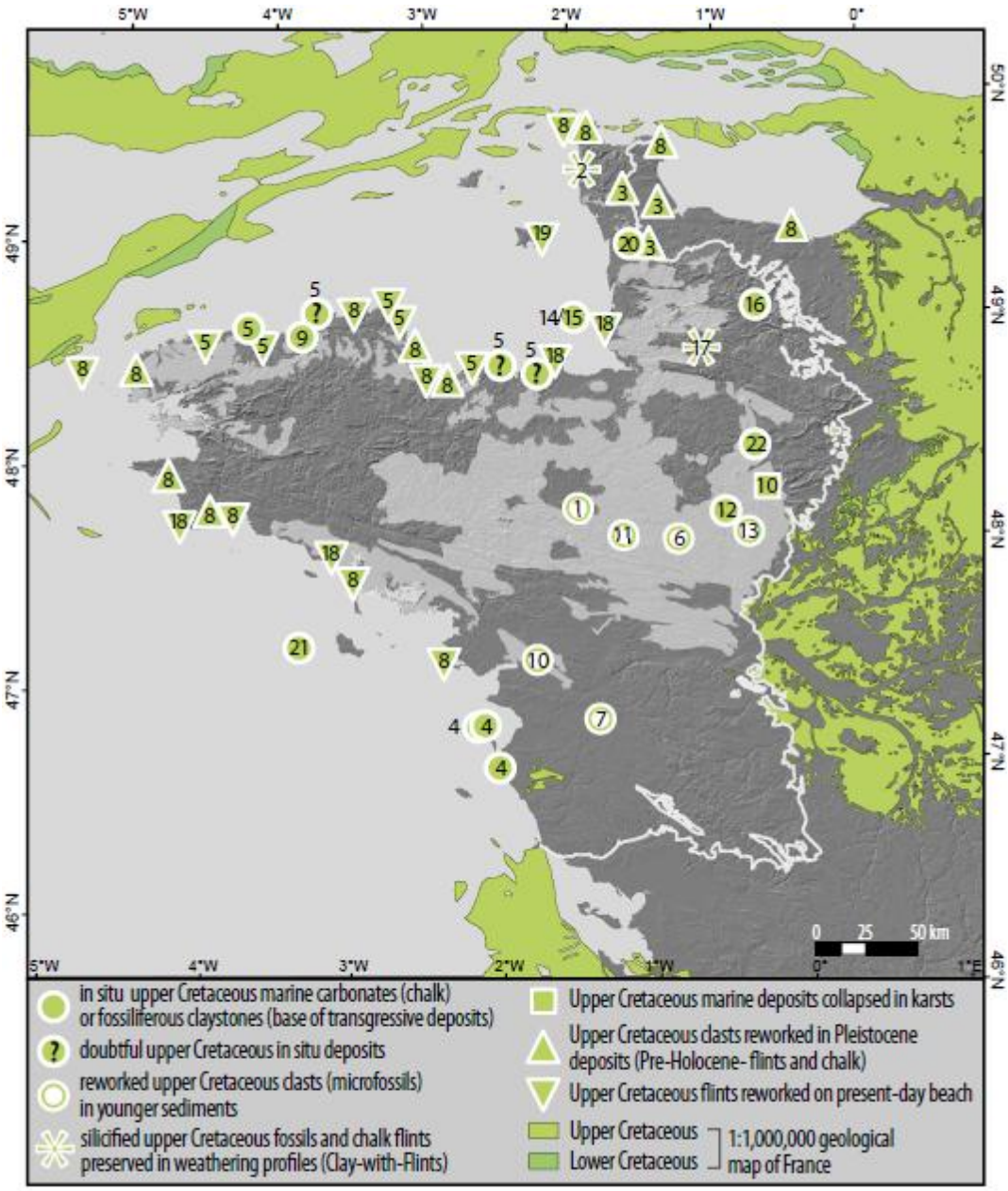

Figure 6

ACCEPTED MANUSCRIPT

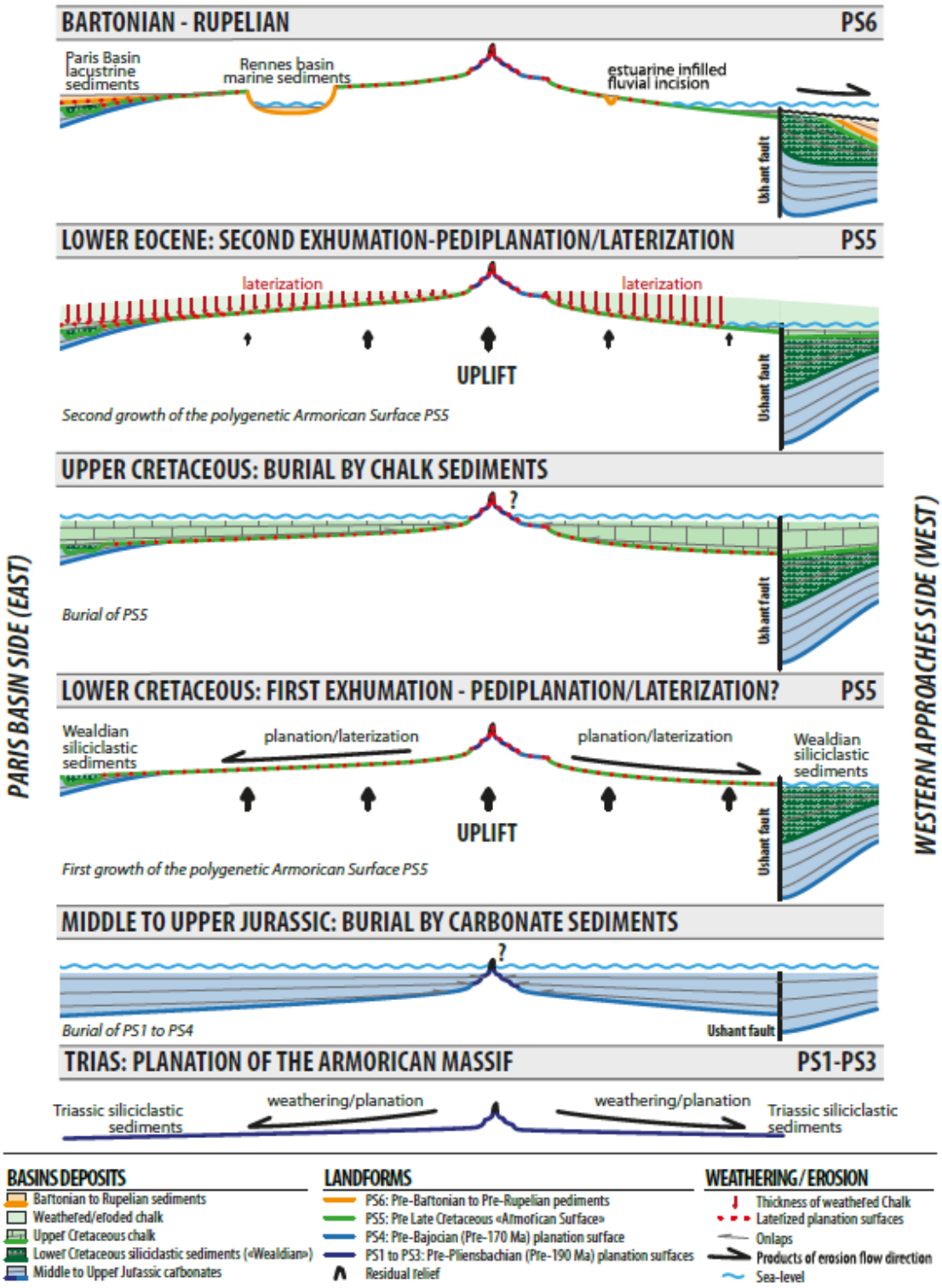

Figure 7

ACCEPTED MANUSCRIPT

Highlights :

- We mapped and dated 6 stepped planation surfaces in Brittany, W. France
- 5 of these surfaces are Mesozoic (pre-late Cretaceous)
- They underwent two cycles of burial by cover rocks followed by exhumation
- We propose a long-term landscape evolution model of the Armorican Massif

ACCEPTED MANUSCRIPT