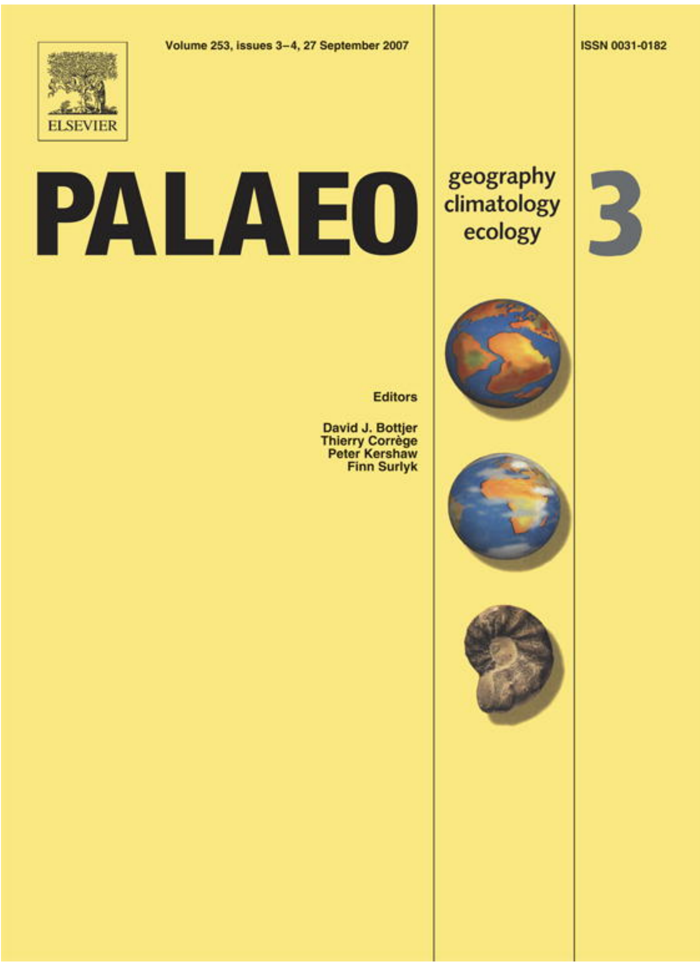
Palaeomagnetic dating of the "Bome de Fer" ferricrete (NE France): Lower Cretaceous continental weathering

Article *in* Palaeogeography Palaeoclimatology Palaeoecology · September 2007

DOI: 10.1016/j.palaeo.2007.01.010

Florence Quesnel
French Geological Survey

Robert Wyns
French Geological Survey


Volume 253, issues 3–4, 27 September 2007
ISSN 0031-0182
ELSEVIER
PALAEO
geography
climatology
ecology
3
Editors
David J. Bottjer
Thierry Corrège
Peter Kershaw
Finn Surlyk

Available online at www.sciencedirect.com
ScienceDirect
PALAEO
Palaeogeography, Palaeoclimatology, Palaeoecology 253 (2007) 271–279
www.elsevier.com/locate/palaeo

Palaeomagnetic dating of the "Borne de Fer" ferricrete (NE France): Lower Cretaceous continental weathering

H. Théveniaut *, F. Quesnel, R. Wyns, G. Hugues

BRGM, CDG, Avenue C. Guillemin, BP 6009, 45060 Orléans, France

Received 14 December 2005; received in revised form 14 January 2007; accepted 23 January 2007

Abstract

A palaeomagnetic study was carried out on the Borne de Fer ferricrete in north-eastern France, close to the Luxembourg border. This ferricrete is overlain by kaolinitic red clay and caps a silto-argilaceous saprolite 15 to 40 m thick showing weathering features, evolution of the clay minerals from the base to the top and karstic solution pipes beneath. This weathering profile lies above Jurassic marl and limestone from around 425 to 450 m a.s.l. and may correspond to a scarce remnant of an old weathering palaeosurface. Palaeomagnetic, rockmagnetic and petrographic analyses reveal presence of a dominant hydroxide contribution with a magnetic remanence carried by goethite. A small contribution of maghemite or hematite carries a more scattered but similar direction. The virtual geomagnetic pole derived from the goethite component lies at lat 73.4°N, lon. 205.9°E, dp 4.3, dm 6.2. This location close to the 120–140 Ma reference poles and presence of normal and reversed polarities are consistent with a Lower Cretaceous age close to the Long Normal Cretaceous Superchron. Our results are consistent with the ones obtained recently in Germany, Belgium and France and prepare the ground for reconstructing the Lower Cretaceous continental palaeosurface geometry and palaeogeography.

Keywords: Palaeomagnetism; Ferricrete; France; Palaeosurface; Palaeoweathering; Geomorphology

1. Introduction

Relative dating of lateritic profiles using palaeomagnetism has been proved as an efficient method. The weathering process concentrates iron oxy-hydroxides which acquire a chemical remanent magnetization during the profile formation. This method has been successfully used to date weathering events in Australia (Schmidt and Embleton, 1976; Schmidt et al., 1976; Idnurm and Senior, 1978; Idnurm and Schmidt, 1986; Schmidt and Ollier, 1988; Nott et al., 1991; Acton and Kettles, 1996), in India (Schmidt et al., 1983), or in South America (Théveniaut and Freyssinet, 1999 and 2002). In Europe, weathered formations are widespread and well known (e.g.: Demoulin, 1995; Bardossy and Combes, 1999, Migon and Lidmar-Bergström, 2001; Quesnel, 2003; Wyns et al., 2003, Thiry et al., 2006) but little is well dated. Only two palaeomagnetic studies of European lateritic rocks are reported. The first one (Wilson, 1961), which is probably the first historical palaeomagnetic study of weathering profile, focussed on the effect of lava and dyke intrusions on the magnetization of an intercalated laterite in Northern Ireland. The other one (Hus and Stiers, 1987), in Belgium, mainly concentrated on mineralogical characteristics accompanied by some palaeomagnetic tests which failed to produce reliable directions. Importance of such continental weathering events and lack or scarce precise

* Corresponding author. Tel.: +33 2 38 64 34 55; fax: +33 2 38 64 36 85.
E-mail address: h.theveniaut@brgm.fr (H. Théveniaut).

0031-0182/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.palaeo.2007.01.010

datings favour such palaeomagnetic approach on lateritic profiles in Europe and especially in north-eastern France, close to the Ardenne basement, where ages can range between the Triassic and the Neogene (Demoulin, 1995; Mees and Stoops, 1999).

In France, Belgium, Luxemburg and in north-western Germany weathering profiles cover very wide areas, occupying the entire Palaeozoic and Precambrian basement and an important part of the surrounding sedimentary basins. These palaeosurfaces are major unconformities, indeed resulting of specific climatic conditions during the Permian to the Lower Jurassic, the Lower Cretaceous, the Palaeogene and the Neogene, but on the first order of long wave vertical movements (Wyns et al., 2003).

The uplifts leading to erosion, levelling and weathering are linked to geodynamic processes of continental plates scale (Summerfield, 1988): doming and uplift of passive margins during the different phases of rifting or lithospheric buckling while plates converge. Since the end of the Jurassic, north-western Europe experienced three long periods of vertical movements (Ziegler, 1990) accompanied by the development of continental palaeosurfaces and thick weathering profiles. These uplitfts occurred during the Lower Cretaceous, from the Palaeocene till the end of the Middle Miocene and from the Late Miocene until now (Quesnel, 2003; Wyns et al., 2003).

Weathering profiles which crop out on the eastern Paris basin Jurassic cuesta and on the Palaeozoic Ardenne basement may be related to one or several of these three main weathering episodes. The lack of sedimentary cover on these often thick but sometimes truncated profiles, prevent any precise stratigraphic dating. The geomorphological study of benches, the reconstruction of the planation surfaces and the investigation of their geometric relationships allow at best expressing hypotheses about the ages of the palaeosurfaces (Désiré-Marchand, 1984) and the palaeoweatherings which mark them.

The palaeomagnetic study of the “Borne de Fer” ferricrete thus aims to provide a regional step in the understanding of the continental evolution and time constraints on palaeosurfaces and uplifts of the north-western European lithosphere.

2. Geomorphological and geologic context

The “Borne de Fer” ferricrete (lat.: 49.45°N; lon.: 5.97°E) is located in north-eastern France close to the

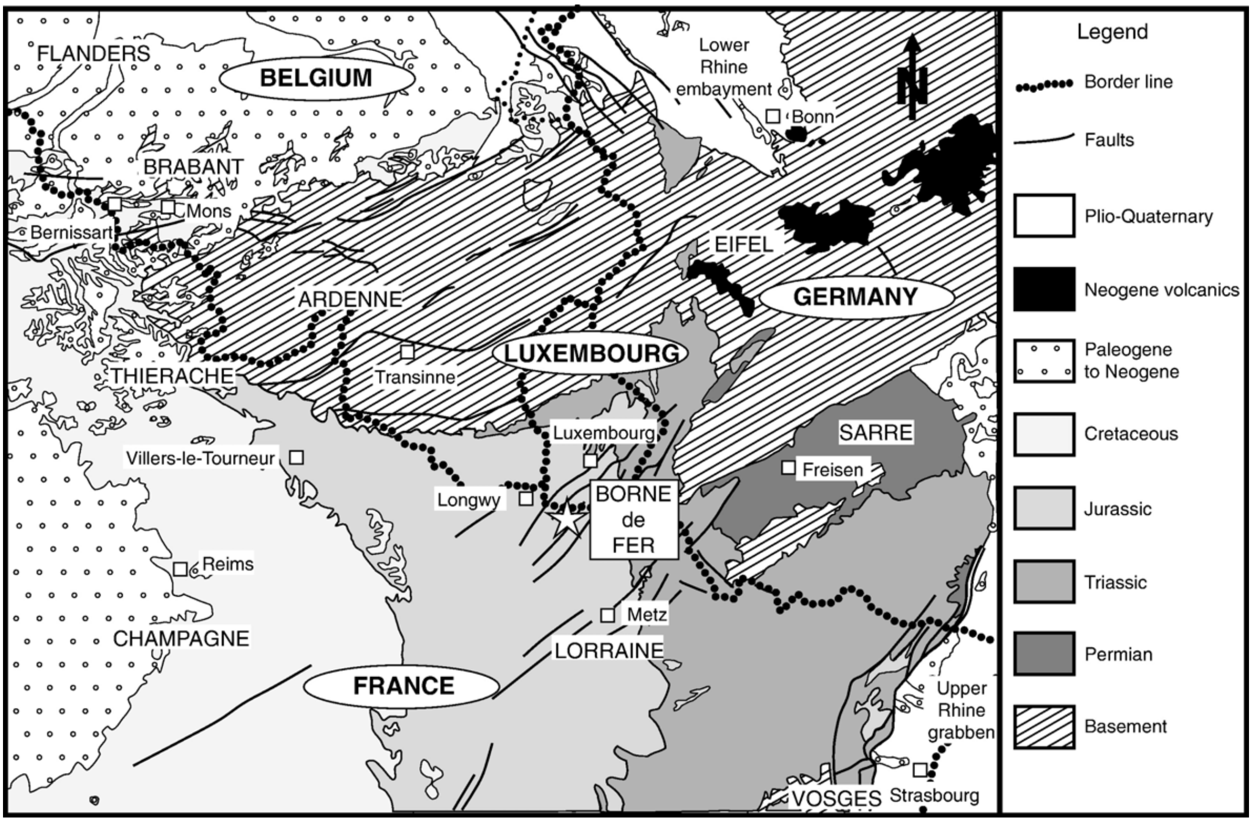


Fig. 1. Geological context of the “Borne de Fer” hill in the north-eastern Paris basin close to the Luxemburg gutter, the Ardenne-Eifel massifs and the Sarre basin.

French–Luxembourg border some 25 km ESE of Longwy (Fig. 1). This ferricrete lies on the upper part of a hill culminating at 450 m a.s.l. (Fig. 2A). It was mined as iron ore ("fer fort") during the Middle Ages and until the 19th century. Coalfaces are still accessible in the forest to allow partial or complete presence of the ferricrete profile and the lower parts of the saprolite crop out in the Ottange Quarry, 20 to 30 m lower on the same plateau, 1.5 km to the East of the "Borne de Fer" (Fig. 2A). Even though indurated, the ferricrete does not correspond to a typical lateritic iron crust. It is an indurated saprolite of highly siliceous origin, probably derived from pyrite-bearing sandstone or sandy marl. The ferricrete forms several metre-thick slabs inter-layered with ochreous saprolitic clay. Field observations and auger hole drilling survey have provided an estimation of the residual thickness of the saprolite of about 15 to 40 m, even 50 m beneath the ferricrete (Fig. 2B). Nevertheless, as shown by the auger holes and the Ottange quarry outcrop, the floor of the saprolite is highly irregular, due to karstification of the underlying limestone.

The saprolite is mainly made up of quartz sand, clay material and goethite (Fig. 2B). The clay minerals assemblage is dominated by kaolinite (95 to 100%) on the top, the kaolinite content decreasing downwards as illite/smectite grows, while the parent rock (marl) is smectitic. On top of the hill and above the ferricrete, the red clay contains numerous goethitic pisolites nodules and gravels. They probably derived from an old lateritic duricrust capping the profile. The pisolites nodules and gravels occur all along the sections and auger holes as well: they exhibit a mineralogical evolution, with an increase of the goethite content upwards (Fig. 2B), as well as the clay content shows the differenciation of the weathering profile.

The parent rock of the saprolite containing the ferricrete beds is probably a sandy, silty, pyrite-bearing marl of Late Bajocian, named "Marnes de Longwy", or the "Marnes d'Audun-le-97 Tiche" of the middle part of the Lower Bajocian, covering the Lower Bajocian limestones. These marls and limestones can be observed in large quarries, a few kilometres East of the "Borne de Fer" hill, respectively in the Ottange (Fig. 2A) and Rumelange quarries.

The hill that bears the ferricrete and the saprolite dominates of some 30 m a large plateau gently dipping, by less than a degree, to the Southwest. This plateau,

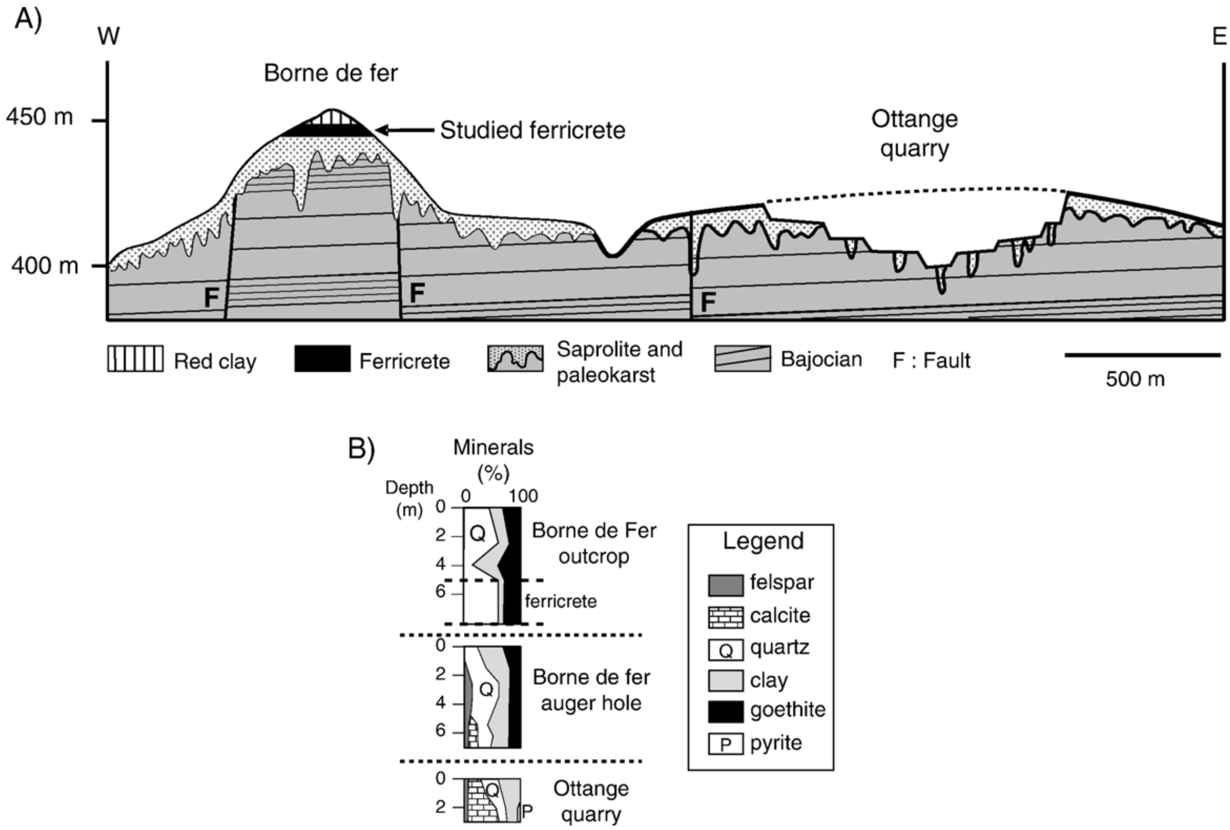


Fig. 2. (A) Geologic section across the "Borne de Fer" and Ottange quarry outcrops showing the distribution of the weathering facies (palaeokarst, saprolite, ferricrete and red clay with pisolites) formed at the expense of the Bajocian limestones and marls. (B) Composite mineralogical log obtained from XRD analyses on the Borne de Fer outcrop, from the Borne de Fer drill hole and from the Ottange Quarry.

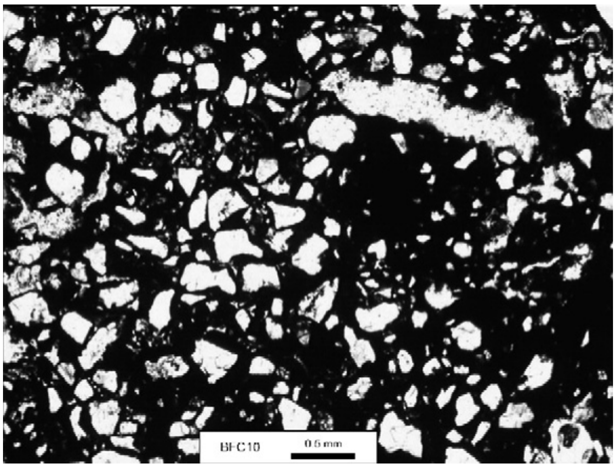


Fig. 3. Thin section of a ferricrete sample from the “Borne de Fer” hill.

made up of horizontal beds of Lower and Middle Bajocian limestones, is capped by residual saprolitic silty clay named “Limon des Plateaux” on the geological maps. It contains occurrences of residual iron hydroxides and siliceous duricrust boulders (“Pierre de Stonne”). This “Pierre de Stone” is regionally known as a silcrete capping the Eocene weathering profile (Quesnel, 2003). Thus, the residual saprolite lying on the plateau at the foot of the “Borne de Fer” can be considered as a remnant of a weathering mantle associated with an Eocene palaeosurface. In this case, the “Borne de Fer” hill could be an outlier of a higher (i.e. older) palaeosurface, possibly the Infra-Cretaceous palaeosurface, which is regionally the most probably older one.

3. Sampling and analyses

The “Borne de Fer” ferricrete was sampled on six outcropping profiles. Two of them are facing each other as inclined towards a karst “pipe” while the others are horizontal. We collected 75 minicores using a portable petrol-powered drill. Cores were taken throughout the profile at 5 to 20 cm interval and in order to possibly evaluate some magnetostratigraphic between profile correlations.

All samples were sliced to standard size (22 mm long, one inch diameter) at BRGM. Left pieces of samples were crushed to powders for susceptibility/temperature experiments. All measurements were done at the BRGM-University of Orléans joint Laboratory (Laboratoire de Magnétisme des Roches). Magnetic remanence was measured with a spinner magnetometer (JR5, AGICO, Czech Republik). Thermal demagnetization procedure was done using a Pyrox furnace. Isothermal remanent magnetization (IRM) was performed with an impulse magnetizer (IM10–30, A.S.C. Scientific, USA). Anisotropy of Magnetic Susceptibility (AMS) measurements were done using a KLY-3 Kappabridge (AGICO, Czech Republik). This tool

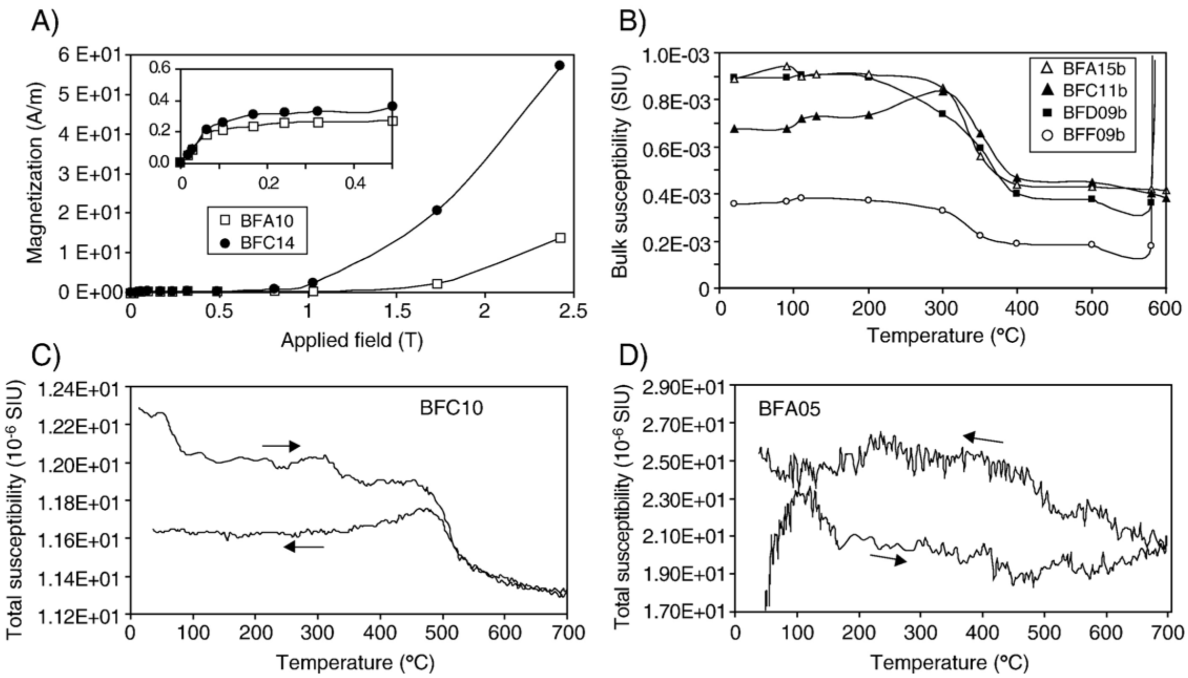


Fig. 4. Rock magnetic experiments. (A) Isothermal remanent magnetization (IRM) curves on representative specimens; (B) evolution of bulk susceptibility during thermal demagnetization of samples detailed in Fig. 5; (C) and (D) temperature variation of magnetic susceptibility for two specimens.

was also used, coupled with a CS3 apparatus (AGICO, Czech Republik) to carry out susceptibility versus temperature experiments.

Some samples of the ferricrete were studied using thin sections and optical microscopes. The latter were followed by microprobe analyses to check the nature of the oxides or oxy-hydroxides of the material. X Ray Diffractometry analyses were performed at the BRGM laboratory on bulk material (Fig. 2B), and also on the clay fraction and the pisolites of the samples collected all along the profiles.

Following demagnetization procedures, principal component analysis (Kirschvink, 1980) was used to calculate the NRM components, and mean directions were calculated using Fisher (1953) statistics.

4. Rock magnetism and mineralogical characterization

On thin sections of the “Borne de Fer” ferricrete, the quartz grains are abundant, partly rounded, their sorting is intermediate, and many of them exhibit corrosion pits, resulting from a superficial weathering (Fig. 3). They are cemented by goethite, without any diagenetic nor pedogenetic structure, confirming the macroscopic observations and our hypothesis of an epigenetic origin

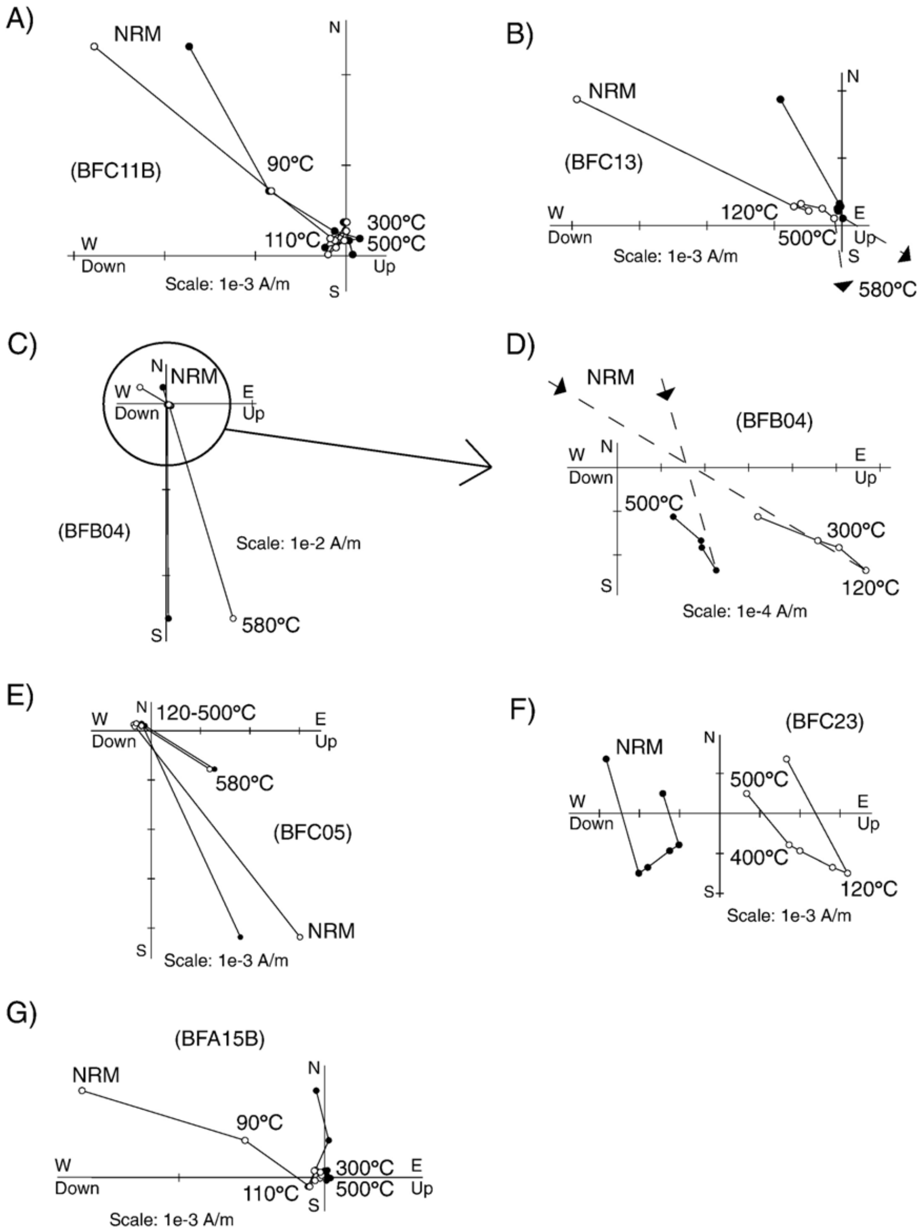


Fig. 5. Representative orthogonal projection plots for thermal demagnetization of specimens from the ferricrete. The arrow between 5C and 5D indicates enlargement of the plot of sample BFB04.

for the oxy-hydroxides induration. XRD analyses indicate (Fig. 2B) quartz, goethite and a little amount of clay. No hematite, maghemite nor pyrite was detected through this method.

In the saprolite beneath the ferricrete the only oxy-hydroxides detected is goethite, while hematite, maghemite and pyrite are absent. In the marly parent rock beneath, pyrite is present in small amount.

A few samples were used to better characterize magnetic mineral carrier by investigating the variations of magnetic susceptibility with temperature and also the acquisition of Isothermal Remanent Magnetization. IRM acquisition curves (Fig. 4A) show saturation is not reached by 2 nor 2.5 T indicating presence of high coercivity mineral. However, at low field (Fig. 4A) a low coercivity mineral is evidenced by a saturation at 0.2–0.3 T. This may correspond to a small amount of maghemite not detected through XRD. The high coercivity mineral is probably goethite as attested by the sharp drop in intensity by 100–130 °C as discussed later. Low field susceptibility measurements during thermal treatment (Fig. 4B) and also on powders (Fig. 4C, D) present similar behaviour with variations around 300–350 °C. This may be attributed to the presence and transformation of maghemite to hematite. During thermal treatment, low field susceptibility may increase above 500 °C (Fig. 4B) as a possible transformation to magnetite of iron sulfides inherited from the parent rock. On Fig. 4C, the low decrease up to 700 °C may indicate a contribution of hematite even though this could be due to transformation of maghemite or dehydratation of goethite and not of presence of a possible magnetic carrier.

In conclusion, goethite appears as the dominant magnetic carrier present in the studied rocks, however maghemite or hematite potentially contributes to the magnetization.

5. Palaeomagnetic analyses

All samples showed similar behaviour through stepwise thermal demagnetization. All treatments were stopped at a maximum of 600 °C after a strong intensity (Fig. 5B, C and E) and susceptibility increase (Fig. 4B) combined with scattering of the remanent directions. A first sharp drop (Fig. 5A to G) in intensity occurred after the first heating step (90 °C or 120 °C) where 75% of the samples lost more than 75% of their initial intensity. This was followed by a low decrease up to 300–400 °C, sometimes 500 °C where a strong increase happened due to mineral transformation. This was accompanied by a strong increase in low field susceptibility (Fig. 4B). Thermal demagnetization confirms the domination of a goethite component to the magnetization. Above 150 °C, due to the chemical transformation around 500 °C, it is not possible to ascertain the magnetic carrier of the second component which may be carried by maghemite or hematite. This is probably due to the presence of pyrite particles, not detected trough XRD, inherited from the "marnes silto-gréseuses" which are transformed into magnetite during heating.

The low temperature component is probably carried by goethite as attested by the strong decrease in intensity below 120 °C. Directions for this component were defined on two to four points between the NRM and

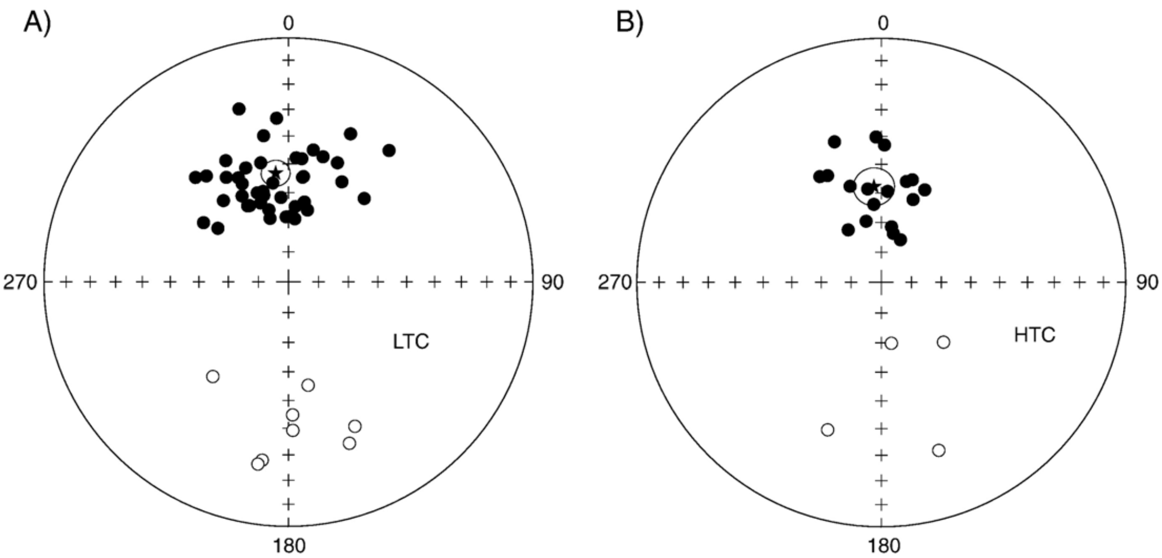


Fig. 6. Equal-area projections of: (A) the Low Temperature Component (LTC) directions of the ferricrete; (B) the High Temperature Component (HTC) directions of the ferricrete.

Table 1
Mean direction and Virtual Geomagnetic Poles (VGP) of the Low (LTC) and High Temperature Component (HTC)

Component	Samples	Declination	Inclination	*K*	a95	VGP latitude °N	VGP longitude	Dp	dm
LTC	51	353.3°	53.0°	20.2	4.5	73.4°N	205.9°E	4.3	6.2
HTC	22	355.6°	57.7°	23.4	6.6	78.5°N	205.6°E	7.1	9.7

200 °C. They were all similar giving weigh to the mean direction. Most samples were of normal polarity (Fig. 5A to D, F and G), a few others being clearly of reversed polarity (Fig. 5E).

Above 200 °C, a high temperature component, sometimes of opposite polarity (Fig. 5D and F) appears. Due to the chemical transformation which occurred above 500 °C, it was not possible to reach the complete demagnetization for this component. Directions were therefore less well defined.

There is no apparent overlapping of both components spectra as evidenced by the sharp change in direction on samples having two different polarities (Fig. 5D, E and F).

On Fig. 6, we represented the magnetic direction obtained for the low temperature component (Fig. 6A) and for the high temperature component (Fig. 6B). For the high temperature component, a few samples were rejected as their directions were away from the mean by more than 50°. Even though slightly scattered, directions are similar, with presence of both polarities. The low temperature component is better defined (Table 1) and on more samples. The strong presence of goethite attested by mineralogical and rockmagnetic experiments give weight to a LTC component carried by goethite formed during the profile weathering.

Presence of both polarities for each component demonstrates the remanent magnetization was acquired during a sufficient period to avoid any secular variation record. Both polarities sometimes found within a sample may also correspond to a diachronous ferruginization process with goethite and maghemite formed one after the other.

The two profiles which faced each other gave results which were rejected for the mean calculation. Indeed, directions were scattered from one sample to the other and from one profile to the other, independently of the bedding correction. These results are shown on Fig. 7. Data from each site lie on a great circle which crosscut the mean LTC direction. The bedding strike of site BFD is N240° with a dip of 40°NW. For site BFE, the direction is N085°–50°S. For site BDF directions, the great circle has a pole direction at N239° 21°S, while it is at N111° 11°E for site BFE directions. The polar directions of each great circle are quite similar to the bedding strike directions of the two facing profiles. It therefore looks like that each sample appeared tilted independently of varying degrees but along a same bedding direction as the one presently observed. The fact that all directions may reach the LTC direction by a tilt of different degrees around a similar bedding strike shows the inclined profiles probably acquired their magnetization at the same time the horizontal profile were formed. The progressive karst formation may have lead to progressive tilting of each part of the profiles which, in turn presently appears with all samples apparently belonging to small blocks which tilted with varying degrees around a same direction.

6. Discussion: age of the ferruginization and karst formation

All samples showed a strong contribution of goethite on the magnetization with a low and disturbed contribution of maghemite or hematite. Palaeomagnetic directions (Table 1, Fig. 6) appeared better defined for the low temperature component than for the high temperature component, both being similar. The comparison of the derived virtual geomagnetic pole (VGP)

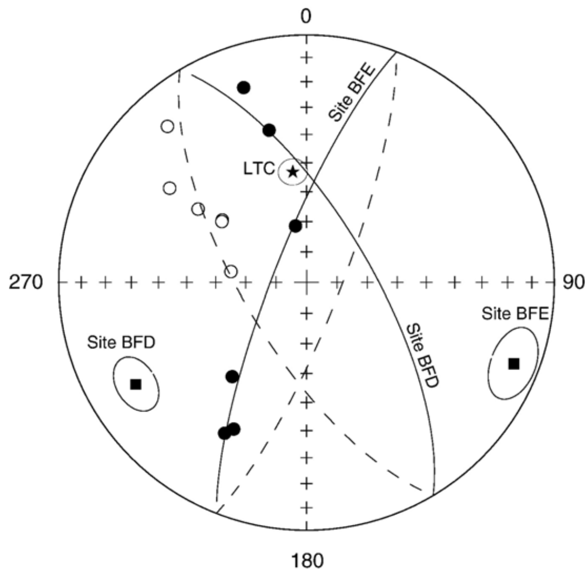


Fig. 7. Equal-area projections of the Low Temperature Component (LTC) directions of the two inclined (karst) beds with the great circles and their poles passing through these directions.

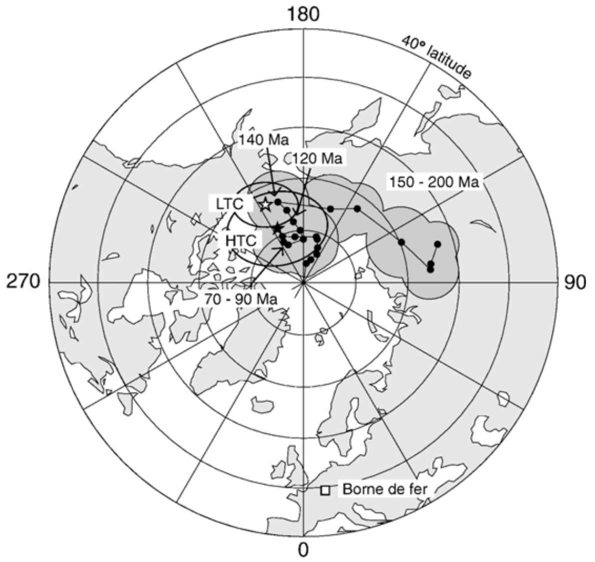


Fig. 8. Virtual geomagnetic poles (VGP) obtained from the Low (LTC) and High (MTC) Temperature Component compared to the 0–200 Ma Master European APWP of Besse and Courtillot (2003).

for both component (Table 1, Fig. 8) with the apparent polar wander path (APWP) for stable Europe (Besse and Courtillot, 2003) allows relative dating of the components. The HTC pole falls close to the 70 Ma pole with its errors around the mean intersecting nearly all the 150–30 Ma time period. Better defined, the LTC pole falls close to the 140 Ma pole with its error around the mean intersecting the APWP for the 120 to 140 Ma part. Presence of normal and reversed polarities indicates that the magnetization was acquired prior to the Long Normal Polarity Superchron (LNPS, Gradstein et al, 1995) which also coincides with an age older than 120 Ma. Goethite acquired a chemical remanent magnetization (ChRM) during a weathering process which occurred during Lower Cretaceous times. A minimum Barremian age may therefore be assigned to the formation of the "Borne de Fer" profile and the karstification underneath for which the best age estimate is 130+/−10 Ma.

This age supports the hypothesis expressed by the geometric relationship between the two palaeosurfaces in this part of Lorraine. The "Borne de Fer" hill can now be ascribed to an outlier of the Infra-Cretaceous continental surface while the wide plateau around 30 m lower corresponds to the Palaeogene palaeosurface. Moreover, this result is consistent with other data obtained in a wider area around the "Borne de Fer" (Fig. 1).

In the Sarre area (Germany), at Freisen, some Lower Cretaceous ages (ie between 120 and 142 Ma) have been obtained on different samples by the U/Th/He method on supergene goethite developed on volcanic rocks (Lippolt et al., 1998). In the Ardenne, in south-east Belgium, the kaolinitic weathering profiles of the Ardenne plateau (Dupuis et al., 1996) are not sealed and may be up to 65 m thick in the Transinne Quarry. Palaeomagnetic, radiometric (K–Ar method) and oxygen isotope ratios have been recently tested on this Quarry (Yans, 2003). They are consistent with a Lower Cretaceous weathering for the top of the profile. On the Brabant Massif, in Belgium, thick weathering profiles are older than the Late Cretaceous marine deposits which cap them (Mees and Stoops, 1999). The famous Iguanodon accumulations of the Bernissart "puits naturels" (natural solution pipes) are within black clay of Middle Barremian to basal Aptian age (Yans, 2003). Other weathering occurrences of different types have also been described South and West of the "Borne de Fer" within the Wealden gutter in the Lower Cretaceous marine and continental deposits like in Champagne and southern Lorraine where ferruginisation is recorded in the Upper Valanginian and Lower Barremian deposits (Quesnel, 2003). All these weathering profiles and palaeokarsts of north-eastern France, western Germany and Belgium now allow reconstructing the palaeogeography of the Lower Cretaceous continent (Thiry et al., 2006). The paleomagnetic, radiometric and stratigraphic dating of the alterites of Palaeozoic basement and Jurassic cover in Belgium (Brabant and Ardenne), France (North and East of the Paris basin) and Germany (Sarre) highlights the potential thickness and the northern latitudes (33.6°North for the "Borne de Fer" during the Lower Cretaceous) of the Lower Cretaceous weathering event.

7. Conclusion

Palaeomagnetic dating of the "Borne de Fer" ferricrete revealed a Lower Cretaceous age carried by neoformed goethite minerals. This relative constraint is consistent with field observations of surrounding countries mainly in Germany and Belgium. It highlights the progressive and slow uplift of the Ardenne massif, maintained under continental conditions during the Lower Cretaceous. It could indicate a stepwise phenomenon controlled by variations of the climatic/eustatic context which has been recorded during this time and is known to occur during part of the Palaeocene, of the Eocene and during almost all the Miocene and Pliocene with intercalation of marine episodes. This result confirms the complex continental history of the eastern border of the Paris Basin where new data are still needed to decipher the Mesozoic palaeogeographic evolution of Western Europe.

Acknowledgements

Ottange Quarry (Intermoselle SARL) and Audun-le-Tiche City for access authorisations very kindly given to us. This paper was written as part of BRGM-ANDRA research project Sedimor with facilities from the French Geological mapping program.

References

Acton, G.D., Kettles, W.A., 1996. Geologic and palaeomagnetic constraints on the formation of weathered profiles near Inverell, Eastern Australia. Palaeogeogr. Palaeoclimatol. Palaeoecol. 126, 211–225.

Bardossy, G., Combes, P.-J., 1999. Karst bauxites: interfingering of deposition and palaeoweathering. In: Thiry, M., Simon-Coinçon, R. (Eds.), Palaeoweathering, palaeosurfaces and related continental deposits. Spec. Publ. Intern. Ass. Sediment., vol. 27, pp. 189–206.

Besse, J., Courtillot, X., 2003. Apparent and true polar wander and the geometry of the geomagnetic field over the last 200 Myr: correction. J. Geophys. Res. 108 DOI 10.1029/2003JB002684.

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

Désiré-Marchand, J., 1984. Geomorphological map of the Grand Duché de Luxembourg 1/100 000, one sheet.

Dupuis, C., Charlet, J.-M., Dejonghe, Y., Thorez, J., 1996. Reconnaissance par carottage des paléoaltérations kaolinisées mésozoïques de la Haute Ardenne (Belgique). Le sondage de Transinne (194E-495): premiers résultats. Ann. Soc. Géol. Belg. 2, 91–109.

Fisher, R.A., 1953. Dispersion on a sphere. Proc. R. Soc, Lond. A217, 295–305.

Gradstein, F.M., Agterberg, F.P., Ogg, J.G., Hardenbol, J., Van Veen, P., Thierry, J., Huang, Z., 1995. A Triassic, Jurassic and Cretaceous time scale. Geochronology Time Scales and Global Stratigraphic Correlation. SEPM Special Publication, vol. 54, pp. 95–126.

Hus, J.J., Stiers, W., 1987. The magnetic properties of an ironcrust in SE Belgium and synthetic Mn-substituted goethites. Phys. Earth Planet. Inter. 46, 247–258.

Idnurm, M., Senior, B.R., 1978. Palaeomagnetic ages of late Cretaceous and Tertiary weathered profiles in the Eromanga Basin, Queensland. Palaeogeogr. Palaeoclimatol. Palaeoecol. 24, 263–272.

Idnurm, M., Schmidt, P.W., 1986. Palaeomagnetic dating of weathered profiles. Geol. Surv. India Mem., 120, 79–88.

Kirschvink, J.L., 1980. The least-square line and plane and the analysis of paleomagnetic data. Geophys. J. R. Astron. Soc., 139, 133–143.

Lippolt, H.J., Brander, T., Mankopf, N.R., 1998. An attempt to determine formation ages of goethites and limonites by (U+Th)-4He dating. N. Jb. Miner. Mh., Stuttgart, vol. 11, pp. 505–528.

Mees, F., Stoops, G., 1999. Palaeoweathering of Lower Palaeozoic rock of the Brabant Massif, Belgium: a mineralogical and petrological analysis. Geol. J. 34, 349–367.

Migon, P., Lidmar-Bergström, K., 2001. Weathering mantles and their significance for geomorphological evolution of central and northern Europe since the Mesozoic. Earth Sci. Rev. 56, 285–324.

Nott, J.F., Idnurm, M., Young, R.W., 1991. Sedimentology, weathering, age and geomorphological significance of Tertiary sediments on the far south coast of New South Wales. Aust. J. Earth Sci. 38, 357–373.

Quesnel, F., 2003. Paleoweathering and paleosurfaces from northern and eastern France to Belgium and Luxembourg: geometry, dating and geodynamic implications. Paleoweathering and paleosurfaces in the Ardennes-Eifel region — Preizerdaul, Luxembourg, 14–17/mai/2003. Géol. Fr., vol. 1, pp. 95–104.

Schmidt, P.W., Embleton, B.J.J., 1976. Palaeomagnetic results from sediments of the Perth Basin, Western Australia, and their bearing on the timing of regional lateritization. Palaeogeogr. Palaeoclimatol. Palaeoecol. 19, 257–273.

Schmidt, P.W., Curey, D.T., Ollier, C.D., 1976. Sub-basaltic-weathering, damsites, palaeomagnetism and the age of lateritisation. J. Geol. Soc. Aust., 23, 367–370.

Schmidt, P.W., Ollier, C.D., 1988. Palaeomagnetic dating of late Cretaceous to early Tertiary weathering in New England, N.S.W., Australia. Earth Sci. Rev. 25, 363–371.

Schmidt, P.W., Prasad, V., Ramam, P.K., 1983. Magnetic ages of some Indian laterites. Palaeogeogr. Palaeoclimatol. Palaeoecol. 44, 185–202.

Summerfield, M.A., 1988. Global tectonics and landform development. Progr. Phys. Geogr., 12, 389–404.

Théveniaut, H., Freyssinet, P., 1999. Paleomagnetism applied to lateritic profiles to assess saprolite and duricrust formation processes: the example of the Mont Baduel profile (French Guiana). Palaeogeogr. Palaeoclimatol. Palaeoecol. 148, 209–231.

Théveniaut, H., Freyssinet, P., 2002. Timing of lateritization on the Guiana Shield: synthesis of paleomagnetic results from French Guiana and Suriname. Palaeogeogr. Palaeoclimatol. Palaeoecol. 178, 91–117.

Thiry, M., Quesnel, F., Yans, J., Wyns, R., Vergari, A., Théveniaut, H., Simon-Coinçon, R., Ricordel, C., Moreau, M.-G., Giot, D., Dupuis, C., Bruxelles, L., Barbarand, J., Baele, J.-M., 2006. Continental France and Belgium during the Early Cretaceous: palaeoweathering and palaeolandscapes. Bull. Soc. Géol. Fr 177, 155–175.

Wilson, R.L., 1961. The palaeomagnetic history of a doubly-baked rock. Geophys. J. Lond 6 (3), 397–399 1962.

Wyns, R., Quesnel, F., Simon-Coïnçon, R., Guillocheau, F., Lacquement, F., 2003. Major weathering in France related to lithospheric deformation. Paleoweathering and paleosurfaces in the Ardennes-Eifel region — Preizerdaul, Luxembourg, 14–17/mai/2003. Géol. Fr., 1, pp. 79–97.

Yans, J., 2003. Chronologie des sédiments kaoliniques faciès wealdiens (Barrémien moyen Albien supérieur; Bassin de Mons) et de la saprolite polyphasée (Crétacé inférieur et Miocène inférieur) de la Haute-Lesse (Belgique). Implications géodynamiques et paléoclimatiques. PhD thesis, Faculté Polytechnique de Mons and Université de Paris-Sud Orsay, 316 p.

Ziegler, P., 1990. Geological Atlas of Western and Central Europe. Shell International Petroleum Maatschappij, Den Haag.