Erosion Surfaces in the Ardenne–Oesling and Their Associated Kaolinic Weathering Mantle

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Abstract

This chapter deals with the long-term geomorphology of the Paleozoic Ardenne–Oesling massif of S Belgium and the landforms that currently attest the very long persistence and high resistance to erosion of landscape elements created as far back in time as the Lower Cretaceous in a region of predominantly continental regime and constant low to moderate elevation since the Permian. We first present recent results regarding the antiquity of kaolinic weathering mantles preserved in four sites on or close to the plateau surfaces characteristic of the Ardennian landscape, showing that they record at least three main weathering phases, namely in the Early Cretaceous (extending in the early Late Cretaceous), the Late Paleocene, and the Early Miocene. Then, having provided a working definition of the erosion surface and listed criteria helping recognize them in the landscape, we focus on the Hautes Fagnes massif, the highest NE part of the Ardenne–Oesling. We describe the geometric and sedimentary evidence that allow one to recognize a succession of four erosion surfaces formed during the Cretaceous and the Cenozoic and reconstruct the morphogenetic evolution of the area that responded to the variable interplay of the marine transgression-regression, climatic, and tectonic controls. Finally, we present the few estimates of long-term denudation rates available for the Ardenne massif, fission track and cosmogenic nuclide studies both suggesting Cenozoic denudation rates in the order of a few 10 m/Myr, and comment on their compatibility with field observations.

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5.1 Introduction

It has long been recognized that erosion surfaces are a main component of the landscape in the southern part of Belgium and the northern Grand-Duchy of Luxembourg, where they impose the levelled horizons and extended flat areas characterizing the Paleozoic Ardenne–Oesling Plateau (Oesling, or Éislek in Luxembourgian, is the name given to the part of the Rhenish massif situated in the Grand-Duchy of Luxembourg). Bearing witness to the Mesozoic and Cenozoic geomorphological evolution of the region, they constitute the long-term frame in which incision of the Plio-Quaternary drainage network has not yet so much nibbled that one could not identify this pre-Quaternary heritage.

The Ardenne massif is famous for his well-preserved erosion surfaces, the so-called peneplains that W. Davis commented on already in the end of the nineteenth century (Davis 1896, 1899) after having visited the area with A. de Lapparent during one of his European travels. Already in that time went the discussion on the age of the surfaces and on the uplift history of the massif revealed by their arrangement. This testing by Davis of his normal cycle of erosion in the Ardennian landscape was possible because, ten years earlier, Gosselet (1888) had provided a very modern overview of the nature and age of the post-Paleozoic sediments sparsely preserved on the surfaces and had discussed the tectonic deformations implied by their distribution.

However, although many studies dealt with the Ardennian erosion surfaces in the first half of the twentieth-century, building on the Davis' theory or sometimes adapting it, like Baulig (1926) with his multifaceted Ardennian platform, it was a long time before one realised that these surfaces had been formed under climatic conditions totally different than those currently prevailing. Being the product of a long evolution under tropical conditions, they essentially respond to the etchplanation model of Wayland (1933), possibly flavoured with features of the pedimentation model of King (1947), much more than to the normal erosion model of Davis (1899). Gullentops (1954) was probably the first to show real interest in the remnants of the weathering mantle often accompanying the old surfaces and to take advantage of them in his reconstruction of the long-term geomorphic history of the massif. Recently, qualitative observations gave way to quantitative data about the age of the Ardennian kaolinic saprolites, which bring additional support to the chronology of such reconstructions (Yans 2003; Thiry et al. 2006).

In this chapter, the geomorphic history of the Ardenne–Oesling massif will be reexplored through the analysis of four archetypal sites of the Ardenne. We first describe the deep weathering profile exposed at Transinne, in the last quarry active in kaolin exploitation in west-central Ardenne,

and present age data. Then, moving to the eastern part of the Ardenne (Plateau des Tailles area, Bihain site), we provide a new Ar–Ar dating of the weathering. The Hautes Fagnes Plateau, a recently uplifted area that has preserved several well-developed erosion surfaces of Cretaceous and Paleogene age will also be described because it offers a condensed view of various modes of their evolution. Finally, new dating of supergene minerals from the northern part of the Ardenne (Beez and Morialmé sites, Entre-Sambre-et-Meuse) will be discussed against the background of the Ardenne evolution.

5.2 Weathering Mantles

5.2.1 Geographical and Geological Setting

Located in the southern part of Belgium, the Ardenne region geologically corresponds to the Ardenne allochthon, which is part of the Rheno-hercynian fold-and-thrust belt. Belanger et al. (2012) recently distinguished the following structural units, from north to south across the Paleozoic of Belgium: the Brabant Massif and the base of its Devonian cover unaffected by the Variscan orogeny, the Brabant parautochthon, the Haine-Sambre-Meuse overturned thrust sheets (HSM-OTS) and the Ardenne allochthon where the Transinne and Bihain sites are located (Fig. 5.1). The third presented site, Morialmé, is situated in the Entre-Sambre-et-Meuse area, which is the northwestern part of the Ardenne allochthon, whereas the fourth one, Beez, is located in the HSM-OTS.

Thick saprolites are widespread in Belgium (e.g., Quesnel et al. 2002; Yans 2003; Dejonghe and Boni 2004; Dusar and Lagrou 2007). Yans (2003) highlighted at least ten areas that experienced period(s) of deep chemical weathering in Belgium. Figure 5.2 provides an overview of those affected by weathering period(s) well constrained in time in and around the Ardenne, but additional areas with unconstrained timing of weathering may also be listed (e.g., Welkenraedt, Hautes Fagnes, Rocroi, northern part of the Mons Basin) (Yans 2013). The weathering led to the formation of saprolites up to 80- and 65 m-thick in the Brabant Massif and the Haute-Lesse area, respectively.

North of the Ardenne, the long phase of weathering and kaolinitisation, that affected the Paleozoic basement of the Brabant Massif to depths reaching a preserved maximum of 80 m started in the Early Cretaceous and continued up until the Cenomanian along the southern margin of the massif and the Santonian or later along its northern margin, depending on the local time of flooding and onset of subsequent marine sedimentation (Dusar and Lagrou 2007). The saprolites are widely preserved, with thickness varying strongly even at the local scale (Mees and Stoops 1999). In the Belgian
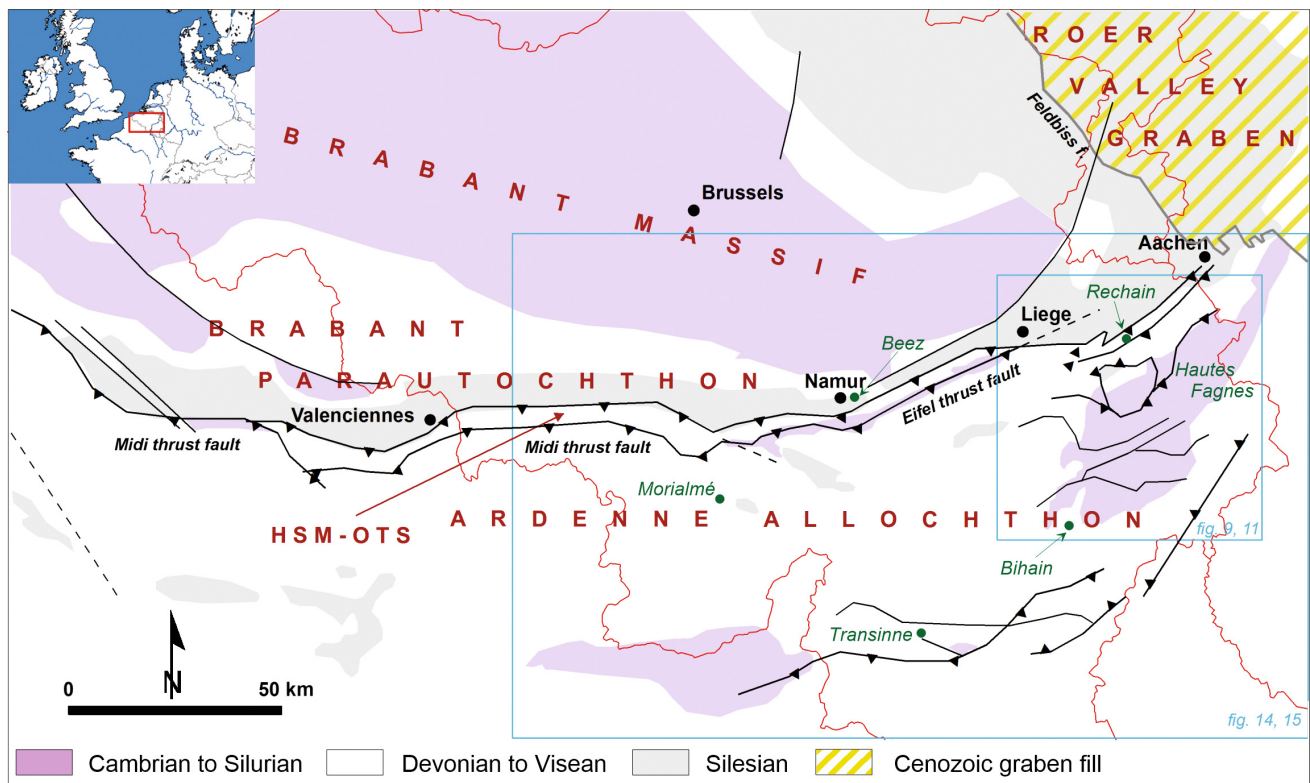
Fig. 5.1 Main structural units of the Paleozoic in Belgium and Luxembourg (stripped of their Meso-Cenozoic cover in Middle and Low Belgium). Four units are distinguished within the Paleozoic basement (Brabant Massif, Brabant parautochthon, HSM-OTS: Haine-Sambre-Meuse overthrust sheets, and Ardenne allochthon). The Variscan front is marked by the Midi and Eifel thrust faults, from west to east. In the NE, up to 1.5-km-thick Cenozoic deposits were accumulated in the Roer Valley Graben. *Green* dots and names locate the sites mentioned in this chapter

Lorraine, south of the Ardenne, the Lower Devonian sediments were similarly weathered before being covered by Permo-Triassic sediments (Boulvain et al. 2000).

West of the Ardenne, in the eastern Mons Basin, weathering of glauconiferous levels of the Grandglise Member (Hannut Formation, Late Thanetian) was likely responsible for the formation of the so-called Landenian quartzites and Sparnacian silcretes (e.g., Dupuis 1979; Quesnel et al. 2002), possibly in relation with volcanic ashfalls (Baele et al. 2016), before they were buried beneath the Ypresian sediment cover.

5.2.2 Characterization and Dating of Key Ardennian Saprolites

Residual saprolites are especially widespread in the little dissected plateau areas of central Ardenne. While occurrences, more limited in extent and depth, are also present outside the Early Devonian core of the massif, it is remarkable that the summit ridges of the Condroz area, at elevations between 250 and 400 m north of central Ardenne, are totally devoid of more than very local spots of in situ

weathering (Gullentops 1954; Alexandre and Thorez 1995). Although the Ardennian saprolites were developed by ferrallitic processes under climates warmer than present, the ferruginous upper part of the profiles has mostly been removed by later erosion of the uplifted plateau and is only preserved in scattered places around the massif (e.g., at the Borne-de-Fer, French–Luxembourgian border; Théveniaut et al. 2007), where uninterrupted Mesozoic and Cenozoic tectonic stability strongly limited denudation. Elsewhere, only the saprolite sensu Nahon (1991), i.e., the bulk of the deeply weathered bedrock below the lateritic soil, is (partly) preserved. Depending on bedrock lithology, the neoformed minerals are essentially made of kaolinite, often poorly crystallized and mainly derived from the chlorite component of the Ardennian shales (Alexandre and Thorez 1995), and iron oxides and hydroxides. Quartz is the dominant residual mineral over sandstone and quartzitic bedrock. The saprolite retains the sedimentary and metamorphic structures of the parent rock, as exemplified by the Transinne outcrop, in west-central Ardenne, where stratification is clearly preserved in the weathered material (Fig. 5.3). The distribution of weathering depths may be highly unequal at the local scale over the Ardennian erosion surfaces because erosion
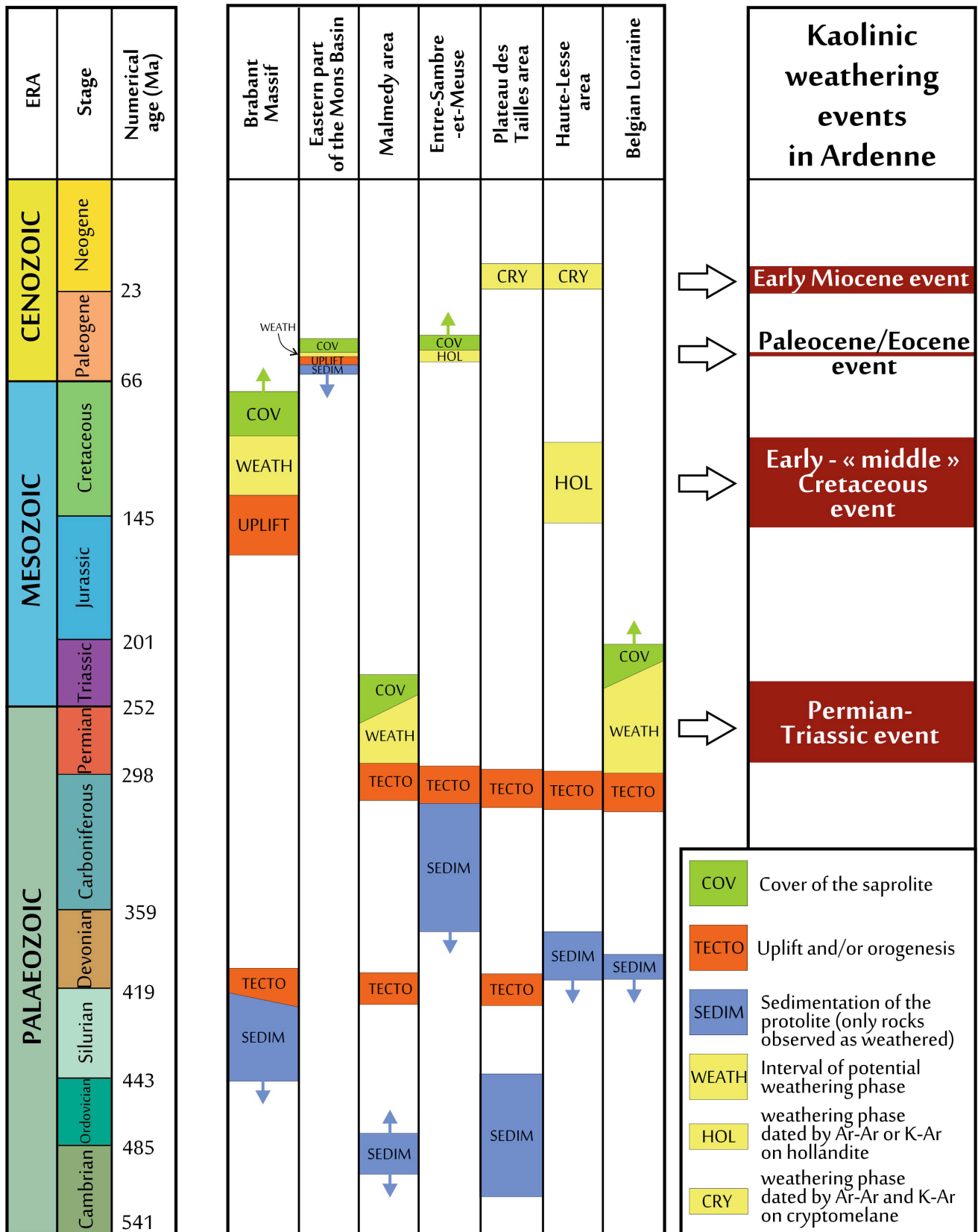
Fig. 5.2 Chronology of sedimentation (only rocks affected by deep weathering are represented here), geodynamic activity—essentially uplift, weathering, and burial, defining the history of the saprolites recognized in Belgium (and Luxembourg)

led to preservation of only the roots of the original weathering mantles and the weathering front is very irregular, mainly in relation with the variable degree of bedrock fracturing and the fracture geometry.

In order to improve the understanding and, especially, the chronology of the long-term geomorphic evolution of the Ardenne–Oesling, its erosion surface landscape and the associated kaolinic weathering mantles, we focused on four sites sampling saprolites in central Ardenne (Transinne in the Haute-Lesse area and Bihain in the Plateau des Tailles), the Entre-Sambre-et-Meuse (Morialmé), and the Haine-Sambre-Meuse overturned thrust sheets (Beez, a karst-controlled site near Namur). The dating of weathering periods is obviously very helpful for reconstructing the chronology of paleosurface development because, by definition, the erosion surface itself leaves few datable traces of its evolution. Moreover, it contributes to highlight the interplay between weathering and erosion processes,

including the estimation of denudation rates and sediment budgets in the adjacent basins (e.g., De Putter et al. 2015).

Transinne

The Paleozoic basement of the Ardenne and adjacent areas experienced intense weathering during successive post-Variscan periods. These weathering phases generated kaolinic profiles that reach a depth of 65 m below the levelled plateau surface cut by the Transinne quarry at 445 m asl (Fig. 5.4). By contrast, outcrops in the nearby valley of the Haute Lesse expose fresh, though densely jointed bedrock at elevations of ∼330 m. Discovered by Jerôme in 1907, the kaolin has been mined since 1922 in this area and is now used for the cement and tile industries. In Transinne, the mineralogy of the saprolite developed over Late Lochkovian shales and sandstones mainly consists of neoformed kaolinite, iron, and manganese oxides in various

Fig. 5.3 View of the kaolinized Lochkovian shales and sandstones at Transinne (see location in Fig. 5.1) showing the preservation of the rock structures by the saprolite

proportions, with residual illite and quartz (Dupuis et al. 1996; Yans 2003).

Weathered mantles may contain neoformed cryptomelane, a potassium-bearing Mn oxide with tunnel structure, and hollandite, its barium-bearing equivalent that may also include potassium cations. Belonging to the hollandite supergroup (Biagioni et al. 2013), both are suitable for radiometric dating using the K–Ar system. The $^{39}Ar-^{40}Ar$ and $^{40}K-^{40}Ar$ methods have been widely used on Mn oxides to date weathering periods around the world (e.g., Vasconcelos et al. 1995), including in Western Europe (e.g., Hautmann and Lippolt 2000; Dill et al. 2010). Dating hollandites and cryptomelanes of the Transinne section by these methods, Yans (2003) showed that the saprolite in Transinne is the result of a polyphase weathering. K–Ar ages of hollandites in the upper part of the profile range between 120 and 135 Ma (Early Cretaceous), while Ar–Ar and K–Ar results consistently point to ages around 21 Ma (Early Miocene) for cryptomelanes of the basal part of the profile. Additional K–Ar ages on hollandites provided by Thiry et al.

(2006) date the intermediate part of the profile to $\sim$88–94 Ma (early Late Cretaceous). Moreover, paleomagnetic dating on iron (hydr)oxides sampled in the upper part of the Transinne profile yielded ages around 110–120 Ma, fully supporting the K–Ar ages obtained in that part of the profile (Yans 2003; Thiry et al. 2006). This vertical succession of ages is consistent with the long-term development of the weathering mantle by downward progression of the weathering front whenever the climatic and tectonic conditions were favourable to deep chemical weathering. The very old age of the upper part of the preserved profile underlines that Cenozoic denudation was almost zero in interior parts of the Ardennian erosion surfaces, and the ages obtained close to the weathering front suggest that the Early Miocene was the last period favourable to resumption of kaolinization in the Ardenne. Finally, Pb–Pb dating of secondary U-bearing phosphates emplaced *per descensum* in fractures located just below the weathering front and probably closed since the time of phosphate precipitation might indicate active weathering as early as the Late Permian-Early Triassic,

Fig. 5.4 The Transinne quarry cuts into Lochkovian shales and sandstones outcropping on the Selandian erosion surface of western and central Ardenne, here at 445 m asl, exposing a $\sim$65-m-thick mantle of deeply kaolinized rocks (© Google Earth 2015)

further confirming the antiquity of parts of the Ardennian landscape (Yans and Dupuis 2005). However, this dating requires further investigation because lead is very mobile during weathering.

Bihain

Saprolite thicknesses up to 50 m have also been recorded over phyllites and quartzites of the Cambrian, Revin Group, of the Stavelot massif, for instance in the Plateau des Tailles area (Cosan 1969) (Fig. 5.5). At Bihain, a hamlet established at 580–600 m asl on a remnant of an Early Paleocene erosion surface (see below), the saprolite formed on the phyllites of the Ordovician Ottré Formation. Here too, weathering led to the neoformation of kaolinite, iron oxi-hydroxides and iron–manganese oxides (Fig. 5.6); Fransolet (1979) already identified the presence of cryptomelane in the lower part of the saprolite of this area. Recent $^{39}Ar−^{40}Ar$ dating of homogeneous cryptomelane and of a mixture of cryptomelane-lithiophorite suggests an Early Miocene age for the lower part of the weathered profile at Bihain (Fig. 5.7), consistent with findings in Transinne.

Of course, such ages obtained close to the weathering front do not preclude older period(s) of weathering for the upper parts of the profile. Interestingly, K–Ar dating of neoformed Mn oxides found in deposits at the base of dissolution pockets within Dinantian limestones at Rechain, just north of NE Ardenne (Fig. 5.1), yielded ages between 88 and 95 Ma (Cenomanian to Santonian; Demoulin et al. 2010). These Late Cretaceous ages are in good agreement with the topographic position of the samples, situated very close beneath the trace of the pre-Cretaceous erosion surface emerging from below the nearby Cretaceous cover of the Herve Plateau. These deposits thus represent the westernmost extension of the continental sediments making the basal Hergenrath Member of the Late Cretaceous cover in the area, corresponding to a wealden-type lowland sedimentation contemporaneous with the deep weathering that took place farther inland (Demoulin et al. 2010).

Morialmé

The Morialmé weathering profile is located in the "Le Faya" quarry, at 260 m asl near Morialmé, in the Entre-Sambre-et-Meuse (ESEM). The quarry cuts the southern flank of an anticline and is mined for the brick industry. The saprolite was developed on micaceous slates of the Famennian Etroeungt and Ciney Formations, weathering processes being mainly kaolinite neoformation in the upper part of the profile and swelling clay formation in its lower part (Barbier et al. 2012). Although the degree of weathering is highly variable inside the quarry (Barbier et al. 2010), the top of the weathering profile still displays the alloterite (Barbier et al. 2012), i.e., the upper part of the profile that has undergone structure collapse and compaction (Wyns et al. 1999), showing that the profile top was quasi unaffected by erosion at the time of its burial under fluviatile sediments in the Late Paleocene (Schuler et al. 1992) to Early Eocene (Barbier et al. 2012) (Fig. 5.8). Two samples of hollandite from the lower middle part of the profile yielded K–Ar ages of 53.3 ± 2.3 Ma and 58.2 ± 2.4 Ma (Barbier et al. 2010) (Table 5.1), confirming that weathering was still active just prior to this fluvial sedimentation episode at the Paleocene-Eocene transition. This sequence of events is also consistent with the Selandian age assigned by Demoulin (1995) to the erosion surface preserved in the western part of the Ardenne and ESEM, which continued to evolve during the Thanetian where it was not drowned by the Early Thanetian Sea.

Beez

Cut into a bench at ∼160 m asl along the northern valley side of the Meuse valley close to Namur, the Beez quarry exposes a cryptokarst developed in Visean limestones. In this karstic setting, possibly in relation with the circulation of acid fluids originating from pyrite leaching and oxidation in the overlying Namurian black shales, the weathering paragenesis includes neoformed halloysite, gibbsite, Fe and Mn (hydr)oxides, gypsum, and jarosite. Based on data from neighbouring cryptokarsts and saprolites, Bruyère et al. (2003) pointed to a possible Miocene age of this weathering. New K–Ar analyses performed on jarosite yielded ages of 16.5 ± 0.8 and 16.8 ± 0.5 Ma that confirm the Miocene timing of weathering in Beez (Table 5.1). One notes that these ages are somewhat younger than those obtained at the base of the Transinne and Bihain profiles. However, the weathering history at Beez might have responded mainly to local geochemical (leaching of iron sulphides) and drainage conditions (karstic vertical transfer, possibly linked to the Meuse valley downcutting) and have a more limited climatic and geodynamic meaning than that assigned to the weathering mantles dated elsewhere in the Ardenne. Moreover, the unknown original depth of the cryptokarst makes it very difficult to relate this weathering episode with any contemporaneous topography.

Summarizing, the available age data for weathering mantles and residues in the Ardenne identify periods favourable to deep weathering that are in excellent agreement with those recognized in neighbouring areas throughout the Mesozoic and the Cenozoic, namely during the Early and early Late Cretaceous, the Late Paleocene, and the Early Miocene plus, to a lesser extent, the Late Permian-Early Triassic. As we will show in the next section, these periods fit
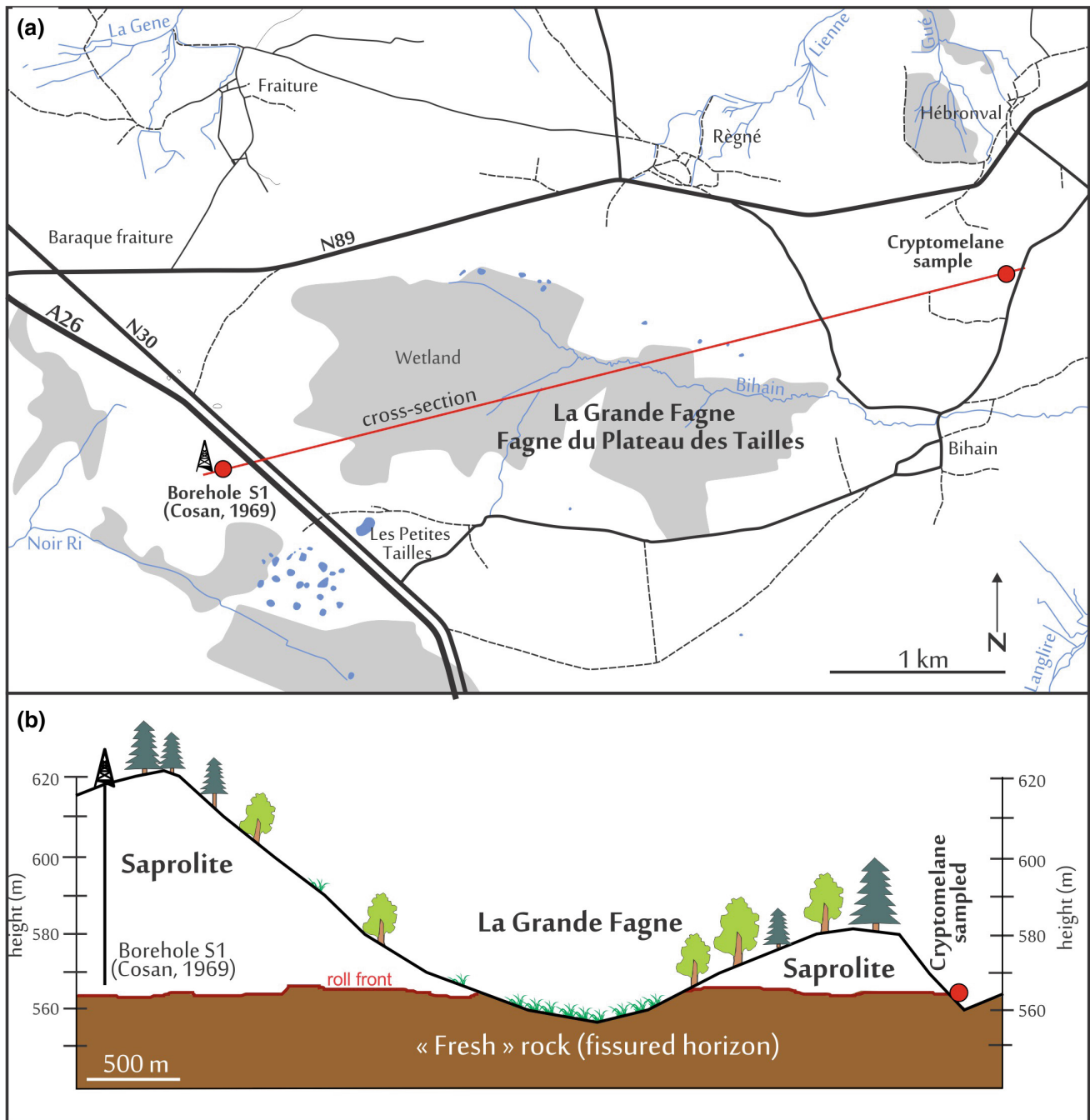
Fig. 5.5 a Map of the Bihain site in the Plateau des Tailles (see location in Fig. 5.1), one of the few areas of central Ardenne-Eifel whose summits still bear witness to the pre-Senonian surface in a region where the Late Cretaceous topography was possibly never covered by marine transgressions. **b** Weathering profile across the Plateau des Tailles. Note the location of the dated saprolite close to the weathering front (roll front) at 565 m asl, i.e., ∼90 m below the summit surface of Cretaceous age

also very well with the periods of planation and surface development inferred in the Ardenne from independent data, weathering and planation going hand in hand under conditions of warm humid climate and relative tectonic stability in regions where mean elevation is high enough to create the vadose zone required for effective leaching. It remains of course a possibility that further dating of weathering products may point to other phases of weathering, whose climatic/geodynamic meaning will have to be examined carefully in any case, avoiding to put too much emphasis on isolated occurrences linked to specific environments (e.g. karstic setting, water table fluctuation zone).
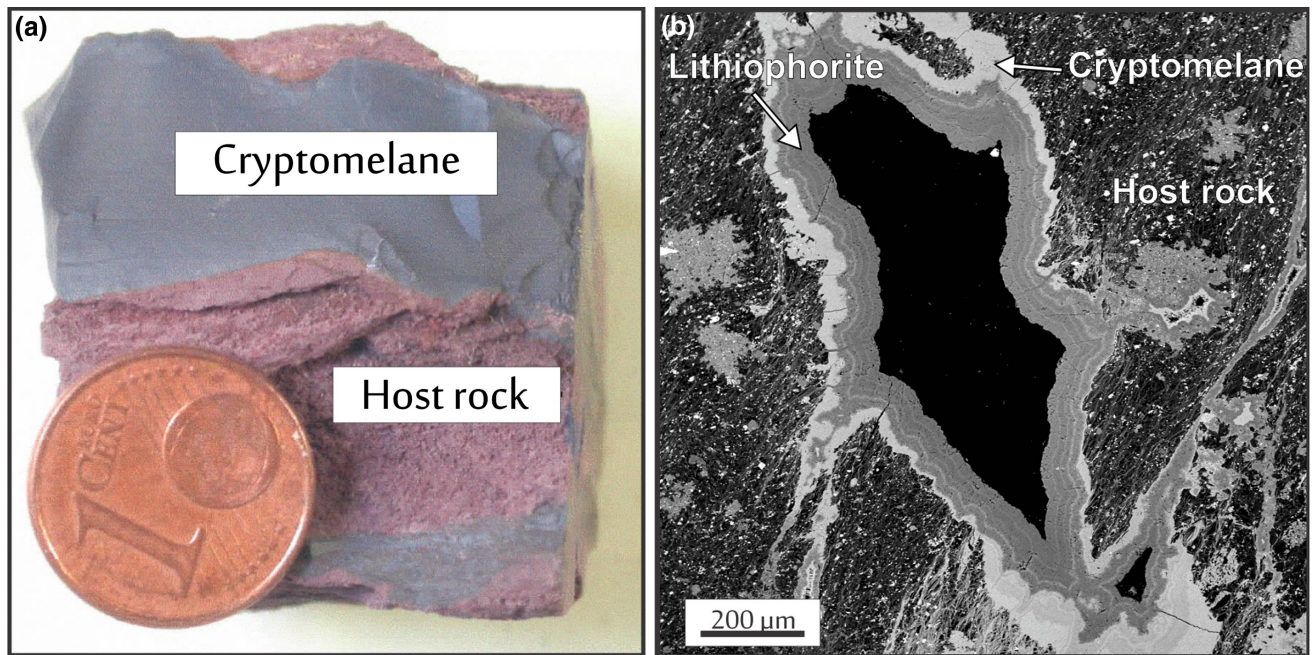
Fig. 5.6 **a** Sample of cryptomelane of the Bihain quarry (collection of the Laboratory of Mineralogy, University of Liège, courtesy A.-M. Fransolet). The host rock is an alternation of Ordovician quartzite and phyllite. **b** SEM-EDS (Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy) view of the mixture cryptomelane-lithiophorite in Bihain

5.3 Erosion Surfaces in the Ardenne and Oesling

5.3.1 Geographical and Geological Setting

Beyond being famous for its unique periglacial features (see Chap. 7), the Hautes Fagnes Plateau of NE Ardenne (E Belgium) exposes remarkably well-preserved remnants of erosion surfaces of various Mesozoic and Cenozoic ages. Located at the tip of the recently uplifted Paleozoic Ardenne (e.g. Demoulin et al. 2009), this old erosional landscape of stepped surfaces dominates by ~ 400 m the Pays de Herve, the northern foreland of the massif, to which it connects by a narrow margin of moderately steep slopes drained by the Vesdre River flowing at its foot. While all slopes are covered by dense forests, the top of the plateau above 550 m bears extended moorland that enhances the flat character of the inherited topography, which is still only marginally affected by the Plio-Quaternary incision of rivers. This presence of large peat bogs is a specificity of the Hautes Fagnes Plateau, which is otherwise similar to all plateau areas of the Ardenne (and the nearby Eifel as well).

The Ardenne–Oesling massif belongs mostly to the Rheno-hercynian zone of the Variscan fold-and-thrust belt of middle Europe, the northern limit of the present-day plateau corresponding more or less to the Variscan front (Fig. 5.9). Structures inherited from the Caledonian orogeny and deformed again in Variscan times crop out along the axis of

the uplifted massif, and especially in its northeastern part, resulting in a structurally complex basement wherein longitudinal ENE–WSW folds and thrust faults are cut by numerous NW–SE to NNW–SSE striking normal faults (Demoulin and Ek 1995). The Hautes Fagnes Plateau pertains almost entirely to the Cambrian-Ordovician Stavelot inlier, one of these inherited Caledonian structures aligned along the axis of the Ardenne anticlinorium and essentially made of variably erodible phyllites and very resistant quartzites. To the south of this anticlinorium, the bulk of the Ardenne Plateau corresponds to the Neufchateau synclinorium, which mainly exposes fairly homogeneous Lower Devonian slates and where marked lithological contrasts arise only locally from intercalations of conglomerate or arkose formations. Such arkoses crop out for instance along the eastern limit of the Stavelot inlier, in the SE of the Hautes Fagnes area. To the north of the Ardenne anticlinorium, the northern part of the Ardenne allochthon corresponds to the Dinant synclinorium, where the slaty bedrock of the Ardenne *s.s.* gives way to alternating Middle Devonian to Lower Carboniferous sandstones, shales and limestones. These rocks define the particular landscapes of the Famenne, a wide depression carved in Fammenian shales, and of the Condroz plateau, with alternating elongated ridges on sandstones and valleys cut in the limestones (Fig. 5.9). Scattered over the Condroz ridges and the flat summits of W and NE Ardenne, few remnants of loose sediments, mainly marine sand and clay-with flints, also attest that the massif
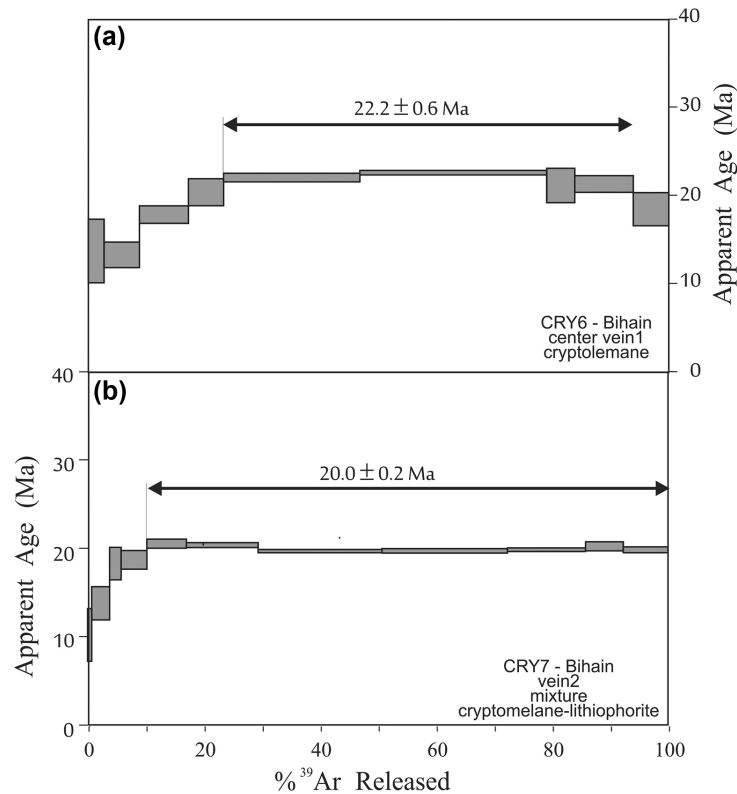
Fig. 5.7 ^{39}Ar–^{40}Ar age spectra of the Bihain cryptomelane. **a** ^{39}Ar–^{40}Ar age spectrum obtained for an homogeneous vein of cryptomelane, yielding a calculated plateau age of 22.2 ± 0.6 Ma (70, 6% of ^{39}Ar released). **b** ^{39}Ar–^{40}Ar age spectrum of a mixture of cryptomelane and lithiophorite, yielding a calculated plateau age of 20.0 ± 0.2 Ma (89, 8% of ^{39}Ar released)
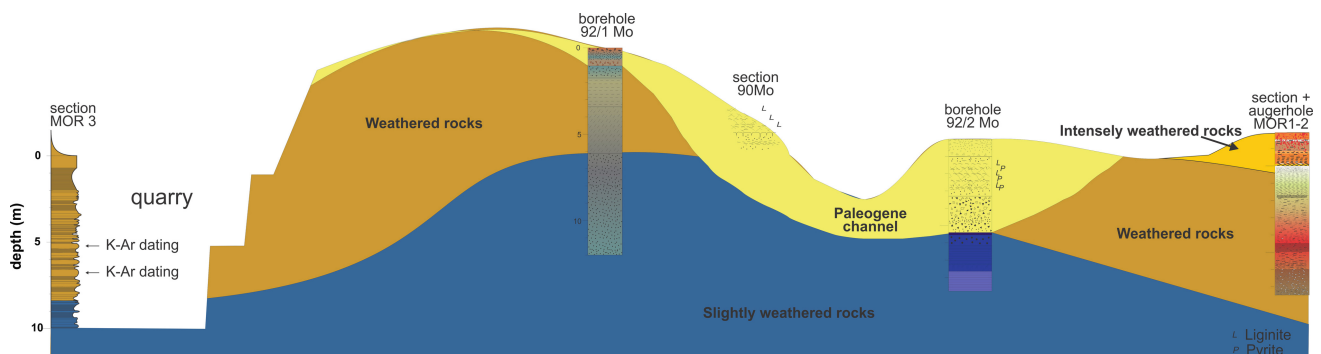

Fig. 5.8 The weathering profile at Morialmé (see location in Fig. 5.1), with location of the samples for K–Ar dating on hollandite

was partly drowned by marine transgressions coming either from the north or the west during the Cretaceous and the Paleogene (e.g. Demoulin 2003; see also Chap. 2).

Morphologically, the Ardenne represents a western annex to the Rhenish shield in the form of an E–W elongated relief whose flat summits gradually descend from elevations above 600 m in the east to 500–600 m in the central domain and below 400 m west of the Meuse valley. As a consequence, the transition from the massif to its N and S forelands, rather sharp in the east, is progressively less conspicuous westward and, would geology not witness its limit, the Ardenne goes imperceptibly into the Mesozoic cover of the Thiérache to the west. Except its SE confines drained by the Sûre River towards the Mosel and the Rhine, the Ardenne Plateau is drained by rivers of the Meuse basin that have incised 100- to 150-m-deep Plio-Pleistocene valleys through it (history of

Table 5.1 K–Ar dating results on hollandite in Morialmé and jarosite in Beez (see location in Fig. 5.1)

Location	Sample	K$_2$O (%)	Ar (%)	^{40}Ar (10^{-6} cm^3/g)	Age (Ma ± 2σ)
Morialmé	08mori-oxmn1	0.52	17.38	0.90	53.3 ± 2.3
	08mori-oxmn2	0.66	13.00	1.25	58.2 ± 2.4
Beez	Jar-Beez-A	3.39	67.50	1.85	16.5 ± 0.8
	Jar-Beez-B	1.92	18.25	1.05	16.8 ± 0.5
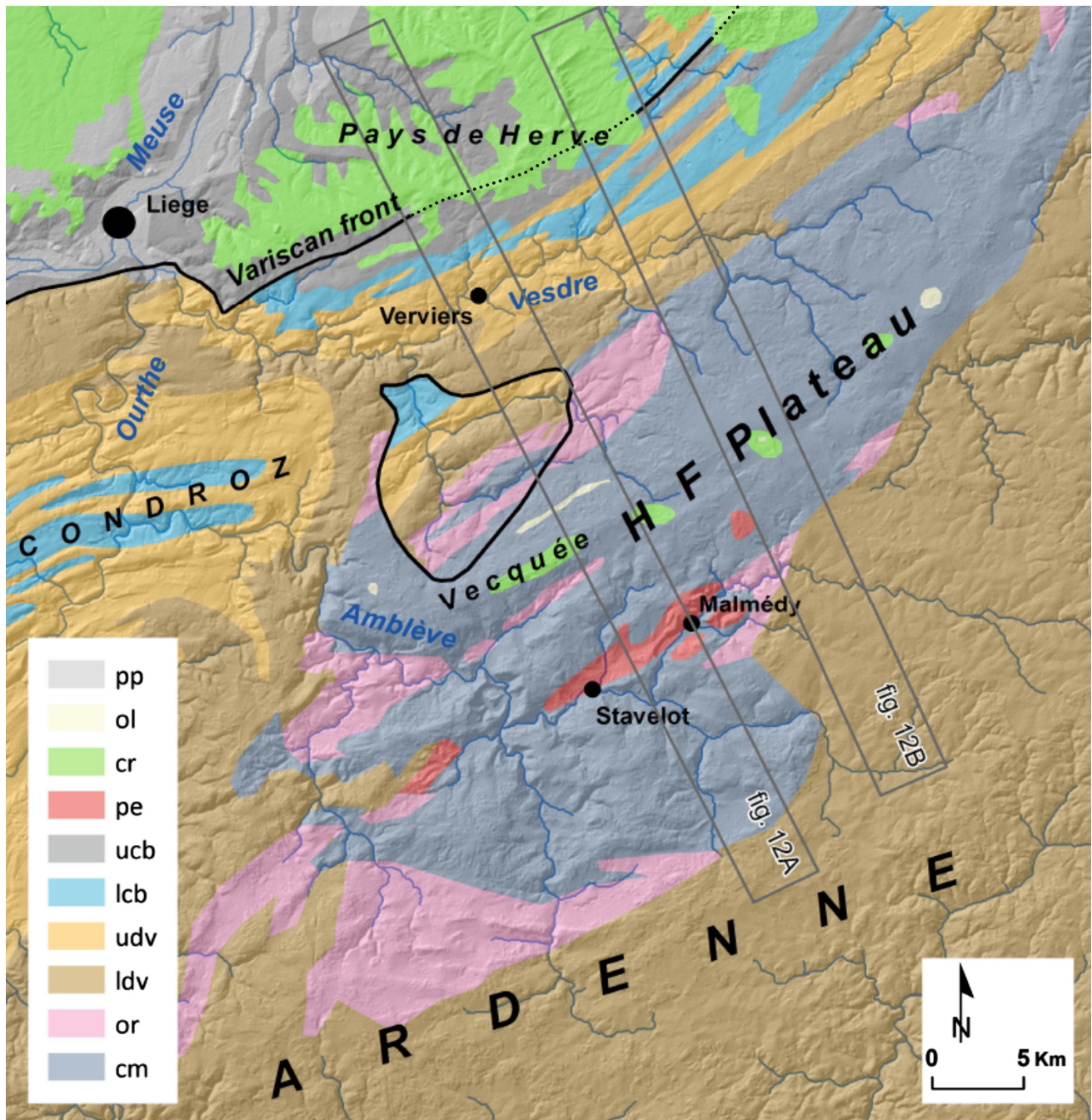
Fig. 5.9 Simplified geological map of the Hautes Fagnes Plateau and surrounding areas in NE Ardenne (see location in Fig. 5.1) draped on a hillshade of the SRTM 3″ digital elevation model. *cm* Cambrian or Ordovician. *ldv* Lower Devonian. *udv* Middle and Upper Devonian. *lcb* Lower Carboniferous. *ucb* Upper Carboniferous. *pe* Permian. *cr* Cretaceous. *ol* Oligocene. *pp* Plio-Pleistocene

the incision is dealt with in Chap. 10). Culminating at ~700 m asl, the Hautes Fagnes Plateau corresponds to the highest part of the massif.

5.3.2 Shape and Characteristics of an Erosion Surface

Being remote descendants of etchplains formed under warm-humid conditions, the Ardennian erosion surfaces display a variable mix of extremely flat areas and more undulating topographies (Fig. 5.10). In principle, active etchplains are essentially flat and remarkably horizontal as long as a deep weathering mantle covers them uniformly, leaving only large-scale inselbergs emerge abruptly from the surrounding surface and dominate it often by 100 or more meters (Thomas 1994). However, when climatic conditions turn drier or cooler, it is common that the etchplain is stripped of part or all of its weathering mantle and that the weathering front becomes exposed. Being more sensitive to lithological and joint density contrasts, this front usually presents irregularities at all scales that appear then at the surface, forming topographic bumps from m- to dm-sized whalebacks to large subdued hilly reliefs up to a few tens of meters in height. This is the large-scale shape most usually shown by the Ardennian surfaces, in agreement with the patchy preservation of their associated weathering mantles, whose stripping probably mainly resulted from the drastic slowdown of weathering imposed by generally cooler conditions since the Oligocene. Recognising the weak relief currently displayed by the erosion surfaces is important in paleolandscape reconstructions because it prevents one from the temptation of distinguishing supposed surfaces vertically too close to each other.

5.3.3 Identifying an Erosion Surface

The most obvious criterion of surface identification is the overall geometry of individual levelled elements and ensembles of elements in the present landscape. However, it relies on the assumption that the envelope of part of the topography may correspond to one particular ancient erosion surface, which is sometimes questionable in regions with a complex history involving many episodes of planation and intervening deformation and degradation. Nevertheless, the reconstructed surfaces display in general, and especially in the Ardenne, a large-scale plane shape, more or less tilted, sometimes locally or regionally flexured, and admitting a relief amplitude in the order of 20–30 m (Demoulin 2006). Beyond post-planation deformation, two factors complicate such geometry-based surface reconstructions. The first one relates to the inherent relief of any erosion surface,

especially when stripped of their weathering mantle. It implies that the reconstruction allows for a careful balance between topographic variations within a single-stage paleolandscape and close positions of successive surfaces in some areas, especially where differently tilted surfaces are intersecting each other. The second factor refers to the issue of defining the moment when a given surface ceases to evolve as such and begins to degrade, thus giving way to the formation of a new, distinct landscape. This comes to find a clear separation between pure acyclism and clear-cut morphogenetic cyclicity, whereas all transitions actually exist between these end-members in real landscape evolution (Klein 1990).

Facing such difficulties, geometric reconstructions are advantageously supported by the analysis of the so-called correlative deposits. In particular, when geometry allows the connection of the exhumed part of a paleosurface with its counterpart buried as the base surface of a sedimentary cover in the massif's foreland, the very existence of the latter attests an episode of aggradation, continental or marine, that clearly ends the previous planation stage and defines its specific topography. In such cases, there is most often a more or less extended transition zone where scattered remnants of the sedimentary cover confirm the position of the exhumed surface within the uplifted massif, at least if they may be unequivocally assigned to this cover. In any case, as scarcely as it may be preserved, the sedimentary evidence is a key element in the analysis of erosional paleolandscapes. In this respect, next to sediments, the weathering mantle associated with the surfaces may also be helpful for distinguishing planation episodes, thanks to specific features such as depth, degree of preservation, secondary products (e.g. duricrusts) and, of course, dating of weathering profiles.

5.3.4 Erosion Surfaces of the Hautes Fagnes Plateau

The area whose successive paleolandscapes we describe in some detail corresponds to the Hautes Fagnes region s.l., which is made of the Hautes Fagnes massif s.s. (HFM), its western prolongation in the Vecquée ridge (VR), their northern margin, gently sloping toward the Plateau de Herve in the north, and the high plateau area to the SE of the HFM (Fig. 5.11). Mapping of the intricate erosion surfaces will be aided by the analysis of topographic swath profiles (Fig. 5.12).

The most conspicuous surface element is represented by the remarkably flat, almost horizontal plateau surface covering the HFM at >600 m asl and currently occupied by peat bogs and extensive heath that confer to the area its wild character and wide horizons (Fig. 5.10). In the east, this surface is dominated by a few subdued summits rising a few

Fig. 5.10 The pre-Senonian surface as it appears on top of the Hautes Fagnes Plateau, near Baraque Michel, underlain by a widespread peat cover that still locally overlies residual Cretaceous clay-with-flint and sand, and Oligocene marine sands. The faint ∼8‰ slope to the north (toward the *left* of the *photograph*) was produced by post-Cretaceous tilting of N Ardenne (essentially in the very Early Paleogene, as all Cenozoic erosion surfaces are horizontal across central and northern Ardenne)

tens of meters above their surroundings. To the NW, it goes rather abruptly in a tilted and dissected surface that makes the margin of NE Ardenne. The forested interfluves materialising the surface remnants slope regularly (by ∼4 %) down to ∼320 m asl, where they join the upper edge of the incised Plio-Quaternary valley of the Vesdre. On the opposite side of the HFM, steeper slopes rapidly lead down southeastward to another very regular, hardly dissected surface at 560–580 m asl, covered by pasture and interrupted by small wooden areas only where upper valley reaches of the Roer catchment begin to incise. Though essentially horizontal, this 560–580 m landscape element shows imperceptible slopes going up in a residual relief that culminates in the SE at ∼690 m asl at the Weisser Stein (Fig. 5.12). On its southwest flank, the HFM displays a stepped descent toward the perfectly horizontal ridge of the Vecquée. Extending at 560–570 m asl for ∼15 km to the

SW and with a width of 0.5–1.5 km, the VR represents a distinct topographic element in the present landscape of the area. On the north, it is bordered by a ∼120-m-high escarpment that links it to a lower surface well preserved on the interfluves between the incised valleys of the Gileppe, the Hoëgne, and the Wayai. This surface, which skirts the western end of the ridge, is observed at elevations around 450 m at its foot, from where it slopes very gently (∼0.6 %) toward NW. It includes extended levelled areas at 360–390 m asl between the villages of Theux, Sart-lez-Spa, and Jalhay (Figs. 5.11 and 5.13). On the south of the VR, a smaller, ∼60-m-high escarpment leads down to a local intramontane basin whose levelled bottom appears in the form of wide flat interfluves at uniform elevations of 500–510 m asl. Centred on the area where weak rocks of the Permian graben of Malmédy crop out (Fig. 5.9), this erosional feature opens towards the massif's exterior in the

Fig. 5.11 Map of the erosion surface remnants in the Hautes Fagnes area of NE Ardenne, draped on a hillshade of the SRTM 3″ digital elevation model. All flat interfluves and broader plateau areas belong to pre-Quaternary topographies of various ages. *PSS* Pre-Senonian surface. *DS* Danian surface. *POS* Pre-Oligocene surface. *EMP* Early Miocene planation, developed in less resistant Permian conglomerates and Ordovician shales. Talus: ∼100-m-high erosional riser between the pre-Senonian/Danian and the pre-Oligocene surfaces as it is preserved since it was carved in the regional topography during the Paleogene
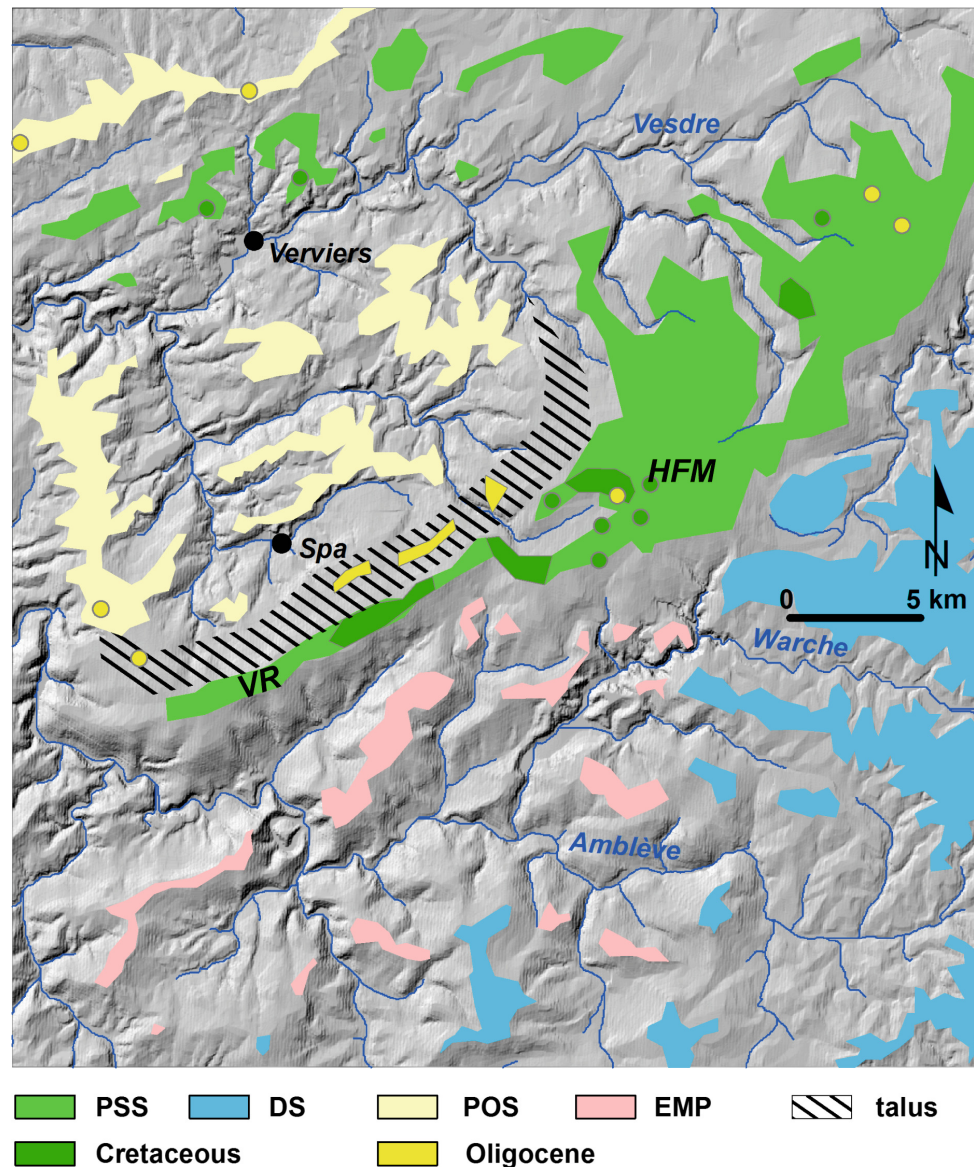
west, where it is geometrically connected to the 450-m surface.

In the northern foreland of the massif, the Meso-Cenozoic sedimentary cover of the Pays de Herve offers an opportunity for reconstructing the profile of two paleosurfaces onto which transgressing seas encroached. The first one is the base surface of the Senonian deposits (the clays and sands of the basal Aachen Formation are dated to the Santonian), which shows a slight but consistent tilt of 1.4% towards NNW. Emerging at the topographic surface in the south of the Pays de Herve, it appears there in the form of large exhumed remnants, similarly tilted and preserving sands and clays of early Late Cretacous age in solution pockets of the underlying Dinantian limestones (Demoulin et al. 2010). Prolonged southward toward the Hautes Fagnes summits, the 1.4% tilt angle connects the VR surface and the tilted

surface on the northern flank of the HFM with the Senonian base surface in the Pays de Herve (Fig. 5.12). The second marker interface in the Meso-Cenozoic cover is the base surface of the sand formation that accumulated during the last marine transgression that covered the northern part of the Ardenne in the Oligocene (Rupelian?). Again, NNW–SSE sections of the cover indicate a minor (0.6%) but uniform NNW tilt of this interface that can easily be followed across the Vesdre valley to the 360–450-m surface in the massif, north of the VR, which shows exactly the same tilt in the same direction.

Finally, remnants of the Cretaceous sands and clay-with-flints and Oligocene marine sands scattered over the northern margin and summits of the Hautes Fagnes region provide additional evidence of the geometric connections established between the massif's erosion surfaces
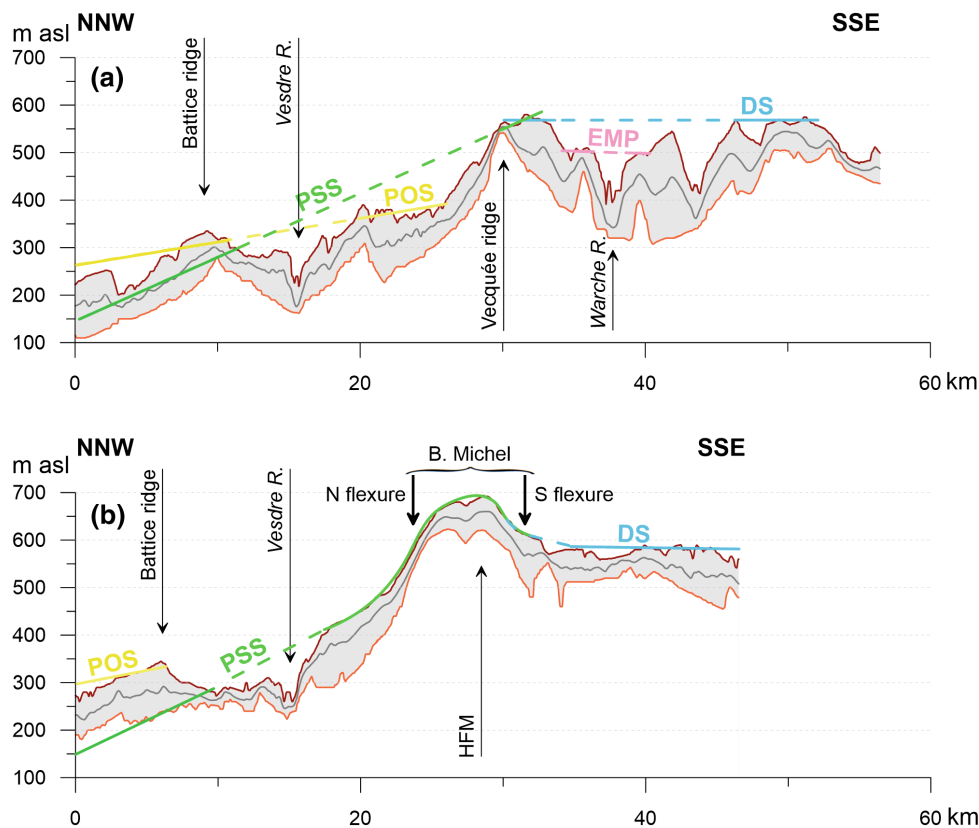
Fig. 5.12 NNW-oriented 4-km-wide swath profiles (see location in Fig. 5.9; *orange, grey,* and *ruby brown lines* are for minimum, mean, and maximum elevations, respectively) showing the geometry of the erosion surfaces across the northern margin of NE Ardenne at the height of the Vecquée ridge (**a**) and the Hautes Fagnes Plateau (**b**), where the general tilt to north is complicated by post-Oligocene uplift of the Baraque Michel block inducing the flexure of the surfaces. *PSS* Pre-Senonian surface. *DS* Danian surface. *POS* Pre-Oligocene surface. *EMP* Early Miocene planation level. The trace of exhumed erosion surfaces obviously follows maximum elevation lines of the swath profiles. By contrast, north of the Vesdre valley, the pre-Senonian surface is still buried under a continuous Upper Cretaceous cover. Height exaggeration ×33

and their buried counterpart in the Pays de Herve. Discontinuous clay-with-flint, often overlying Aachen sand and gravel, are still widespread over the VR and the HFM and are found locally on the sloping surface leading up to the latter, especially southeast of Eupen (Fig. 5.11). Elsewhere, beyond rare occurrences of isolated reworked flints lying around on the 500-m surface south of the VR, the 360–450-m surface in the north and the 560–580-m surface in the south are completely devoid of Cretaceous sediments. By contrast, sparse deposits of Oligocene sands are mainly encountered all over the 360–450-m surface, while rarer remnants of this cover also exist next to, and sometimes over, Cretaceous sediments on the HFM summit and northern slope and on the VR.

Integrating all these observations, one obtains the following consistent reconstruction of the successive paleo-surfaces whose fingerprint is still visible in the present landscape (Fig. 5.11). The oldest preserved surface in the Hautes Fagnes area is pre-Senonian in age and includes the levelled summits of the region (VR and HFM) and also the tilted surface that makes the northern margin of the HFM and links it to its foreland east of a line joining Verviers to Malmédy (Fig. 5.12). The unity of this surface made of distinct topographic elements is demonstrated by the Cretaceous deposits that all of them still expose. However, the pre-Senonian surface underwent strong post-planation deformation during the Cenozoic, mainly in the form of a marked differential uplift of the HFM. Its overall geometry shows that the HFM block uplift was limited by flexures on its northern and southern sides (Fig. 5.12b), while a series of NNW-striking Variscan faults, reactivated in normal mode, accommodated the ~100 m height difference with the adjacent Vecquée ridge to the west.

Even if they share the VR summit (Fig. 5.12), the 560–580-m surface to the SE of the HFM represents a planation episode different than that attested by the pre-Senonian surface. Indeed, with the exception of few residual reliefs such as the Weisser Stein, whose summits are probably hardly degraded isolated remnants of the pre-Senonian surface, the remarkable horizontality of the 560–580-m surface
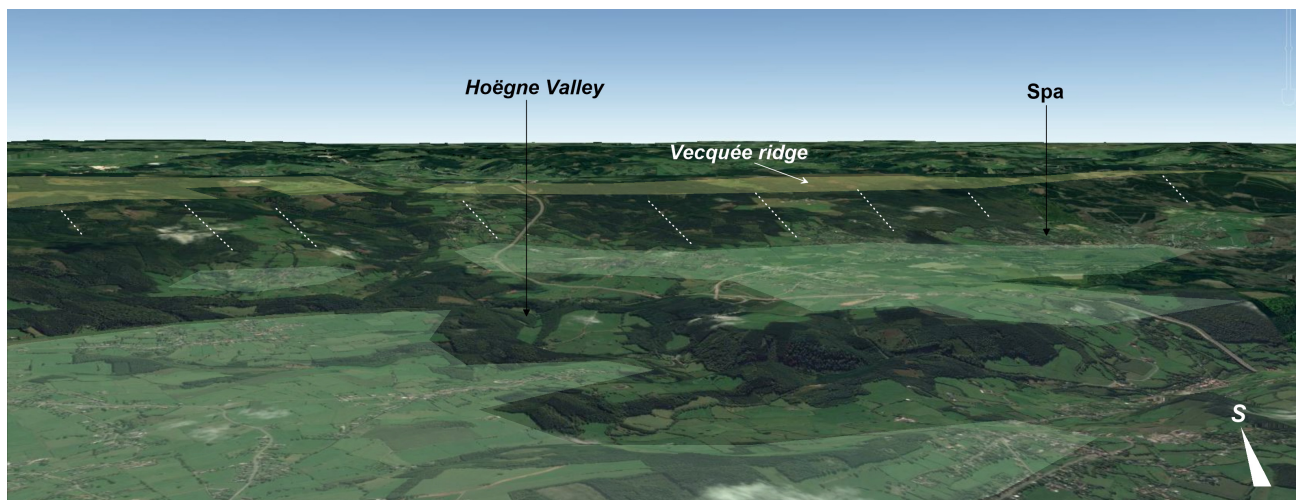
Fig. 5.13 S-looking oblique *aerial* view of the pre-Oligocene surface (in *light green* transparency) developed at 350–400 m asl north of the Vecquée ridge, which represents the pre-Senonian surface, exhumed and reexposed since the Danian (in *light yellow* transparency). The erosional scarp between both surfaces (*dotted white lines*) clearly appears as a regional morphological feature. In the background, beyond the barely visible Early Miocene planation level developed in the Stavelot-Malmédy area, south of the Vecquée, the uniform *horizon line* evidences the well-preserved Danian surface of central Ardenne. *Scale* the visible length of the Vecquée ridge is ∼20 km. Elevation factor 2 (© Google Earth 2015)

across the whole central Ardenne and nearby Eifel shows that it resulted from low-angle bevelling of the slightly tilted previous (pre-Senonian) topography, the intersection between both surfaces occurring along the VR (Fig. 5.12a). This interpretation is further supported by the absence of Cretaceous sediments on the 560–580-m surface south of the VR, where their complete removal (their former presence in this area being only proved by isolated clay-with-flints remains on the SE flank of the Weisser Stein) had to precede regradation of their base surface (regradation being the process of tending towards a new grade after a perturbation; Fairbridge 1968).

Finally, the last envelope surface of the topography locates a third nested paleolandscape that is chiefly associated with the 360–450-m surface developed in the north and west of the Hautes Fagnes region and prolonged inside the massif by the 500-m intramontane basin south of the VR. However, whereas remnants of the Oligocene sand cover scattered over the surface north of the VR attest that it was developed before the Oligocene transgression on the massif, the absence of corresponding deposits in the intramontane basin despite drowning of the VR by the Oligocene sea strongly suggests that this inward extension of the 360–450-m surface was carved in later times.

Separation between the different surfaces occurs in two ways. While the 560–580-m and, north of the Vesdre valley, the 360–450-m surfaces both cut at low angle the tilted older pre-Senonian surface, a well-developed 60- to 150-m-high erosion scarp, making the northern flank of the VR, separates them from each other (Fig. 5.12a). The erosional nature

of this scarp, as opposed to the tectonic flexures limiting the uplifted HFM, is demonstrated by the fact that N–S sections north of the VR show no equivalent to this flexure in the older, uniformly tilted pre-Senonian surface (Fig. 5.12). The two types of surface separation evidence distinct erosional mechanisms. Low-angle bevelling is typical of acyclic morphogenesis where surfaces temporally distinguished by their associated sedimentary evidence gradually regrade their predecessor under etchplanation regime in response to slow, low amplitude deformation. By contrast, erosional scarps signal morphogenic cyclicity, implying a combination of etchplanation and scarp retreat in response to more rapid, larger tectonic deformation with a significant component of en-bloc uplift.

5.3.5 Dating a Surface

It is clear from the Hautes Fagnes example that geometric relationships between paleosurfaces and their links to buried base surfaces within foreland sedimentary covers already provide powerful tools for unravelling the chronology of long-term geomorphology in erosional settings. Taking into account the various types of discontinuity that give rhythm to such a "surface stratigraphy" further allows inferences about the nature of the often tectonic triggers of morphogenesis.

The paleolandscape chronology is also aided by the analysis of correlative deposits preserved on the erosion surfaces. In the Ardenne–Oesling, the oldest sediments of

interest in this respect correspond to the band of Bunter sandstones (Lower Triassic) cropping out at the southern edge of the Oesling, and continuing eastward inside the massif into the N–S Eifel zone. More to the west, the Mesozoic deposits directly resting on the southern border of the Ardenne are younger, mainly Liassic, and ending with Turonian and Coniacian chalks at the limit between W Ardenne and Thierache (Fig. 5.14). The equivalent first post-Variscan sediments present on the northern side of the massif are Upper Cretaceous sands and chalks (weathered to clay-with-flint). Their outcrop zone is restricted to the Hautes Fagnes region in the NE (Bless and Felder 1989), where they nevertheless covered large areas inside the massif as witnessed by the clay-with-flint retrieved at Dalhem, east of the Weisser Stein (Fig. 5.14). Later, further seas which encroached upon the Ardenne are recorded during the Early Thanetian in the west, where Upper Thanetian continental sands also sparsely cover the western Rocroi Plateau, and during the Rupelian, when marine sands were deposited not only in the Hautes Fagnes but also over the whole Condroz Plateau and in the ESEM region (Fig. 5.14).

Finally, as indicated in the first part of this chapter, dating techniques applied in the past two decades to minerals neoformed during weathering brought significant improvement in the appraisal of the age of erosional paleolandscapes in uplifted massifs, and especially in the Ardenne, by incorporating in the discussion quantitative information about the age of the associated weathering mantles. The next section brings a brief overview of the current understanding of the long-term geomorphic evolution in the Ardenne–

Oesling at the light of this diverse, recently enlarged deal of evidence.

5.3.6 The Whole Picture: Stepped Surfaces of the Ardenne–Oesling

During Mesozoic and Cenozoic times, the Ardenne–Oesling underwent many phases of subaerial denudation, only interrupted by limited marine transgressions. The seas that drowned the margins of the massif came from E to SE in Triassic and Liassic times, from W during the Eocene and from N in the Early Oligocene. Only the Late Cretaceous sea probably submerged larger parts of central Ardenne.

Seven generations of paleolandscape may be recognized (Demoulin 1995, 2003) (Fig. 5.15). A pre-Triassic topography, mainly observed in W Eifel, where it displays a fairly animated relief (Junge 1987), also emerges from below the Triassic cover to form the slopes of the SE margin of the Oesling. It is continued westwards by the diachronic, so-called post-Hercynian peneplain, which constitutes the southern margin of the Ardenne, with interfluves tilted by 1–3% to the south. In NE Ardenne, following a longer phase of post-Variscan denudation, the oldest paleosurface preserved as part of the modern landscape dates back to the Late Cretaceous. As stated above, remnants of this pre-Senonian surface are also preserved as the highest summits, at 650–700 m elevation, in the heart of the massif (Baraque Michel, Baraque Fraiture, Weisser Stein, Schneifel). Then, after the Late Cretaceous regression, acyclic erosion of the Ardenne–

Fig. 5.14 Map of the Mesozoic and Cenozoic marine transgressions over the Ardenne massif (modified after Demoulin 1995). *Horizontal brown hatching* denotes the area of occurrence of Upper Thanetian continental deposits

Oesling removed its Cretaceous cover almost completely and caused an extensive erosion surface to develop over northern and central Ardenne by regrading the pre-Cretaceous landscape during the Danian. Corresponding to the 'surface supérieure' of Macar (1938), this Danian surface is now observed at altitudes of 560–580 m, going down slowly in the south to reach ∼500 m asl along the southern border of the massif. In contrast with previous surfaces, it developed independently of any marine ingression and its age is primarily inferred from geometrical considerations and the derived "surface stratigraphy". Another information is, however, provided by the Early Cretaceous radiometric ages obtained for the upper part of the weathering profile at Transinne, which roughly locates the weathering front at (modern) 450 m asl at 130 Ma, i.e.,

∼80 m lower than the trace of the Danian surface in the same location, suggesting that the Danian regradation of the pre-Cretaceous topography was minimal in this area.

The Danian surface represents the end product of the long-lasting acyclic evolution of the Ardenne–Oesling under conditions of prevailing tectonic stability during the Mesozoic. From the Middle Paleocene onwards, rather than regrading the older surfaces more or less uniformly and cutting them at low angle, new paleosurfaces developed at their expense by creating 50–170 m-high scarps that retreated inward, progressively nibbling the higher topography and producing a stepped landscape in response to more perceptible tilt of the massif. This happened so first on the western side of the massif, where the Danian landscape was replaced by a lower erosion surface during the
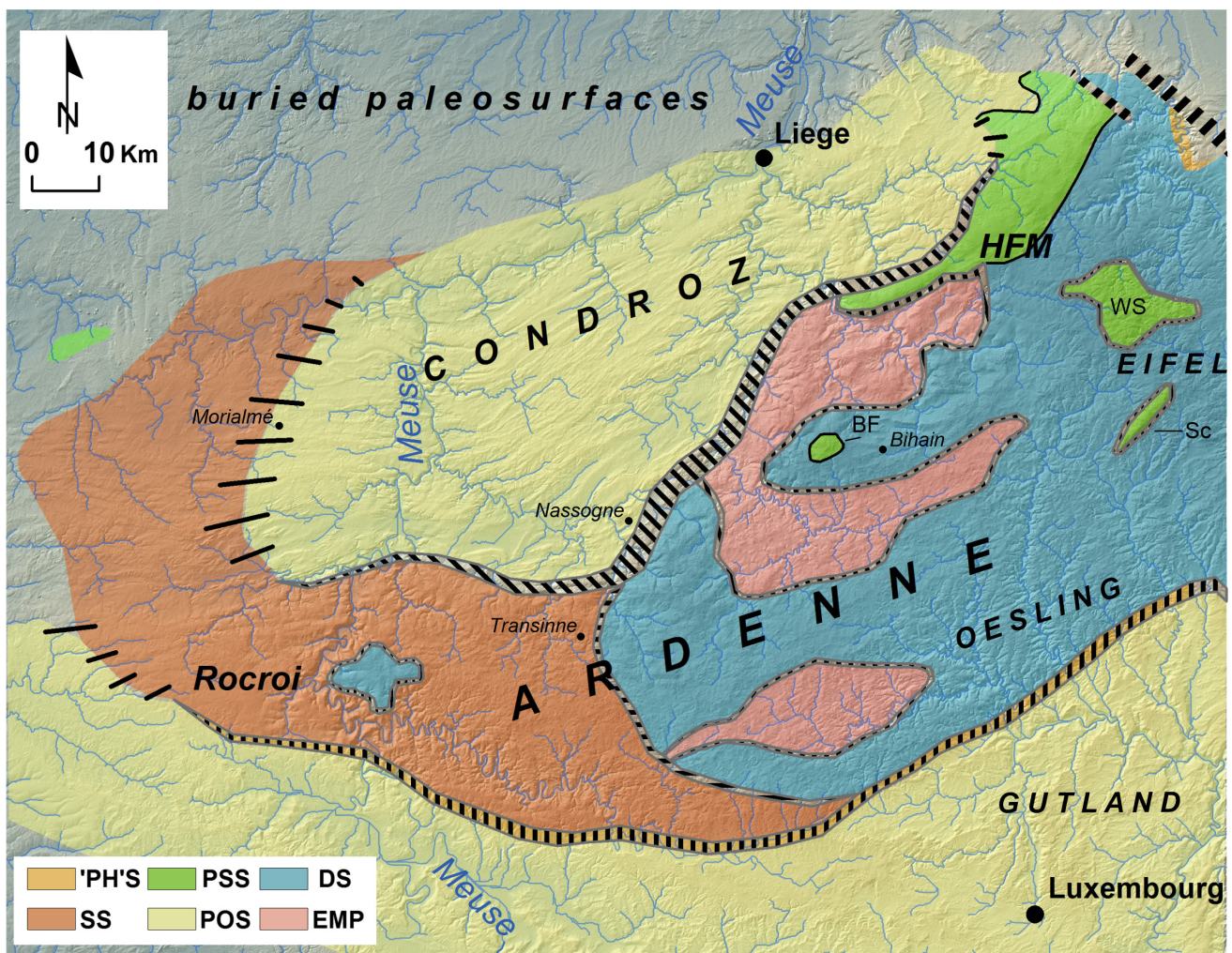

Fig. 5.15 Map of the erosion surfaces of the Ardenne and its margins, draped on a hillshade of the SRTM 3″ digital elevation model. 'PH'S. Post-Hercynian surface (including its more specific pre-Triassic variant in Luxembourg and north Eifel). PSS. Pre-Senonian surface. DS. Danian surface. SS. Selandian surface. POS. Pre-Oligocene surface. EMP. Early Miocene planation level. Thin hatching denotes erosional scarps between surfaces. In the west, the scarps between the Selandian and pre-Oligocene surfaces are progressively less conspicuous, finally giving way to a regradational type transition between the two surfaces (widely spaced black lines). Bold hatching (in top right corner of the map) is for fault scarps. BF Baraque Faiture. WS Weisser Stein. Sc Schneifel

Selandian, until this surface was buried by the Early Thanetian Sea in the west. In the east, it probably remained emerged and continued to evolve and proceed inward for some time, as attested by the 55 Ma radiometric age of the Morialmé weathering profile and the presence of Upper Thanetian continental sands scattered on the Rocroi Plateau (Voisin 1981) (Fig. 5.15). At its eastern limit, east of the Meuse valley, the Selandian surface abuts the Danian one through a ~70-m-high gently sloping erosional scarp.

Then, another phase of massif uplift caused new surfaces to develop along the northern and southern sides of the Ardenne–Oesling, news scarps separating them from the inner Selandian and Danian topographies. Such a Late Eocene surface (usually called 'pre-Oligocene') formed in N Ardenne, erasing the former landscape in part of the ESEM, in the Condroz, and along the NW slopes of the Hautes Fagnes before being sealed by the sand cover abandoned by the Rupelian sea. The scarp leading to the Danian surface is up to 170-m-high near Nassogne (Fig. 5.15). Likewise, south of the massif, active denudation and scarp retreat produced another well-developed surface with elevations around 300–420 m asl in the NE Paris basin and the Gutland area, prolonging eastward in the Moselle trough. While the age of this surface, Upper Eocene to Miocene, is still debated (Baeckeroot 1942; Quesnel 2003; Demoulin 2006), its antiquity is not disputed, identifying the southern margin of the Ardenne –Oesling as a Tertiary erosional feature and disqualifying the assumption that it primarily resulted from the Plio-Quaternary differential uplift of the massif.

Finally, while the Paleogene sand covers were progressively removed from the younger surfaces, the Oligo-Miocene evolution of the massif's interior was restricted to the development of intramontane planation basins of limited extent within the Danian topography, owing to climatic conditions generally less favourable to chemical weathering and etchplanation. These basins formed preferentially on weaker bedrock, in relation with the main drainage axes of the massif, and open all to the west, where their base level corresponded to the top surface of the sand covers of the pre-Oligocene and Selandian surfaces (Fig. 5.15). Their Early Miocene age is consistently supported by the absence of Paleogene marine deposits and the evidence of a last phase of active bedrock kaolinization around 20 Ma from K–Ar and Ar–Ar dating of cryptomelanes at the base of the weathering mantle at Transinne and on the Plateau des Tailles (Bihain).

5.4 Erosion Surfaces, Tectonic Uplift, and Denudation Rates in the Ardenne–Oesling

Although paleosurface reconstruction is now often deemed superseded by developments in the thermochronological and cosmogenic nuclide approaches of long-term landscape

evolution, the recent progress in the dating of weathering products allows for sounder such reconstructions, with important implications regarding the underlying tectonic evolution of the Ardennian erosional setting and the associated denudation volumes.

Beyond local tectonics such as the HFM block uplift, broad-scale differential deformation between the originally almost horizontal surfaces of different ages suggests that every particular uplift episode of the massif during the Cenozoic did not exceed a few hundred meters with respect to the forelands. For example, the difference of tilt between the pre-Senonian and Danian surfaces in NE Ardenne indicates a ~400-m-high broad upwarping of central Ardenne in the Early Paleocene, which however never raised the massif's heart to such elevations, as surface regradation more or less kept pace with uplift. The varying tilt angle of the external facets of the acyclic surface developed over Ardenne–Oesling, systematically larger for older facets, attest that this slow doming of the massif was a background trait of its tectonic behaviour during the Mesozoic.

The change for cyclic morphogenesis during the Selandian was probably related to more focused uplift of the massif, highlighted especially in N Ardenne by the contrast between horizontal topography in the massif's interior and abruptly, though weakly, tilted surfaces close to its margins. At least in the north, probably in relation with the dawn of the Lower Rhine rift activity, subdued doming thus gave way to more en-bloc, multiphased uplift. The cumulated heights of the erosional scarps that were consequently produced between the successive surfaces amount to ~200 m from Selandian to Rupelian times, while the surfaces' deformation points to an additional few tens of meters of Neogene marginal tilt and the Plio-Quaternary component of en-bloc uplift may be estimated from river incision in the order of 150 m (see Chap. 11).

Paleosurface analysis and the dating of weathering products are also useful tools to assess the plausibility of long-term landscape evolution and denudation rates derived from thermochronology and cosmogenic nuclide data in regions of low to moderate uplift and elevation. In the Ardenne, thermochronological data are so far limited to fission track (FT), mainly on apatite (Glasmacher et al. 1998; Xu et al. 2009; Bour 2010) and led to a variety of interpretations. From the stand-alone analysis of their FT data, Xu et al. (2009) infer that slow exhumation prevailed in the Ardenne from 230 to 45 Ma, as indicated by cooling rates of 0.1–0.3 °C/Ma. Based on the usually used thermal gradient of 30 °C/km, this corresponds to denudation rates of 4–13 m/Ma. Then, from 45 Ma onwards, they model a phase of faster cooling (0.7–1.1 °C/Ma) that translates in denudation rates of 20–30 m/Ma, and suggest that an exhumation of 0.9–1.3 km would have occurred since the Middle Eocene. However, in a thermal history modelling that does not call for

a thick Upper Cretaceous cover over the Ardenne, this km-scale amount of Cenozoic exhumation is in contradiction with field data attesting the preservation of Lower Cretaceous weathering products and Upper Cretaceous sediments on the Ardennian surfaces. In order to overcome such discrepancies between field data and FT inferences, Bour (2010) introduces in the modelling of his own FT data constraints imposed by the measured ages of the weathering mantle and the timing of marine transgressions upon the massif's margins. Consequently, following a long stay from 230 to 90 Ma in the [10–50 °C] domain not resolved by FT but most probably with insignificant denudation rates, his best-fit thermal histories display a heating episode indicating that the Upper Cretaceous sea would have buried the N Ardenne under a more than 1 km-thick sediment cover, succeeded by rapid cooling during the Cenozoic, which Bour (2010) interprets as the result of tectonic inversion and massif uplift. However, though consistent with Lower Cretaceous kaolinic weathering in central Ardenne and the observed burial under Upper Cretaceous chalks along the massif's northern margin, this thermal history faces another difficulty because the Thanetian marine cover directly resting on the Paleozoic basement of the ESEM's western confines and the 55-Ma age of weathering products at Morialmé imply that this thick Cretaceous cover should have been removed very rapidly in the beginning of the Paleocene, at rates of 100–150 m/Ma. Though not impossible per se, such rates would imply comparatively high Paleogene rock uplift rates in the Ardenne, which no other evidence supports so far. Independent information about the volume of the Late Cretaceous Ardennian cover is thus required, which might perhaps be derived from estimates of the fraction of reworked Cretaceous material included in the Selandian and Thanetian sediment covers surrounding the massif. While the apparent inconsistencies between paleosurface and paleoweathering observation on one hand, FT modelling results on the other hand, might refer to the use of inappropriate T°-depth profiles in the latter, they especially stress the importance of the former data type and the need for further efforts towards dating of weathered material, sediments, and exposed surfaces in slow-evolving erosional settings, which the Ardenne massif is highly representative of.

Likewise, cosmogenic radionuclide (CRN) studies have yielded a lot of denudation estimates in uplifting massifs, and especially in the Ardenne (Schaller et al. 2002, 2004; Sougnez et al. 2011) and the Rhenish shield (Meyer et al. 2010), which, though indicative of shorter term denudation, are often compared to the long-term evolution of the massif. These estimates are obtained from measurements of cosmogenic ^{10}Be concentration in the quartz sand fraction of river bed loads, assumed to carry information on the average denudation rate in the river's catchment upstream of the sampling point. Most CRN estimates from Ardennian rivers fall in the range 20–80 mm/ky, being thus meaningful at best for the last 50 ky. However, as secular

equilibrium is assumed in the calculation of CRN denudation rates and the climatic conditions of the last 50 ky are indeed representative of those of at least the last 1 My, this suggests that a rock slice 50–200 m-thick would have been removed from the massif just during the Quaternary, a figure hardly compatible with the preservation of >30-Ma-old loose sediments and kaolinized rocks over many levelled interfluves. Moreover, Demoulin et al. (2009) showed that these rate estimates are much closer to the rates of valley incision since 0.7 Ma in the Ardenne, concluding that the CRN rate estimates in the massif are not representative of average denudation because the river bed load does not sample the extended horizontal remnants of the paleosurfaces where virtually no erosion takes place currently. Here again, the geomorphological reconstructions of paleolandscapes appear thus as a welcome counterweight to sometimes hasty conclusions derived from new techniques.

5.5 Conclusion

Praised by writers, celebrated by painters, the Ardenne's scenic landscapes have also been studied for more than a century by geoscientists. While several local names were chosen already in the nineteenth century, and are still often in use, to describe stages, especially of the Devonian System, of the international stratigraphic chart, geomorphologists studied the Ardennian relief as a well-preserved example of the long-term geomorphic features of temperate latitudes' old massifs, highlighting their typical evolution most probably under former warm, often wet, climatic conditions. Within the Ardenne, the Hautes Fagnes area, with its wild beauty, is certainly one of the best places to observe the general character of extended remnants of etchplains and unravel the complex relationships between regional tectonic deformation, continental weathering and relief development, and episodic marine transgressions leading to the present layout of variously intersecting or stepped paleosurfaces. The sections offered by the Transinne quarry and the Bihain outcrop across the deeply kaolinized bedrock of west- and north-central Ardenne are also reference places for the easy observation they allow of the thick profile produced by long-lived chemical weathering, indispensable to etchplanation. In other words, the Ardenne–Oesling is not only a world-class area for its contribution to the history of the understanding of long-term landscape evolution in temperate regions (i.e. the typical setting of the Davisian "normal" geomorphic evolution) but also a remarkable example of how the geomorphic landscape record may be as powerful a tool as the geological rock record for reconstructing the long-term history of regions where continental, tectonically stable or weakly active regimes prevailed over 10^7–10^8 yr timescales. Moreover, the recent results presented in this overview reveal new perspectives for future research and advances, especially in

the chronology of the Ardennian evolution and its meaning as a piece in the history of the large-scale foreland domain of the Alpine collision zone in Europe. Meanwhile, every rambler walking through the Ardenne plateau's wild scenery and deep forested valleys cannot keep from having a strong feeling of the grandeur and long time scale of the landscapes in which humans pass so quickly.

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