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1	Environmental and climatic controls of the clay mineralogy of Albian deposits in
2	the Paris and Vocontian basins (France)
3	Pauline CORENTIN ¹ , Jean-François DECONINCK ¹ Pierre PELLENARD ¹ ,
4	Francis AMÉDRO (^{1,2}), Ludovic BRUNEAU ¹ , Elise CHENOT (^{1,3}), Bertrand
5	MATRION (^{1,4}), Emilia HURET ⁵ and Philippe LANDREIN ⁵
6	(1) Université de Bourgogne-Franche-Comté, UMR 6282, CNRS, Biogéosciences, 6
7	boulevard Gabriel, 21000 Dijon, France. E-mail: pauline.corentin@u-bourgogne.fr
8	(2) 26 rue de Nottingham, 62100 Calais, France.
9	(3) Université de Lorraine, UMR 7359 CNRS Géoressources, 54506 Vandœuvre-lès-
10	Nancy Cedex, France
11	(4) 1 ter rue du Pont, 10450 Bréviandes, France.
12	(5) Agence Nationale pour la gestion des déchets radioactifs, Centre de Meuse/Haute-
13	Marne, RD 960, 55290 Bure, France.
14	
15	Abstract
16	High-resolution clay mineral analyses were performed on lower and middle Albian
17	deposits from the Paris and Vocontian basins in order to specify the weathering conditions
18	that prevailed at that time. The clay mineral assemblages are composed of small proportions
19	of chlorite and vermiculitic clays associated with abundant illite, R0 type illite-smectite

mixed-layers (smectite) and kaolinite. Clay minerals originated from the physical alteration
and chemical weathering of rocks and soils outcropping on the Variscan massifs bordering the
studied areas. In the Paris Basin, the covariation of illite and kaolinite suggests the reworking
of these latter minerals from palaeoalterations and saprolites coupled with an intense runoff
on the London-Brabant Massif under a warm-temperate climate.

In comparison with the Paris Basin, the lower Albian series deposited in the Vocontian 25 Basin are enriched in smectite because of the preferential deposition of this mineral in deep 26 offshore environments. In this basin, illite and kaolinite did not show any covariation 27 28 suggesting that kaolinite is rather the chemical weathering product of rocks exposed in the French Massif Central. The stratigraphic distribution of clay minerals in both studied areas is 29 consistent with a cooler and dryer climate around the Aptian/Albian transition. An enhanced 30 precipitation rate is suggested by an increasing proportion of kaolinite from the 31 Douvilleiceras mammillatum Zone upward. This humid interval ended in the Anahoplites 32 intermedius Zone contemporaneous with the smectite-rich sedimentation in the Paris Basin 33 34 revealing semi-arid conditions consistent with palynological data. This semi-arid interval encompassing the *Dimorphoplites niobe* and *D. biplicatus* zones (and possibly the *Dipoloceras cristatum* Zone) is interrupted at the base of the *Mortoniceras pricei* Zone by a
return to a more humid climate.

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Keywords: Clay minerals, Albian, Paris Basin, Vocontian Basin, Palaeoclimate

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41 **1. Introduction**

Most often, the reconstruction of Cretaceous climates is based on an estimate of the 42 ocean surface or deep water temperatures from a variety of proxies including δ^{18} O, TEX₈₆ and 43 more recently Δ_{47} (Friedrich et al., 2012, O'Brien et al., 2017; Meyer et al., 2018). The global 44 climate evolution during the Albian is well known in terms of temperatures inferred from 45 numerous δ^{18} O data measured on foraminifera and belemnite guards (Friedrich et al., 2012). 46 47 After the late Aptian 'coldhouse' climate (Herrle and Mutterlose, 2003; Pirrie et al., 2004; Bodin et al., 2015; Rodríguez-López et al., 2016), the Albian stage is characterized by a 48 49 regular increase in temperature from the base to the top. This trend continued until the Cretaceous thermal maximum that occurred around the Cenomanian/Turonian boundary 50 51 (O'Brien et al., 2017; Huber et al., 2018).

The estimation of the fluctuations in the hydrological cycle and the intensity of the 52 precipitation during the Albian is discussed much less often (Föllmi, 2012), even though this 53 54 stratigraphic interval corresponds to dramatic changes in the Earth's history. Albian environments are notably characterized by a radiation of angiosperms and their development 55 in floodplain areas and by the emergence of a narrow humid equatorial climatic belt in 56 comparison with the earlier stages of the Early Cretaceous during which the equatorial humid 57 belt was absent (Chumakov et al., 1995; Poulsen et al., 2001; Chaboureau et al., 2014). A 58 59 warm and humid belt around the equator is deduced from the common occurrence of bauxite and coal during the Albian (Chumakov et al., 1995). This re-organization of the climatic belts 60 is likely a consequence of the widening of the South and North Atlantic Oceans which thereby 61 introduced a source of moisture (Chaboureau et al., 2014). Therefore, it appears that the 62 Albian was a pivotal period from a climatic point of view that may have had consequences on 63 64 the hydrological cycle.

In the Anglo-Paris Basin, Albian seawater temperatures were estimated using δ^{18} O analysis of the belemnite guards and fish teeth from the Wissant section outcropping in the Boulonnais area (northwest of the Paris Basin, Bomou et al., 2016, Fig. 1). The measured

temperatures on the belemnite guards (bottom waters) range from 13.5 to 19.3°C with an 68 increase from the middle to late Albian. The δ^{18} O values for the phosphate in the fish teeth 69 indicate temperatures (from intermediate or sea surface waters) that varied between 22° and 70 28°C with a similar trend. Increasing temperatures during the Albian are consistent with the 71 long-term global warming recorded from the Albian to the Cenomanian using either $\delta^{18}O$ 72 73 measured in the foraminiferal test or the TEX₈₆ proxy (Friedrich et al., 2012; O'Brien et al., 74 2017; Kanungo et al., 2018). However, although moisture is a key palaeoclimate parameter, 75 the changes in humidity and weathering conditions that occurred during the Albian are much 76 less documented (Ufnar et al., 2002; Herrle et al., 2003b; Horikx et al., 2017). Our objective is therefore to improve knowledge on humidity/aridity conditions prevailing during the Albian 77 using clay mineral assemblages from sediments deposited in two distinct provinces: the Paris 78 79 basin (Boreal Province) and the Vocontian basins (Tethyan Province).

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2. Geological context

During the Albian, the Anglo-Paris Basin was an epicontinental sea connecting the 82 Boreal domain to the north-west and the Tethyan domain to the south-east. It was located at a 83 latitude close to 35°N within a mid-latitude warm humid belt (Fig. 1, Boucot et al., 2013; 84 Amédro and Matrion, 2014; Gély et al., 2014). The Albian deposits from the type locality 85 (stratotype, department of Aube, south-east of the Paris Basin) were only known by temporary 86 outcrops or quarries where only a few metres of the sedimentary succession can be observed 87 88 (Amédro, 1992; Amédro and Matrion, 2007; 2008, 2014). Consequently, a complete continuous succession could not be established in this part of the Paris Basin. Recently, 89 90 boreholes were drilled by ANDRA (French agency for nuclear waste disposal) in the department of Aube, allowing the whole lower to middle Albian clayey succession to be 91 92 examined. The sedimentary series belongs to the so-called 'Argiles tégulines de Courcelles' 93 unit which overlies the Aptian and lowermost Albian greensands, the so-called 'Sables Verts 94 de l'Aube'. In one of the boreholes, the succession encompasses the lowermost part of the 95 overlying 'Marnes de Brienne' of late Albian age.

The Paris Basin was bordered to the south-west by the Armorican Massif and the French Massif Central, and to the north-east by the London-Brabant Massif (Fig. 1, Amédro and Matrion, 2014; Amédro and Robaszynski, 2014). At that time, north-west Europe was made up of large islands inherited from the Variscan orogeny. Although clay minerals are likely to be deposited very far from their detrital source, the French Massif Central and the London-Brabant Massif were probably the main sources of detrital clay mineral since coeval detrital sandy deposits of the Paris Basin originated from these massifs (Amédro and
Robaszynski 2014). These massifs were located at slightly different latitudes and are made up
of distinct parent rocks, therefore, significant differences in the composition of clay
assemblages can be expected.

The Vocontian Basin was located on the northern margin of the Tethys Ocean, around 106 30°N at a somewhat lower palaeoaltitude and closer to the semi-arid belt than the Paris Basin 107 (Chumakov et al., 1995, Hay and Floegel, 2012; Fig. 1). This basin was surrounded by 108 shallow platforms except to the east where it was largely opened to the Tethys Ocean (Fig. 1). 109 110 Lower to middle Albian deposits (Blue Marls Formation) are well-exposed in several sections (Bréhéret, 1997; Gale et al., 2011). The Col de Pré-Guittard section was chosen for this study 111 112 considering its location in the western part of the Vocontian Basin, far from thermal influences that would transform detrital clay minerals. This reference section is also clearly 113 114 defined with biostratigraphy (Kennedy et al., 2000, 2014; Petrizzo et al., 2012), and was approved recently as the Albian Global Boundary Stratotype Section and Point (GSSP) 115 116 (Kennedy et al., 2017).

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3. Lithology and biostratigraphy

119 3.1. Boreholes from the Paris Basin

Two boreholes (AUB111 and AUB220) located close to Juzanvigny, and one borehole drilled close to Vallentigny (AUB240) were studied (Fig. 2). Samples were taken every meter in the borehole AUB240 and every 50 centimeters in the boreholes AUB111 and AUB220.

The distance between boreholes AUB111 and AUB220 is only 1 km. One of the cores 123 (AUB111, Fig. 3) has been described in detail including a precise biostratigraphic scheme on 124 the basis of the abundant ammonite fauna (Amédro et al., 2017) following the ammonite 125 biozonation proposed by Amédro and Matrion (2014). Lower to middle Albian deposits 126 (Argiles tégulines de Courcelles) essentially consist of bioturbated clays and silty clays with 127 occasional pyrite and phosphate nodules (Knight 1999). Phosphate nodules are either 128 129 scattered or in the form of thin horizons that may be correlated at a regional scale. The base of the unit is more or less sandy, with increasingly more abundant glauconite further down the 130 core, until the boundary with the Aptian greensands (Sables Verts de l'Aube Formation). 131 Borehole AUB 220 shows a sedimentary succession quite similar to that described in borehole 132 AUB111, but it can be used to provide more descriptions further upward in the series (Figs. 4 133 and 5; Supplementary Appendix). In addition, the recovery across the boundary between the 134 135 Sables Verts de l'Aube and the Argiles tégulines de Courcelles is better than in the AUB111

borehole. Notably, a condensed horizon composed of a 10 cm-thick phosphatic crust 136 corresponding to a hardground is particularly well preserved in this borehole (Fig. 5). The age 137 of the deposits recovered in the lower part of the two boreholes is not well established. In this 138 part of the Paris Basin, the Sables Verts de l'Aube unit is considered to be Aptian in age 139 (Amédro and Matrion 2007) because of the occurrence of the benthic foraminifera 140 Verneuilinoides subfiliformis which suggests that the Sables verts de l'Aube belong to the 141 Hypacanthoplites jacobi Zone from the upper Aptian (Damotte & Magniez-Jannin, 1973; 142 143 Mutterlose et al., 2003).

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The phosphatic crust corresponds to a condensed interval that, according to previous 145 146 studies on outcrops located in the same region, likely includes the Leymeriella tardefurcata and Leymeriella regularis ammonite zones (Amédro and Matrion 2007, 2014). At the base of 147 148 the two boreholes, the 5 m-thick interval between the phosphatic crust and the first occurrence of *D. mammillatum* is not well dated as only *Beudanticeras* sp. have been found. This interval 149 150 probably successively corresponds to the Sonneratia kitchini, Cleoniceras floridum and Hemisonneratia puzosiana zones compared with the sections outcropping to the south-east of 151 152 the Paris Basin (Destombes in Rat et al., 1979; Amédro et al., 2000; Amédro and Matrion, 153 2008). Above this poorly dated interval, the borehole is precisely dated by numerous ammonites which can be used to draw an accurate biostratigraphic scheme (Figs. 3-5). The 154 two boreholes can be easily correlated in particular by using marker beds that include 155 horizons of phosphate nodules and bio-events (Amédro et al., 2019). 156

The change from the Aptian greensands, deposited in shoreface, estuarine or fluviodeltaic environments (Guillocheau et al., 2000), to the Argiles tégulines de Courcelles deposited in offshore environments clearly indicates a deepening of the depositional environments as a consequence of the early Albian transgression from the south-west through the Burgundy high (Pictet et al., 2018). This transgressive trend is also expressed by the occurrence of cosmopolitan ammonites indicating the opening of the Burgundy threshold (Fig. 1).

The third borehole, AUB240 (Fig. 2), shows a similar lithological succession but the upper part of the borehole has permitted the recovery of the topmost part of the Argiles tégulines de Courcelles and the lowermost part of the Marnes de Brienne (Fig. 7). The recognition of marker beds between the three boreholes allows precise correlations to be drawn (Amédro et al., 2019). In the upper part of this borehole, all ammonite zones were recognized except the *Dipoloceras cristatum* Zone which is condensed and corresponds to the
occurrence of a phosphate nodule bed (Amédro et al., 2019).

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3.2. The Col de Pré-Guittard section (Vocontian Basin)

The Col de Pré-Guittard section (Fig. 8) shows the lower to middle Albian 173 sedimentary succession, which is part of the Blue Marls Formation. It mainly consists of 174 hemipelagic blue-grey marls punctuated by several marker beds and bundles of micritic 175 limestones used as marker horizons to refine the correlations throughout the basin (Friès, 176 177 1987; Bréhéret, 1997). Organic matter-rich layers (black shales) are also common, the most prominent of these being the Paquier horizon corresponding to the sedimentary expression of 178 179 Oceanic Anoxic Event (OAE) 1b (Bréhéret, 1985 a and b; Tribovillard and Gorin, 1991; Hart et al., 1996; Erbacher et al., 1999; Herrle et al., 2003b). The section has been measured from 180 181 the Aptian/Albian transition (Kilian bundle) to the lowermost middle Albian. Samples were taken every metre. 182

183 Because different ammonite biozonations (Boreal vs Tethyan) are used in sections from the Paris Basin and the Vocontian Basin, correlations are difficult, however a comparison 184 185 between the ammonite biozones used in both study areas is given in Table 1. Notably, the D. mammillatum Zone used in the Vocontian Basin includes the S. kitchini, C. floridum, H. 186 puzosiana, Otohoplites subhilli and Hoplites (Isohoplites) steinmanni zones. During the 187 Albian, the Paris Basin belonged to the Northern European Faunal Province of the Boreal 188 Domain, characterized by the presence of rich populations of Hoplitidae that followed each 189 other (including genera Sonneratia, Hemisonneratia, Otohoplites, Hoplites, Anahoplites, and 190 Dimorphoplites), allowing the definition of many biozones. The Vocontian Basin, located on 191 the northern margin of the Tethyan Domain, contains more occasional and less diversified 192 faunas at the top of the lower Albian and in the middle Albian (Douvilleiceras, then 193 Lyelliceras and Oxytropidoceras). At the top of the lower Albian, the correlation between the 194 two basins is based on the vertical distribution of the species Douvilleiceras mammillatum 195 196 which appears just above the L. regularis Zone and disappears at the top of the Lyelliceras lyelli Zone (or Subzone). In the middle Albian, Oxytropidoceras roissyanum is known at Col 197 de Palluel at the top of this Substage (Gale et al., 2011), but here, the absence of ammonite in 198 the lower levels does not allow to recognise the total vertical distribution of this species. The 199 appearance of O. roissyanum is however well documented both in northern France (Amédro, 200 2009) and Kent in south-east England (Young et al., 2010), from the Hoplites dentatus Zone. 201 202 Therefore, the O. roissyanum Total Range Zone used in this paper comprises successively the

Hoplites dentatus, Anahoplites intermedius, Dimorphoplites niobe and D. biplicatus zones in
the Anglo-Paris Basin.

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- **4. Methods**
- 207 4.1. Mineralogy

A total of 400 samples were analysed using X-Ray Diffraction (XRD). After moderate 208 209 grinding in a mortar, powdered samples were decarbonated with a 0.2N HCl solution. The $< 2 \,\mu m$ fraction (clay-sized particles) was extracted with a syringe after decantation of the 210 211 suspension for 95 minutes following Stokes' law; this fraction was then centrifuged. Clay 212 residue was then smeared on oriented glass slides and run in a Bruker D4 Endeavour 213 diffractometer with CuKa radiations, a LynxEye detector and a Ni filter with a voltage of 40 kV voltage and an intensity of 25 mA (Biogéosciences laboratory, University of Burgundy, 214 France). Goniometer scanning ranged from 2.5° to 28° for each analysis. Three runs were 215 216 performed for each sample to discriminate the clay phases: 1) air-drying; 2) ethylene-glycol solvation; and 3) heating at 490°C, as recommended by Moore and Reynolds (1997) (Fig. 9). 217 Clay minerals were identified using their main diffraction (d_{001}) peak and by comparing the 218 three diffractograms obtained. The following main clay minerals were identified (Fig. 9) : a 219 R0 type illite-smectite mixed-layer (17 Å based on a glycolated run condition) referred to as 220 smectite for the following sections; a R1 type illite-smectite mixed-layer (around 11.5 Å in 221 air-drying conditions and 13 Å after ethylene-glycol solvation); chlorite (14.2 Å, 7.1 Å, 4.7 Å 222 and 3.54 Å peaks); illite (10 Å, 5 Å, 3.33 Å peaks); kaolinite (7.18 Å and 3.58 Å peaks) and 223 vermiculitic clays including true vermiculite (14 Å in air-drying conditions, 14.5-15 Å after 224 ethylene-glycol solvation and 10 Å peaks after heating) and chlorite-vermiculite mixed-layers. 225 The relative proportions of clay minerals are estimated using peak intensity ratios, the most 226 relevant of these being the ratio between the 7.18 Å and 17 Å peaks corresponding to 227 kaolinite + chlorite/smectite (K+C/S). The error of this method is approximatively ± 5 %. 228 This ratio can be taken as an estimate of the humidity vs aridity. 229

Fifteen samples have been measured for CaCO₃ content on the AUB 111 borehole with a Bernard's calcimeter device (uncertainty of ~1%). No measurement were done in the Vocontian Basin as Bréhéret, (1997), previously performed it. We only compared the GRS signal that we measured on the field with the CaCO₃ content given by Bréhéret (1997).

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4.2 Spectral gamma ray (SGR)

SGR measurements were taken on the Col de Pré-Guittard section every 50 cm at the 236 237 same position as for the samples collected for XRD. Field SGR measurements were taken with a constant 1-min acquisition time using a Geofyzica-Statis-Geo GS-512 spectrometer 238 with a Cesium 137 scintillation detector. For all readings, the detector was placed against 239 outcrop surfaces that had been cleaned of weathered material and smoothed. A scintillometer 240 arrangement was used to produce an energy spectrum for the natural gamma rays emitted 241 from an outcrop. This spectrum was interpreted electronically to yield concentrations of the 242 principal gamma ray sources involved, namely potassium (K), thorium (Th) and uranium (U). 243 244 K and Th are usually concentrated in clay minerals whereas U is associated with organic matter (Myers and Wignall, 1987). SGR values are given in ppm (eq. U). Measurement 245 246 reproducibility is assessed at 5% (1 σ) by repeating the same measurement 30 times (Martinez et al. 2013). The spectral gamma ray is an effective tool for the preliminary assessment of the 247 248 degrees of palaeoweathering (clay content) and is therefore commonly used for palaeoclimate reconstructions (Ruffell et al., 2016). 249

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5. Results

252 5.1. Paris Basin

In the Argiles tégulines de Courcelles unit, the CaCO₃ proportions are between 10%and 15% except in some marly limestones where the CaCO₃ content reaches 40%. Smear slides performed on some clayey samples show abundant nannofossils which are likely responsible for the CaCO₃ content. Consequently, clay minerals represent a significant amount of the deposits.

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259 Clay mineralogy

The clay mineral assemblages of the AUB111 borehole are mainly composed of illite 260 (28% on average), vermiculitic clays (10% on average), smectite (22% on average) and 261 kaolinite (26% on average). They also contain chlorite (\leq 5%), R1 type illite-smectite mixed-262 263 layers and chlorite-vermiculite mixed-layers, which are both estimated to be 5% or less (Fig. 3). The composition of the mineralogical assemblages along the borehole allows to 264 distinguish three different intervals. At the base of the borehole, from 69.10 to 63.96 m, the 265 first poorly-dated interval is characterized by abundant smectite (up to 70%), illite, and very 266 low proportions of kaolinite. Some illite-rich samples occur in the glauconitic interval, close 267 to the transition with the greensands. The presence of glauconite in the deposits is confirmed 268 by the observation of smear slides. Above, the second interval is marked from 63.96 to 13.35 269

m by increasing proportions of kaolinite and illite together with vermiculitic clays in significant proportions (up to 15%), while the smectite proportion decreases. In this interval, the proportions of illite generally range between 20 and 30%, with occasionally more abundant proportions reaching 40% (Fig. 3). The disappearance of vermiculitic clays and the higher proportions of smectite (\sim 40%) characterize the third interval, above 13.35 m while the percentages of kaolinite and illite decrease. The transition from the second to the third interval occurs around the transition from the *A. intermedius* to *D. niobe* ammonite zones.

The clay mineralogy of the AUB220 borehole is quite similar to that described in AUB111 indicating that the clay mineralogy of the Argiles Tégulines de Courcelles is, as expected, homogeneous at a kilometer scale (Figs. 4 and 5). The increase in smectites content in the third interval is better expressed, since this borehole includes an upper part of the Argiles tégulines de Courcelles (Figs. 4 and 5).

In the upper part of borehole AUB240, a fourth interval is observed from 8.75 to 27.3 m marked by a decrease in smectite while increasing proportions of illite, vermiculitic clays and kaolinite are observed in the *pricei* Zone (Fig. 7). Therefore, within the Argiles tégulines de Courcelles, the *D. niobe/D. biplicatus* time-equivalent interval is characterized by a smectite-rich sedimentation compared to the rest of the formation. This evolution in the clay assemblages confirms the low-resolution clay mineral data published by Fauconnier (1975) and Pomerol (1986).

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5.2. Vocontian Basin

The clay mineral assemblages of the Col de Pré-Guittard section are mainly composed 291 of smectite (63% on average), illite (19% on average) and kaolinite (11% on average). They 292 also contain about 5% of chlorite (Fig. 10). Traces of R1 type illite-smectite mixed-layers and 293 294 chlorite-vermiculite mixed-layers may be present ($\leq 2\%$) in some samples and although they were taken into account in the calculation, they are not represented in Figure 10. The clay 295 composition is marked by a gradual smectite decrease from 70% from the base to 60% at the 296 297 top of the section. This decrease corresponds to a clear increase in kaolinite with values in the order of 5% down section to values greater than 15% above. Interestingly, as in the Paris 298 Basin, sedimentary rocks located around the Aptian/Albian boundary are depleted in 299 kaolinite. The proportion of kaolinite increases during the *L. tardefurcata* ammonite Zone but 300 remains generally below 10%, while in the D. mammillatum Zone, the proportions of 301 kaolinite are higher than 10%. 302

According to Bréhéret (1997), the CaCO₃ content is approximately 20% at the base of the section and increases to approximately 40% at the top, which is consistent with our SGR measurements that show a reverse long-term trend with decreasing values from the base to the top of the section (Fig. 10). This expected inverse relationship between the SGR measurements and the CaCO₃ content was already observed in the Aptian part of the Blue Marls Formation (Ghirardi et al., 2014).

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310 **6. Discussion**

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6.1. Influence of burial diagenesis

Burial diagenesis may transform clay mineral assemblages leading to a misreading of the original paleoclimatic and paleoenvironmental signal. Before examining the environmental significance of the clay minerals, it is important to ensure that they are dominantly detrital without any significant influence of burial diagenesis.

In the Paris Basin, the post-Albian geological history includes the deposition of the 316 317 Upper Cretaceous chalk, the maximum thickness of which probably never exceeded 1000 m. At least 700 m of the Cenomanian to lower Campanian chalk was preserved in the depocentre 318 319 of the Paris Basin (Robaszynski et al., 2005) but the total thickness was greater since the 320 upper Campanian to Maastrichtian chalks have been dissolved (the Maastrichtian chalk is known as reworked pebbles) and eroded during the latest Cretaceous. Consequently, the 321 Upper Cretaceous chalk is separated from the Cenozoic deposits by a major unconformity 322 323 truncating Late Cretaceous folds (Guillocheau et al., 2000). In the eastern part of the Paris Basin, the chalk series was probably thinner but this was difficult to evaluate. Detailed 324 reconstructions of the thermal evolution of the eastern part of the Paris Basin indicate that 325 even in the Late Jurassic, the maximum burial temperature reached by the end of the 326 Cretaceous never exceeded 50-60°C (Pellenard et al., 1999; Blaise et al., 2014; Mangenot et 327 al., 2018). Consequently, in the overlying Albian deposits, the temperature remained low; this 328 is confirmed by the abundance of smectite, as these minerals are known to be particularly 329 330 sensitive to burial diagenesis and are transformed into R1 illite-smectite mixed-layers and illite through illitization processes at temperatures over 60-70°C (Merriman and Frey, 1999; 331 Lanson et al., 2009; Środoń et al., 2009; Dellisanti et al., 2010). As a result, the abundance of 332 smectite from the lowermost part of the studied boreholes indicates that the temperatures 333 never exceeded 60-70°C and that the clay minerals are mostly primary and detrital in origin. 334

In the Vocontian Basin, for the same reasons, the abundance of smectite indicates a negligible influence of burial diagenesis on the clay mineralogy. Numerous studies have shown that in the western part of the Vocontian Basin, the influence of diagenesis on clay minerals from Lower Cretaceous formations is weak (Deconinck and Chamley, 1983; Ferry et al., 1983; Deconinck and Debrabant, 1985, Levert and Ferry, 1988). In the Col de Pré-Guittard section, Rock-Eval analyses performed on organic matter-rich horizons show that T_{max} values are comprised between 417 and 437°C indicating that organic matter is immature or at the onset of the oil window, thereby confirming that the influence of thermal diagenesis remained weak on this section (Bréhéret, 1997).

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6.2. Authigenic clay minerals

Detrital clay assemblages may be modified by the authigenesis of clay minerals 346 347 formed either during early or late successive diagenetic steps. Authigenic glauconite (ironrich illite) is common in Albian deposits notably at the transition between the greensands and 348 349 the Argiles tégulines de Courcelles that is at the base of the boreholes studied in the Paris Basin. Although glauconite granules are much coarser than the clay fraction, after grinding 350 351 the samples, glauconitic illite is inevitably partly incorporated in the clay fraction and could be responsible for some abnormally high proportions of illite thus corresponding to a mixture 352 353 of detrital and authigenic minerals (Fig. 3). This likely occurs at the base of the boreholes at 354 the transition between the Sables verts de l'Aube and the Argiles tégulines de Courcelles.

A detailed study of clay minerals from similar Albian deposits (Gault clay) from the 355 Wissant section in the Boulonnais area (Northwest of the Paris basin) shows that the clay 356 fraction includes two types of smectites corresponding to beidellite (dioctahedral Al-Fe 357 smectite). The first type, showing a fleecy shape under transmission electron microscope 358 (TEM), is considered to be detrital, while the second displays a lathed shape due to the 359 development of crystalline overgrowths indicating authigenesis (Holtzapffel, 1985; Steinberg 360 et al., 1987). It is hypothesized that crystalline overgrowths are the result of an early 361 diagenetic recrystallization of detrital smectites and may represent an early stage of 362 glauconitization. Lath-shaped smectites are widespread in Meso-Cenozoic deposits 363 364 (Holtzapffel et al., 1985; Deconinck and Chamley, 1995) and result from dissolution/recrystallization processes in relatively closed environments (Clauer et al., 1990). 365 However, the development of this type of authigenic minerals does not seem to significantly 366 modify the composition of the detrital clay fractions. 367

In both studied areas, we therefore consider that the clay minerals are mainly detrital and originated from the erosion of nearby emerged lands, knowing that 1) glauconitic illite may be associated with detrital illite, notably in the Paris Basin at the transition between the 371 Sables Verts de l'Aube and the Argiles tégulines de Courcelles and 2) authigenic smectite
372 may have marginally enhanced the total proportion of smectites in specific closed
373 environments.

- 374
- 6.3 Origin of clay minerals
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Although clay particles may be transported over long distances (Chamley, 1989), 377 during the Albian, a large part of the clay minerals potentially originated from the landmasses 378 379 composed of the French Massif Central and the Armorican massifs, and from the London-380 Brabant Massif which were the main emerged lands around the studied areas (Fig. 1). Clay 381 minerals were likely transported to the sea mainly by rivers and then deposited by decantation relatively far from the shoreline. In the Paris basin, the erosion of the two massifs probably 382 383 fed the sedimentation, whereas the clays from the Vocontian Basin had to come from the basement and the sedimentary cover of the French Massif Central and other emerged lands 384 385 located to the south (Corso-Sarde microcontinent?, Fig. 1).

The lithology of the London-Brabant Massif and the French Massif Central is 386 387 different. These massifs are both inherited from the Variscan orogeny, but magmatic and high-grade metamorphic rocks (granitoids, migmatites, and gneiss) are predominant in the 388 French Massif Central, whereas low-grade metamorphic and sedimentary rocks dominated in 389 the London-Brabant Massif (schists, slates, limestones and shales; Fielitz and Mansy, 1999; 390 Han et al., 2000). Therefore, a different nature can be expected from the contributions of clay 391 minerals originating from these two massifs. In addition, they were not located at the same 392 latitudes, and according to the estimated precipitation rates during the 'Mid-Cretaceous' 393 (Ufnar et al., 2002; 2004), the French Massif Central was located between 25 and 30°N close 394 to an arid to semi-arid climatic belt extending southward toward Portugal and West Africa 395 (Fenner, 2001; Heimhofer et al., 2008), while the London-Brabant Massif was located 396 between 30 and 35°N in a more humid tropical belt. 397

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- 400 6.3.1. Primary clay minerals

Primary clay minerals, i.e. chlorite and illite, are mainly formed through weathering
processes of metamorphic and igneous rocks yet these minerals can be also reworked from a
sedimentary basement (Chamley, 1989; Weaver 1989). In Albian deposits, chlorite never
exceeds 5% of the clay fraction which is common in Cretaceous sedimentary rocks that have

not undergone a deep burial (Deconinck et al., 1985; Kühn et al., 2001). The scarcity of 405 chlorite is explained by the overall warm and humid climate that prevailed at that time, as 406 chlorite is easily weathered under such climate conditions (Deconinck et al., 1985). Illite 407 primarily characterizes the mechanical erosion of a mica-rich crystalline basement (notably 408 409 muscovite). The common occurrence of significant amounts of this mineral is explained by its reworking from the Variscan igneous and metamorphic massifs. The higher illite abundance 410 in the Paris Basin (close to 30%) than in the Vocontian Basin (close to 20%) likely results 411 from the differential settling processes of clay minerals: illite is preferentially deposited 412 413 nearshore whereas smectites, because of their better buoyancy, are exported further out in the ocean (Gibbs, 1977; Chamley, 1989). This difference is then explained by the distinct 414 palaeogeographical context of the two sedimentary basins, as the Col de Pré-Guittard 415 Formation was likely in a more distal position compared with the emerged lands than the 416 417 boreholes located in the eastern part of the Paris Basin.

418 6.3.2. C

6.3.2. Origin of kaolinite

There are two possible origins of kaolinite in the deposits. Kaolinite may originate 419 from soils where it accumulated due to the partial hydrolysis of silicates including feldspars 420 and other minerals which can be easily weathered (Chamley, 1989); it is subsequently 421 transported and integrated into marine sediments. Kaolinite may be also reworked from older 422 kaolinite-bearing sedimentary rocks or palaeoalterations (Deconinck and Vanderaveroet, 423 1996; Thiry, 2000). In the first case, kaolinite is indicative of a warm and humid climate 424 responsible for strong hydrolysis, whereas in the second case, kaolinite is only indicative of a 425 426 significant runoff on the continents. In both cases, the occurrence of kaolinite indicates a humid climate (Chamley, 1989; Ruffell et al., 2002; Dera et al., 2009; Bougeault et al., 2017). 427 428 However, when kaolinite is reworked from ancient rocks, it can be expected to observe a covariation with illite as this mineral results from the same process, whereas when kaolinite 429 originates from soils, its evolution through time should be decoupled from that of illite. 430

A clear covariation of illite and kaolinite is observed in the Paris Basin, suggesting that kaolinite is dominantly reworked from kaolinite-bearing rocks and palaeoalterations rather than from soils formed at the time of sedimentation. After the Purbeckian (latest Jurassic/earliest Cretaceous) regressive facies (Brigaud et al., 2018), the Paris Basin corresponded to a continental area where early Cretaceous Wealden facies accumulated. At that time, the surrounding massifs, remnants of the Variscan orogeny, were deeply weathered with the formation of kaolinite-rich soils, saprolites and bauxites over the French Massif

Central, the London-Brabant Massif and the Armorican Massif (Thiry et al., 2005). Apatite 438 439 fission-track thermochronology performed on the Ardennes Massif suggests that the sedimentary cover of the London-Brabant Massif was eroded during the Late Jurassic and 440 Early Cretaceous (Barbarand et al., 2018). A major alteration phase favoured by a tectonic 441 rejuvenation in the southern part of the London-Brabant Massif took place during the Early 442 Cretaceous and then this massif underwent a kaolinitic alteration (Quesnel, 2003; Yans, 2003; 443 Thiry et al., 2005; 2006). In agreement with the Mid-Cretaceous study of the Isle of Wight 444 (Gale et al., 1996; Ruffell and Garden, 1997), we suggest that clay minerals from the Albian 445 446 deposits of the Anglo-Paris Basin preferentially originated from the north (i.e. the London-Brabant Massif). However, Lower Cretaceous bauxitic profiles have also been identified in 447 448 the French Massif Central (Thiry et al., 2005), which could constitute an additional source of reworked kaolinite. Therefore, the high proportions of kaolinite in the Albian deposits of the 449 450 Paris Basin could be explained by the erosion of the kaolinite-rich weathering profile developed over the Variscan massifs during the Early Cretaceous. As detrital clays including 451 452 kaolinite may be reworked from older rocks or from palaeoalterations, their climatic significance may be questioned (Jeans et al., 2001), but overall, the illite and kaolinite 453 454 dominated clay assemblages of the Albian in the Paris Basin point to a significant runoff and 455 consequently humid climate conditions.

In the Vocontian Basin, kaolinite proportions increase slightly from the base to the top of the section, whereas the proportions of illite remain stable. This suggests that kaolinite and illite deposited in the Vocontian Basin primarily originated from distinct sources. Illite likely originated from the crystalline basement whereas kaolinite was probably at least partly derived from soils or palaeoweathering profiles developed over the French Massif Central or other further away areas. These mineralogical features suggest slightly increasing humidity during the early Albian.

463 6.3.3. Origin of smectite

Smectites seem predominantly detrital, whether in the Albian in the Boulonnais area or southern England (Holtzapffel, 1985; 1987; Gale et al., 1996). Their Al-Fe beideillite composition suggests a reworking from soils developed on the Variscan massifs under a warm and seasonally humid climate (Chamley, 1989). These minerals are abundant in a poorlydated interval likely corresponding to the *L. tardefurcata/L. regularis* ammonite Zone in the lowermost part of the Argile tégulines de Courcelles (Figs. 3-5). Smectites are also abundant in the uppermost middle Albian corresponding to the *D. niobe* and *D. biplicatus* ammonite zones (Figs. 3-5, and 7). During these intervals, smectite-rich sedimentation suggests that thesemi-arid climatic belt expanded northward.

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6.3.4. Origin of vermiculitic clays

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In the Paris Basin, the Argiles tégulines de Courcelles contain significant amounts of 476 vermiculitic clays, in association with illite and kaolinite whereas these minerals are almost 477 absent from the Vocontian Basin. These clay minerals are relatively unusual in Mesozoic 478 479 marine sedimentary rocks, although vermiculite is also mentioned in coeval middle Albian deposits (Gault Clay) from the Isle of Wight in England (Gale et al., 1996). Therefore, 480 481 vermiculitic minerals are likely deriving together with illite and kaolinite from a source that could possibly be the London-Brabant Massif (Fig. 11A). This mineral may originated from 482 483 soils formed under cold-temperate climate (Li et al., 2019), but such climatic conditions seem unlikely at relatively low latitudes during the Albian. We therefore suggest that vermiculitic 484 485 clays are reworked from the basement (moderate weathering of chlorite) or from palaeoalterations. 486

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6.4. Environmental controls of the early/middle Albian clay sedimentation

The mineralogical composition of the clay assemblages is the result of a complex interplay of the lithology of the emerged landmasses, their reliefs and tectonic instability, sealevel fluctuations and climate (e.g., Chamley, 1989).

492 In the Paris Basin, clay sedimentation largely dominated by illite and kaolinite suggests that the London-Brabant Massif was submitted to significant runoff conditions. 493 494 Between 30 and 35°N, corresponding to the palaeolatitudes of the London-Brabant Massif, precipitation rates are estimated between 1000 and 1500 mm/yr (Ufnar et al., 2002), which is 495 496 high enough to produce erosional soil processes, the erosion of Lower Cretaceous kaolinite-497 rich palaeoalterations and the bedrock. These conditions were probably responsible for a 498 significant detrital flux of clay minerals such as illite and kaolinite (Fig. 11). As the temperatures were also high (>20°C for these palaeolatitudes, based on δ^{18} O values; O'Brien 499 500 et al., 2017), chlorite was likely rapidly transformed into vermiculite and interstratified minerals including chlorite-vermiculite which are identified in small quantities in the Albian 501 sedimentary rocks (Herbillon and Makumbi, 1975; Proust et al., 1986; Righi et al., 1993; 502 Banfield and Murakami, 1998). 503

The two smectite-rich intervals identified in the Albian of the Paris Basin, the first one 504 505 close to the Aptian/Albian transition and in the lowermost Albian and the second from the A. intermedius to the D. biplicatus ammonite zones in the lower middle Albian, clearly indicate 506 507 that the erosional processes were less intense. A decreasing intensity of erosion may be linked 508 to rising sea level or to a shift from humid to more arid conditions. At the base of the succession in the lower Albian, the long-term transgressive trend may be responsible for the 509 smectite-rich sedimentation, but this trend lasted during the entire Albian (Haq, 2014) while 510 abundant illite and kaolinite replaced the smectite-rich sedimentation. The comparison of clay 511 512 assemblages with short-term sea level curves (Haq, 2014) did not show any relationship 513 between clay assemblages and sea level fluctuation. In addition, in the study area, the time-514 equivalent interval for the D. niobe and D. biplicatus zones is known to correspond to a low relative sea level (Amédro and Matrion, 2014). Consequently, smectite-rich sedimentation 515 516 does not seem to be the result of a rising sea level. However, these particular intervals, previously identified in the Boulonnais area (Holtzapffel 1985; 1987) and in southern England 517 518 (Isle of Wight, Gale et al., 1996) can be explained by more arid climate conditions. As the Aptian-Albian transition is known to be a cool interval (Millán et al., 2014 and references 519 520 therein), the hydrological cycle was probably slower during this period which is consistent 521 with dryer conditions reflected by smectite-rich sedimentation intervals. Such climate conditions are also suggested in southern Portugal (Algarve) where mineralogical and 522 palynological data indicate more aridity (Heimhofer et al., 2008). The smectite-rich 523 sedimentation in the upper part of the middle Albian (A. intermedius to D. biplicatus zones) 524 may be also explained by a semi-arid climate and a cooling trend suggested by calcareous 525 nannofossils and the isotope chemistry of the Gault Clay from south-eastern England 526 (Kanungo et al., 2018). Such climate conditions are also known in northern Spain before more 527 humid conditions occurred during the late Albian (Sender, 2005; Coiffard et al., 2007). In the 528 Lusitanian Basin, in the time-equivalent interval, coupled palynological and clay mineral data 529 indicate drier conditions characterized by the abundance of *Classopollis* and by decreasing 530 531 proportions of kaolinite balanced by increasing proportions of illite-smectite mixed-layers (Heimhofer et al., 2012). 532

In the Vocontian Basin, the Aptian/Albian transition is also characterized by kaolinitedepleted deposits which is consistent with drier conditions (Fig. 11B). The proportions of this mineral slightly increased during the *L. tardefurcata* ammonite Zone but stayed relatively low. A significant increase occurs in the *D. mammillatum* Zone, partly time equivalent to the

O. subhilli and H. steinmanni zones from the Paris Basin, which represents the upper half of 537 the D. mammillatum Zone (see Table 1 and Fig. 11B). This trend is comparable with the 538 increase of kaolinite recorded in the Paris Basin (Fig. 11B) and likely reflects wetter climatic 539 conditions as a consequence of the emergence of a humid equatorial belt during the Albian 540 (Chumakov et al., 1995). There may be several possible explanations for the significant 541 difference between the percentages of kaolinite in the Paris Basin (between 25 and 30%) and 542 Vocontian Basin (between 10 and 15%). It is well-known that differential settling processes 543 of clay minerals favour the nearshore deposition of kaolinite whereas smectite, because of its 544 545 better buoyancy, is deposited further out in the ocean (Deconinck et al., 1985; Godet al., 2008). In addition, clay minerals deposited in the Vocontian Basin may originated from 546 547 distinct detrital sources, some of which are located southward (Corso-sarde micro-continent?) in the semi-arid climatic belt where smectite should form in soils. 548

549 Surprisingly, clay assemblages do not display any particularity in the stratigraphic interval 550 encompassing the organic matter-rich Paquier horizon (OAE1b) in the Col de Pre-Guittard 551 section. However, the K+C/S ratio increases slightly around this level. Most works show that 552 the temperature increased sharply during this event and some authors suggest that the 553 monsoonal climate enhanced the humidity and detrital supply during this peculiar event 554 (Herrle et al., 2003a and b; Hofmann et al., 2008; Jenkyns, 2010; Sabatino et al., 2015), which 555 is consistent with our clay mineralogical results.

In the Paris Basin, the upper Albian deposits (pricei Zone) again show a kaolinite- and 556 illite-rich clay fraction (Fig. 6) indicating a return to more humid climate conditions. The base 557 of the late Albian is characterized by a warm event recorded during the D. cristatum Zone 558 (Kanungo et al., 2018). Unfortunately, this stratigraphic interval is condensed in the boreholes 559 studied here, but the above mentioned warming event (Kanungo et al., 2018) may be 560 responsible for an accelerated hydrological cycle and consequently enhanced erosional 561 processes on the London-Brabant Massif during the overlying M. pricei Zone. Alternatively, 562 the tectonic instability of the London-Brabant Massif during the early late Albian (Owen, 563 564 1971) could be also responsible for the concomitant increase in illite and kaolinite.

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566 Conclusions

567 The clay mineralogy of the Albian deposits in the Paris and Vocontian basins shows 568 some common features suggesting at least a regional climatic control of the clay 569 sedimentation as well as specific characteristics attributable to certain local conditions.

The kaolinite-depleted interval around the Aptian/Albian transition and in the 570 lowermost Albian suggests that a relatively cool and dry climate was likely responsible for a 571 slow-down of the hydrological cycle. From the D. mammillatum Zone in the Vocontian Basin 572 and at least from the *H. puzosiana* to the *A. intermedius* Zone in the Paris Basin, increasing 573 proportions of kaolinite and/or illite suggest increased precipitation rates and a more constant 574 humid climate. This change may be the consequence of the re-organization of the climatic 575 belts, particularly the emergence of the equatorial humid zone favouring a warm humid belt at 576 latitudes between 25 and 35°N. In the Paris Basin, kaolinite is primarily reworked from 577 578 Lower Cretaceous palaeoalterations and from unmetamorphosed rocks outcropping on the 579 London-Brabant Massif, whereas in the Vocontian Basin, this mineral may be also reworked 580 from soils developed over the Central Massif and other continental masses located southwards. In both cases, increasing proportions of kaolinite are indicative of increased 581 582 runoff triggered by a more humid climate and a southward shift of the mid-latitude warm humid belt. 583

584 During the late-middle Albian (at least in the *D. niobe* and *D. biplicatus* ammonite 585 zones), the smectite–rich sedimentation in the Paris Basin suggests a latitudinal expansion of 586 the semi-arid climatic belt which is consistent with palaeobotanical data. During the late 587 Albian (*M. pricei* Zone), illite and kaolinite contents increase again indicating either a return 588 to a more humid climate and/or the influence of a tectonic instability of the London-Brabant 589 Massif.

590 The occurrence of vermiculitic clays restricted to the Anglo-Paris Basin suggests that 591 this mineral originated from the London-Brabant Massif. Finally, the smectite-rich 592 sedimentation recorded in the Vocontian Basin compared with the Paris Basin illustrates the 593 significant role played by the differential settling of clay minerals from nearshore to offshore 594 environments and by palaeogeography.

Finally, the warm climates of the Albian also seem to be characterized by fluctuationsin humidity with significant impacts on the continental weathering processes.

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- 602
- 603 **References**

604

- Amédro, F., 1992. L'Albien du bassin anglo-parisien: Ammonites zonation phylétique, séquences. Bull. Centres Rech. Explor-Prod. Elf Aquitaine 16, 187-233.
- Amédro, F., 2009. Stratigraphie séquentielle des successions albiennes du bassin anglo-parisien et du bassin de Mons (Belgique). Bulletin d'Information des Géologues du Bassin
 de Paris 46 (2) : 12-36.
- Amédro, F., Matrion, B., 2007. Une coupe lithologique synthétique dans l'Albien-type de
 l'Aube. Bull. inf. géol. Bass. Paris 44, 7-23.
- Amédro, F., Deconinck J.F., Matrion, B., 2019. L'Albien type de l'Aube (France) : première
 description litho-biostratigraphique de la totalité des Argiles tégulines de Courcelles.
 Bull. inf. géol. Bass. Paris. In press.
- Amédro, F., Matrion, B., 2008. Corrélations dans l'Albien de l'Yonne et de l'Aube, France
 (lithologie et ammonites). Bull. inf. géol. Bass. Paris 45, 12-24.
- Amédro, F., Matrion, B., 2014. L'étage Albien dans sa région-type, (Aube, France) : une
 synthèse dans un contexte sédimentaire global. Carnets de Géologie 14, 5, 69-128.
- Amédro, F., Matrion, B., Deconinck J.-F., Huret, E. Landrein, P., 2017. Les forages de
 Juzanvigny (Aube, France) : litho-biostratigraphie des formations du Barrémien à
 l'Albien moyen dans l'est du bassin de Paris et datations par les ammonites.
 Geodiversitas 39, 2, 185-212.
- Amédro, F., Matrion, B., Touch, R., 2000. La zone d'ammonite à *Protohoplites*(*Hemisonneratia*) *puzosianus* et sa position dans la zonation réactualisée de l'Albien
 inférieur du bassin anglo-parisien. Bull. inf. géol. Bass. Paris 37, 3-12.
- Amédro F., Robaszynski F., 2014. Le Crétacé du Bassin parisien. *In*, Le Bassin parisien, un
 nouveau regard sur la géologie. J.P.Gely & F. Hanot ed. Association des géologues du
 Bassin de Paris, p. 75-84.
- Banfield, J. F., Murakami, T., 1998. Atomic-resolution transmission electron microscope
 evidence for the mechanism by which chlorite weathers to 1:1 semi-regular chloritevermiculite. American Mineralogist, 83, 3-4, 348-357.
- Barbarand, J., Bour, I., Pagel, M., Quesnel, F., Delcambre, B., Dupuis, C. & Yans, J., 2018.
 Post-Paleozoic evolution of the northern Ardenne Massif constrained by apatite
 fission-track thermochronology and geological data. BSGF Earth Sciences Bulletin
 189, 16. doi:10.1051/bsgf/2018015.
- Blaise, T., Barbarand, J., Kars, M., Ploquin, F., Aubourg, C., Brigaud, B., Cathelineau, M., El
 Albani, A., Gautheron, C., Izart, A., Janots, D., Michels, R., Pagel, M., Pozzi, J.P.,

- Boiron, M.C. and Landrein, P., 2014. Reconstruction of low temperature (<100° C)
 burial in sedimentary basins: A comparison of geothermometer in the intracontinental
 Paris Basin. Marine and Petroleum Geology 53, 71-87.
- Bodin, S., Meissner, P., Janssen, N.M.M., Steuber, T., Mutterlose J., 2015. Large igneous
 provinces and organic carbon burial: Controls on global temperature and continental
 weathering during the Early Cretaceous. Global and Planetary Change 133, 238–253.
- Bomou, B., Deconinck, J.-F., Pucéat, E., Amédro, F., Joachimski, M. M. Quillévéré, F., 2016.
 Isotopic seawater temperatures in the Albian Gault Clay of the Boulonnais (Paris
 Basin): palaeoenvironmental implications. Proceedings of the Geologists' Association
 127, 699-711.
- Boucot, A., J., Chen, X., Scotese, C., R., 2013. Phanerozoic paleoclimate: An atlas of
 lithologic indicators of climate. Tulsa, USA: Society for Sedimentary Geology
 (SEPM).
- Bougeault, C., Pellenard, P., Deconinck, J.F., Hesselbo, S.P., Dommergues, J.L., Bruneau, L.,
 Cocquerez, T., Laffont, R., Huret, E., Thibault, N., 2017. Climatic and
 palaeoceanographic changes during the Pliensbachian (Early Jurassic) inferred from
 clay mineralogy and stable isotope (C-O) geochemistry (NW Europe). Global and
 Planetary Change, 149, 139-152.
- Bréhéret, J.G., 1985a. Indices d'un événement anoxique étendu à la Téthys alpine, à l'Albien
 inférieur (événement Paquier). C.R. Acad. Sci., Paris 300, II, 8, 355-358.
- Bréhéret, J.G., 1985b. Sédimentologie et diagenèse de la matière organique contenue dans le
 niveau Paquier, couche repère de l'Albien inférieur vocontien. C.R. Acad. Sci., Paris
 301, II, 15, 1151-1156.
- Bréhéret, J.G., 1997. L'Aptien et l'Albien de la Fosse vocontienne (des bordures au bassin).
 Évolution de la sédimentation et enseignements sur les événements anoxiques. Société
 géologique du Nord, Publ. n° 25, 644 p.
- Brigaud, B., Vincent, B., Pagel, M., Gras, A., Noret, A., Landrein, P., Huret, E., 2018.
 Sedimentary architecture, depositional facies and diagenetic response to intracratonic
 deformation and climate change inferred from outcrops for a pivotal period
 (Jurassic/Cretaceous boundary, Paris Basin, France). Sedimentary Geology 373, 4876.
- Chaboureau, A.C., Sépulchre, P., Donnadieu, Y., Franc, A., 2014. Tectonic-driven climate
 change and the diversification of angiosperms. PNAS. 111, 39, 14066–14070.
- 671 Chamley, H., 1989. Clay Sedimentology. *Springer Verlag*, Berlin, Heidelberg, 623 p.

- Chumakov, N.M., Zharkov, M.A., Herman, A.B., Doludenko, M.P., Kalandadze, N.N.,
 Lebedev, E.A., Ponomarenko, A.G., Rautian, A.S., 1995. Climate belts of the midCretaceous time. Stratigr. Geol. Correl. 3, 241–260.
- Clauer, N., O'Neil, J.R., Bonnot-Courtois, C. and Holtzapffel, T., 1990. Morphological,
 chemical, and isotopic evidence for an early diagenetic evolution of detrital smectite in
 marine sediments. Clays and Clay Minerals 38, 1, 33-46.
- 678 Coiffard, C., Gomez, B., Thévenard, F., 2007. Early Cretaceous Angiosperm Invasion of
 679 Western Europe and Major Environmental Changes. Annals of Botany 100, 545-553.
- Damotte R., Magniez-Jannin F., 1973. Ostracodes et Foraminifères de l'Aptien inférieur du
 sondage du Bois du Perchois (Aube). Bull. Inf. Géol. Bass. Paris, 36, 3-47.
- Deconinck, J.F., Beaudoin, B., Chamley, H., Joseph, P. Raoult, J.F., 1985. Contrôles
 tectonique, eustatique et climatique de la sédimentation argileuse du domaine subalpin
 français au Malm-Crétacé. Rev. Géol. Dyn. Géogr. Phys. 26, 5, 311-320.
- Deconinck, J.F., Chamley, H., 1983. Héritage et diagenèse des minéraux argileux dans les
 alternances marno-calcaires du Crétacé inférieur du domaine subalpin. C. R. Acad.
 Sc., Paris 297, 589-594.
- Deconinck, J.F., Chamley, H., 1995. Diversity of smectite origins in Late Cretaceous
 sediments: example of chalks from northern France. Clay minerals 30, 365-379.
- Deconinck, J.F. and Debrabant, P., 1985. Diagenèse des argiles dans le domaine subalpin:
 rôle respectif de la lithologie, de l'enfouissement et de la surcharge tectonique. Rev.
 Géol. Dyn. Géogr. Phys. 26, 5, 321-330.
- Deconinck, J.F., Vanderaveroet, P., 1996. Eocene to Pleistocene clay mineral sedimentation
 off New Jersey, western North Atlantic (sites 903 and 905). Proceedings ODP Vol.
 150 Scientific results, 147 170.
- 696 Dellisanti, F., Pini, G.A., Baudin, F., 2010. Use of T_{max} as a thermal maturity indicator in 697 orogenic successions and comparison with clay mineral evolution. Clay minerals 45, 698 115-130.
- Dera, G., Pellenard, P., Neige, P., Deconinck, J.-F., Pucéat, E. Dommergues, J.-L., 2009.
 Distribution of clay minerals in Early Jurassic Peritethyan seas: Palaeoclimatic
 significance inferred from multiproxy comparisons. Palaeogeography,
 Palaeoclimatology, Palaeoecology 271, 39-51.
- Frbacher, J., Hemleben, C., Huber, B.T., Markey, M., 1999. Correlating environmental
 changes during early Albian oceanic anoxic event 1B using benthic foraminiferal
 paleoecology. Marine Micropaleontology 38, 7-28.

- Fauconnier, D., 1975. Répartition des Péridiniens de l'Albien du bassin de Paris. Rôle
 stratigraphique et liaison avec le cadre sédimentologique. Bull. BRGM 4, 235-273.
- Fenner, J., 2001. Middle and Late Albian geography, oceanography, and climate and the
 setting of the Kirchrode I and II borehole sites. Palaeogeography, Palaeoclimatology,
 Palaeoecology 174, 5-32.
- Ferry, S., Cotillon, P. and Rio, M., 1983. Diagenèse croissante des argiles dans les niveaux
 isochrones de l'alternance calcaire-marne valanginienne du bassin vocontien. Zonation
 géographique. C.R. Acad. Sci. Paris 297, 51-56.
- Fielitz, W, Mansy, J-L., 1999. Pre- and synorogenic burial metamorphism in the Ardenne and
 neighbouring areas (Rhenohercynian zone, central European Variscides). In: Sintubin
 M, Vandycke S, Camelbeeck T, eds. Palaeozoic to recent tectonics in the NW
 European Variscan front zone. Tectonophysics 309, 227–256.
- Föllmi, K.B., 2012. Early Cretaceous life, climate and anoxia. Cretaceous Research, 35, 230257.
- Friedrich, O., Norris, R.D., Erbacher, J., 2012. Evolution of middle to Late Cretaceous
 oceans—A 55 m.y. record of Earth's temperature and carbon cycle. Geology 40, 2,
 107-110.
- Friès, G., 1987. Dynamique du bassin subalpin méridional de l'Aptien au Cénomanien. École
 des Mines de Paris. Mémoire des sciences de la Terre 4, 370 p.
- Gale, A.S., Huggett, J.M. Gill, M., 1996. The stratigraphy and petrography of the Gault Clay
 Formation (Albian, Cretaceous) at Redcliff, Isle of Wight. Proceedings of the
 Geologists' Association 107, 287-298.
- Gale, A.S., Bown, P., Caron, M., Crampton, J., Crowhurst, S.J., Kennedy, W.J., Petrizzo,
 M.R. Wray, D.S., 2011. The uppermost Middle and Upper Albian succession at the
 Col de Palluel, Hautes-Alpes, France: an integrated study (ammonites, inoceramid
 bivalves, planktonic foraminifera, nannofossils, geochemistry, stable oxygen and
 carbon isotopes, cyclo- stratigraphy). Cretaceous Research 32, 59-130.
- Gély, J.-P. Hanot F., (dir.). 2014. Le bassin parisien, un nouveau regard sur la géologie.
 Bulletin d'Information des Géologues du Bassin de Paris, Mémoire hors-série 9, 228
 p., 1 pl.
- Ghirardi, J., Deconinck, J.F., Pellenard, P., Martinez, M., Bruneau, L., Amiotte-Suchet, P.
 Pucéat, E., 2014. Multi-proxy orbital chronology in the aftermath of the Aptian
 Oceanic Anoxic Event 1a : Palaeoceanographic implications (Serre Chaitieu section,
 Vocontian Basin, SE France). Newsletters on Stratigraphy 47, 3, 247-262.

- Gibbs, R.J., 1977. Clay mineral segregation in the marine environment. J. Sedimentary
 Research, 47, 237–243.
- Godet, A., Bodin, S., Adatte, T. and Föllmi, K.B., 2008. Platform-induced clay-mineral
 fractionation along a northern Tethyan basin-platform transect: implications for the
 interpretation of Early Cretaceous climate change (Late Hauterivian-Early Aptian).
 Cretaceous Research 29, 830–847.
- Guillocheau, F., Robin, C., Allemand, P., Bourquin, S., Brault, N., Dromart, G., Friedenberg,
 R., Garcia, J.-P., Gaulier, J.-M., Gaumet, F., Grosdoy, B., Hanot, F., Le Strat, P.,
 Mettraux, M., Nalpas, T., Prijac, C., Rigollet, C., Serrano, O. Grandjean, G., 2000.
 Meso-Cenozoic geodynamic evolution of the Paris Basin: 3D stratigraphic constraints.
 Geodinamica Acta 13, 189–246.
- Han, G., Préat, A., Chamley, H., Deconinck, J.F., Mansy, J.L., 2000. Palaeozoic clay mineral
 sedimentation and diagenesis in the Dinant and Avesnes basins (Belgium, France):
 relationships with variscan tectonism. Sedimentary Geology 136, 3-4, 217-238.
- Haq B.U., 2014. Cretaceous eustasy revisited. Global and Planetary Change, 113, 44-58
- Hardenbol, J., Thierry, J., Farley, M. B., Jacquin, T., de Graciansky, P.-C. Vail, P. R., 1998.
 Mesozoic and Cenozoic Sequence chronostratigraphic framework of European Basins, *in* de Graciansky P.-C., Hardenbol J., Jacquin T. and Vail P. R. (Eds.), MesozoicCenozoic Sequence Stratigraphy of European Basins. SEPM Special Publication 60, 313.
- Hart, M., Amédro, F. Owen, H., 1996. The Albian stage and substage boundaries. Bulletin de
 l'institut royal des sciences naturelles de Belgique, vol. 66 (suppl.), Comptes-rendus «
 Second International Symposium on Cretaceous Stage Boundaries », Bruxelles 8-16
 septembre 1995, 45-56.
- Hay, W.W., Floegel, S., 2012. New thoughts about the Cretaceous climate and oceans. Earth
 Science Reviews 115, 262-272.
- Heimhofer, U., Hochuli, P.A., Burla, S., Oberli, F., Adatte, T., Dinis, J.L., Weissert, H., 2012.
 Climate and vegetation history of western Portugal inferred from Albian near-shore
 deposits (Galé Formation, Lusitanian Basin). Geological Magazine 149, 1046-1064.
- Heimhofer, U., Adatte, T., Hochuli, P.A., Burla, S., Weissert, H., 2008. Coastal sediments
 from the Algarve: low-latitude climate archive for the Aptian-Albian. Int. J. Earth Sci.
 (Geol Rundsch) 97, 785–797.
- Herbillon, A.J. Makumbi, M.N., 1975. Weathering of chlorite in a soil derived from a
 chloritoschist under humid tropical conditions. Geoderma 13, 89-104.

- Herrle, J.O., Mutterlose, J., 2003. Calcareous nannofossils from the Aptian–Lower Albian of
 southeast France: palaeoecological and biostratigraphic implications. Cretaceous
 Research 24, 1-22.
- Herrle, J.O., Pross, J., Friedrich, O. Hemleben, C., 2003a. Short-term environmental changes
 in the Cretaceous Tethyan Ocean: micropalaeontological evidence from the Early
 Albian Oceanic Anoxic Event 1b. Terra Nova 15, 14-19.
- Herrle, J.O., Pross, J., Friedrich, O., Kößler, P., Hemleben, C., 2003b. Forcing mechanisms
 for mid-Cretaceous black shale formation: evidence from Upper Aptian and Lower
 Albian of the Vocontian Basin (SE France). Palaeogeography, Palaeoclimatology,
 Palaeoecology 190, 399-426.
- Hofmann, P., Stüsser, I., Wagner, T., Schouten, S., Sinninghe Damsté, J.S., 2008. Climate–
 ocean coupling off North-West Africa during the Lower Albian: The Oceanic Anoxic
 Event 1b. Palaeogeography, Palaeoclimatology, Palaeoecology 262, 157–165.
- Holtzapffel, T., 1985. Smectites authigènes et glauconitisation dans les Argiles du Gault
 (Albien du Boulonnais). Ann. Soc. Géol. Nord, Lille, CIV, 33-39.
- Holtzapffel, T., 1987. Assemblages argileux de nodules phosphatés et de leur matrice dans les
 argiles albiennes du Boulonnais (France). Ann. Soc. Géol. Nord, Lille, CVI, 267-273.
- Holtzapffel, T., Bonnot-Courtois, C., Chamley, H., Clauer, N., 1985. Respective influence of
 detrital supply and marine diagenesis on the formation of Albo-Aptian and Paleogene
 smectites in the North-Atlantic Range. Bull. Soc. Géol. Fr. 1, 25-33.
- Horikx, M., Huck, S., Adatte, T., and Heimhofer, U., 2017. Vegetation dynamics, angiosperm
 radiation and climatic changes in the Lusitanian Basin (Portugal) during Albian times.
 Palaeogeography, Palaeoclimatology, Palaeoecology 465, 30-41.
- Huber, B.T., MacLeod, K.G., Watkins, D.K., Coffin, M.F., 2018. The rise and fall of the
 Cretaceous Hot Greenhouse climate. Global and Planetary Change 167, 1-23.
- Jeans, C.V., Mitchell, J.G., Fisher, M.J., Wray, D.S. Hall, I.R. 2001. Age, origin and climatic
 signal of English Mesozoic clays based on K/Ar signatures. Clay minerals 36, 515539.
- Jenkyns, H.C., 2010. Geochemistry of oceanic anoxic events. Geochemistry, Geophysics,
 Geosystems, 11, 3.
- Kanungo, S., Bown, P.R., Young, J.R. and Gale, A.S., 2018. A brief warming event in the late
 Albian: evidence from calcareous nannofossils, macrofossils, and isotope
 geochemistry of the Gault Clay Formation, Folkestone, southeastern England. J.
 Micropalaeontology 37, 231–247.

- Kennedy, W.J., Gale, A.S., Bown, P.R., Caron, M., Davey, R.J., Gröcke, D., Wray, D.J.,
 2000. Integrated stratigraphy across the Aptian-Albian boundary in the Marnes Bleues,
 at the Col de Pré-Guittard, Arnayon (Drôme), and at Tartonne (Alpes-de-HauteProvence), France, a candidate Global Boundary Stratotype Section and Point for the
 base of the Albian Stage. Cretaceous Research 21, 591-720.
- Kennedy, W.J., Gale, A.S., Huber, B.T., Petrizzo, M.R., Bown, P., Barchetta, A., Jenkyns,
 H.C., 2014. Integrated stratigraphy across the Aptian/Albian boundary at Col de PréGuittard (southeast France): A candidate Global Boundary Stratotype Section.
 Cretaceous Research 51, 248-259.
- Kennedy, W.J., Gale, A.S., Huber, B.T., Petrizzo, M.R., Bown, P., Barchetta, A. and Jenkyns,
 H.C., 2017. The Global Boundary Stratotype Section and Point (GSSP) for the base of
 the Albian Stage, of the Cretaceous, the Col de Pré-Guittard section, Arnayon, Drôme,
 France. Journal of International Geoscience 40, 177-188.
- Knight, R. I., 1999. Phosphates and phosphogenesis in the Gault Clay (Albian) of the AngloParis Basin. Cretaceous Research 20, 507-521.
- Kühn, V., Heydemann, A., Usdowski, E., 2001. Mineralogy of the upper Albian sediments
 from the Kirchrode I borehole with special emphasis on the clay mineralogy. Palaeogeography, Palaeoclimatology, Palaeoecology 174, 145-159.
- Lanson, B., Sakharov, B. A., Claret, F. Drits, V.A., 2009. Diagenetic smectite-to-illite
 transition in clay-rich sediments: a reappraisal of X-ray diffraction results using the
 multi-specimen method. Am. J. Science 309, 476-516.
- Levert, J. Ferry, S., 1988. Diagenèse argileuse complexe dans le mésozoïque subalpin révélée
 par cartographie des proportions relatives d'argiles selon des niveaux isochrones. Bull.
 Soc. Géol. Fr. 4, 1029-1038.
- Li, P., Zhang, C., Guo Z., Deng, C., Ji, X., Jablonski, N.G., Wu, H., Zhu, R. 2019. Clay
 mineral assemblages in the Zhaotong Basin of southwestern China: Implications for
 the late Miocene and Pliocene evolution of the South Asian monsoon.
 Palaeogeography, Palaeoclimatology, Palaeoecology, 516, 90-100.
- 836 Mangenot, X., Gasparrini, M., Rouchon, V., Bonifacie, M., 2018. Basin-scale thermal and 837 fluid flow histories revealed by carbonate clumped isotopes (Δ_{47}) – Middle Jurassic 838 carbonates of the Paris Basin depocentre. Sedimentology, 65, 123-150.
- Martinez, M., Deconinck, JF., Pellenard, P., Reboulet, S., Riquier, L., 2013. Astrochronology
 of the Valanginian Stage from reference sections (Vocontian Basin, France) and

- palaeoenvironmental implications for the Weissert Event. Palaeogeography,
 Palaeoclimatology, Palaeoecology 376, 91-102.
- Merriman, R.J. Frey, M., 1999. Patterns of very low-grade metamorphism in metapelitic
 rocks. In: Frey, M., Robinson, D. (Eds.). Low-Grade Metamorphism. Blackwell
 Science Ltd, 61-107.
- Meyer, K.W. Petersen, S.V., Lohmann, K.C., Winkelstern, I.Z., 2018. Climate of the Late
 Cretaceous North American Gulf and Atlantic Coasts. Cretaceous research 89, 160173.
- Millán, M. I., H. J. Weissert, and M. A. López-Horgue, 2014, Expression of the late Aptian
 cold snaps and the OAE1b in a highly subsiding carbonate platform (Aralar, northern
 Spain): Palaeogeography Palaeoclimatology Palaeoecology, v. 411, p. 167-179.
- Moore, D.M., Reynolds, R.C., 1997. X-Ray diffraction and the identification and Analysis of
 Clay Minerals; second edition (23); Oxford, New York : Oxford University Press :
 378 p.
- Mutterlose J., Bornemann A., Luppold F.W., Owen H.G., Ruffell A., Weiss W., & Wray D.
 2003. The Vöhrum section (northwest Germany) and the Aptian/Albian boundary.
 Cretaceous Research., 23, 203-252.
- Myers, K.J., Wignall, P.B., 1987. Understanding Jurassic organic-rich mudrocks new
 concepts using gamma-ray spectrometry and palaeoecology: examples from the
 Kimmeridge Clay of Dorset and the Jet Rock of Yorkshire. In: Legget, J.K., Zuffa,
 G.G. (Eds.), Marine Clastic Environments: Concepts and Case Studies. Graham and
 Trotman, London, 172–189.
- O'Brien, C.L., Robinson, S.A., Pancost, R.D et al., 2017. Cretaceous sea-surface temperature
 evolution: Constraints from TEX86 and planktonic foraminiferal oxygen isotopes.
 Earth-Science Reviews 172, 224-247.
- Owen, H.G., 1971. The Stratigraphy of the Gault in the Thames Estuary and its Bearing on
 the Mesozoic Tectonic History of the Area. Proceedings of the Geologists'
 Association 82, 2, 187-208.
- Owen, H.G., 1999. Correlation of Albian European and Tethyan ammonite zonations and the
 boundaries of the Albian Stage and substages: some comments. Scripta Geologica,
 Special Issue 3, 129-149.
- Pellenard, P., Deconinck, J.F., Marchand, D., Thierry, J., Fortwengler, D., Vigneron G., 1999.
 Contrôle géodynamique de la sédimentation argileuse du Callovien-Oxfordien moyen

- dans l'Est du Bassin de Paris : influence eustatique et volcanique. C.R. Acad; Sci,
 Paris 328, 807-813.
- Pictet, A., Mojon, P.O., Matrion, B., Adatte, T., Spangenberg, J.E., Föllmi, K.B., 2019.
 Record of latest Barremian-Cenomanian environmental change in tectonically
 controlled depressions from the Jura-Burgundy threshold (Jura Mountains, eastern
 France and western Switzerland). Palaeogeography, Palaeoclimatology, Palaeoecology
 514, 627-654.
- Pirrie, D., Marshall, J.D., Doyle, P. Riccardi, A.C., 2004. Cool early Albian climates; new
 data from Argentina. Cretaceous Research 25, 27-33.
- Petrizzo, M.R., Huber, B.T., Gale, A.S., Barchetta, A., Jenkyns, H.C., 2012. Abrupt planktic
 foraminiferal turnover across the Niveau Kilian at Col de Pré-Guittard (Vocontian
 Basin, southeast France): new criteria for defining the Aptian/Albian boundary.
 Newsletters on Stratigraphy 45, 1, 55-74.
- Pomerol, B., 1986. Minéralogie des argiles albiennes du sud du Pays d'Othe (sud-est du bassin de Paris). Modalités du passage latéral Sables de la Puisaye-Argiles Tégulines.
 Géologie de la France 1, 139-149.
- Poulsen, C.J., Barron, R.J., Arthur, M.A., Peterson, W.H., 2001. Response of the midCretaceous global oceanic circulation to tectonic and CO₂ forcings. Paleoceanography
 16, 6, 576-592.
- Proust, D., Eymery, J.P. Beaufort, D., 1986. Supergene vermiculitization of a magnesian
 chlorite: iron and magnesium removal processes. Clays and Clay Minerals 34, 5, 572580.
- Quesnel, F., 2003. Paleoweathering and paleosurfaces from northern and eastern France to
 Belgium and Luxembourg: geometry, dating and geodynamic implications. Géologie
 de la France 1, 95-104.
- Rat, P., Magniez-Jannin, F., Chateauneuf, J.-J., Damotte, R., Destombes, P., Fauconnier, D.,
 Feuillée, P., Manivit, H., Mongin, D., Odin, G.S., 1979. L'Albien de l'Aube. *Les stratotypes français*, Paris, 5, 446 p., 51 pl.
- Righi, D., Petit., S., Bouchet. A., 1993. Characterization of Hydroxy-Interlayered Vermiculite
 and Illite/Smectite Interstratified Minerals from the Weathering of Chlorite in a
 Cryorthod. Clays and Clay Minerals 41, 4, 484-495.
- Robaszynski, F., Pomerol, B., Masure, E., Bellier, J.P., Deconinck, J.F., 2005. Stratigraphy
 and stage boundaries in a type-section of the Late Cretaceous chalk from the East Paris
 basin: The "Craie 700 boreholes" Cretaceous Research 26, 2, 157-169.

- Rodríguez-López, J.P., Liesa, C.L., Pardo, G., Meléndez, N., Soria, A.R. Skillinga, I., 2016.
 Glacial dropstones in the western Tethys during the late Aptian–early Albian cold
 snap: Palaeoclimate and palaeogeographic implications for the mid-Cretaceous.
 Palaeogeography, Palaeoclimatology, Palaeoecology 452, 11–27.
- Ruffell, A., 2016. Do spectral gamma ray data really reflect humid–arid palaeoclimates? A
 test from Palaeogene Interbasaltic weathered horizons at the Giant's Causeway, N.
 Ireland. Proceedings of the Geologists' Association 127, 18-28.
- Ruffell, A., McKinley, J.M. Worden, R.H., 2002. Comparison of clay mineral stratigraphy to
 other proxy palaeoclimate indicators in the Mesozoic of NW Europe. Philosophical
 Transactions of the Royal Society London A 360, 675-693.
- Ruffell, A. Garden, R., 1997. Tectonic controls on the variation in thickness and mineralogy
 of pebble-beds in the Lower Greensand Group (Aptian-Albian) of the Isle of Wight,
 southern England. Proceedings of the Geologists' Association 108, 215-229.
- Sabatino, N., Coccioni, R., Manta, D. S., Baudin, F., Vallefuoco, M., Traina, A. Sprovieri,
 M., 2015. High-resolution chemostratigraphy of the late Aptian-early Albian oceanic
 anoxic event (OAE 1b) from the Poggio le Guaine section (Umbria-Marche Basin,
 central Italy). Palaeogeography, Palaeoclimatology, Palaeoecology 426, 319-333.
- Sender, L. M., Diez, J. B., Ferrer, J., Pons, D., Rubio, C., 2005. Preliminary data on a new
 Albian flora from the Valle del Río Martínn Teruel, Spain. Cretaceous Research, 26, 6,
 898-905.
- Środoń, J., Clauer, N., Huff, W., Dudek, T. Banaś, M., 2009. K-Ar dating of the Lower
 Palaeozoic K-bentonites from the Baltic Basin and the Baltic Shield: implications for
 the role of temperature and time in the illitization of smectite. Clay minerals 44, 361–
 387.
- Steinberg, M., Holtzapffel, T. Rautureau, M., 1987. Characterization of overgrowth structures
 formed around individual clay particles during early diagenesis. Clays and Clay
 Minerals 35, 3, 189-195.
- Thiry, M., 2000. Palaeoclimatic interpretation of clay minerals in marine deposits : an outlook
 from the continental origin. Earth-Science Reviews 49, 1-4, 201-221.
- 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:
 paleoweatherings and paleolandforms. Bull. Soc. Géol. Fr. 177, 3, 155-175.

- 941 Thiry, M., Simon-Coinçon, R., Quesnel, F. Wyns, R., 2005. Altération bauxitique associée
 942 aux argiles à chailles sur la bordure sud-est du bassin de Paris. Bull. Soc. Géol. Fr.
 943 176, 2, 199-214.
- Tribovillard, N.-P. Gorin, G.E., 1991. Organic facies of the Early Albian Niveau Paquier, a
 key black shales horizon of the Marnes Bleues Formation in the Vocontian Trough
 (Subalpine Ranges, SE France). Palaeogeography, Palaeoclimatology, Palaeoecology
 85, 227-237.
- 948 Ufnar, D.F., González, L.A., Ludvigson, G.A., Brenner, R.L., Witzke, B.J., 2002. The mid949 Cretaceous water bearer: Isotope mass balance quantification of the Albian hydrologic
 950 cycle. Palaeogeography, Palaeoclimatology, Palaeoecology 188, 51-71.
- Ufnar, D.F., González, L.A., Ludvigson G.A., Brenner R.L. Witzke B.J., 2004. Evidence for
 increased latent heat transport during the Cretaceous (Albian) greenhouse warming.
 Geology 32, 12, 1049-1052.
- Weaver, C.E., 1989. Clays, muds and shales. Elsevier, Dev. Sedimentology, 44, 818 p.
- Yans, J., 2003. An overview of the saprolites of Belgium and their potential kaolinitic
 supplies to Mesozoic and Cainozoic sediments. Géologie de la France 1, 33-37.
- Young, J. R., Gale, A. S., Knight, R. I., and Smith, A. B. (Eds.): Palaeontological Association
 Field Guide to Fossils, 12, 312 pp., Palaeontological Association, UK, 2010.
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961 FIGURE CAPTIONS

962

Figure 1. Palaeogeographic map (Albian) showing the location of the studied areas and the
boundary between the semi-arid and the mid latitude warm-humid belts defined by
Chumakov et al. (1995). Abbreviations: AM = Armorican Massif, BT = Burgundy
threshold, MC = Massif Central, IbM = Iberian Massif, LBM = London-Brabant
Massif, CS = Corso-Sarde microcontinent (modified from Amédro and Matrion,
2014).

- Figure 2. Location of the boreholes studied to the south-east of the Paris Basin (Amédro et al.,
 2019).
- 971 Figure 3. Lithology, biostratigraphy and clay mineralogy of the AUB 111 borehole.
 972 Abbreviations: SVA = 'Sables Verts de l'Aube', APT = Aptian, (K+C)/S =
 973 (kaolinite+chlorite)/smectite.

- Figure 4. Lithology, biostratigraphy and clay mineralogy of the AUB220 borehole. The
 detailed lithological description and the biostratigraphic data were published by
 Amédro et al. (2017). Abbreviations : SVA = 'Sables Verts de l'Aube', APT = Aptian,
 (K+C)/S = (kaolinite+chlorite)/smectite.
- 978 Figure 5. Correlation between AUB111, AUB220 and AUB240 boreholes
- Figure 6. Phosphatic crust corresponding to a hardground at the transition between the 'Sables
 Verts de l'Aube' (Greensands) and the Argiles tégulines de Courcelles Formation in
 borehole AUB220 (74.50 m in depth).
- Figure 7. Lithology, biostratigraphy and clay mineralogy of the AUB 240 borehole. The
 detailed lithological description is given in Amédro et al. (2019). (K+C)/S =
 (kaolinite+chlorite)/smectite.
- Figure 8. Detailed geographical location of the Col de Pré-Guittard section and field views ofthis section.
- Figure 9. Diffractograms obtained for the sample AUB220 25,50 m. The minerals identified are : S = smectite (I/S R0), V = vermiculitic clays, C =chlorite, I = illite, K = kaolinite, C/V = interstratified chlorite – vermiculite, Qtz = quartz.
- 990
- Figure 10. Lithology, clay mineralogy and spectral gamma ray of the Col de Pré-Guittard
 section. (K+C)/S = (kaolinite+chlorite)/smectite.
- Figure 11. A. Palaeogeographic map, facies (modified after Amédro and Matrion, 2014) and
 inferred detrital clay mineral sources in the Paris and Vocontian basins. IW = Isle of
 Wight, LBM = London-Brabant Massif.
- B. Correlation between the AUB 220 borehole (Paris Basin) and the Col de Pré-Guittard section (Vocontian Basin).
- Table 1. Correspondences between the ammonite biozonations from the Paris and 998 Vocontian basins. The appearance of the foraminfer Microhedbergella renilaevis is 999 marked in the H. jacobi zone. Abbreviations: U. Apt. = upper Aptian, H. jacobi = 1000 1001 *Hypacanthoplites jacobi, Micr. renil.* = *Microhedbergella renilaevis, L. schrammeni* = Proleymeriella schrammeni, L. germanica = Leymeriella germanica, L. tardefurcata 1002 = Leymeriella tardefurcata, L. regularis = Leymeriella regularis, S. kitchini = 1003 Sonneratia kitchini, C. floridum = Cleoniceras floridum, H. puzosiana = 1004 Hemisonneratia puzosiana, O. subhilli = Otohoplites subhilli, H. steinmanni = 1005 Hoplites (Isohoplites) steinmanni, D. mammillatum = Douvilleiceras mammillatum, 1006 1007 L.l. = Lyelliceras lyelli, L. ps. = Lyelliceras pseudolyelli, H. benettianus = Hoplites

1008	(Hoplites) benettianus, H. dentatus = Hoplites dentatus, A. intermedius = Anahoplites
1009	intermedius, D. niobe = Dimorphoplites niobe, D. biplicatus = Dimorphoplites
1010	biplicatus, O. roissyanum = Oxytropidoceras roissyanum, D. cristatum = Dipoloceras
1011	cristatum, M. pricei = Mortoniceras pricei, M. inflatum = Mortoniceras inflatum.
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20°W









S.V.A. APT.







Lithology

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Stage	Boreal ammonite zonation (Amédro and Matrion, 2014) (Paris Basin)		Tethyan ammonite zonation (Owen, 1999; Kennedy, 2000; Gale et al., 2011) (Vocontian Basin)
	M. inflatum		M. inflatum
Upper Albian p.p.	M. pricei	I	M. pricei
	D. cristatum		D. cristatum
	D. biplicatus		
	D. niobe		O. roissyanum
Middle Albian	A. intermedius		
	H. dentatus	- -	
	H. benettianus <u>L.I.</u>	interva	L. lyelli
	H. steinmanni	Studied i	
	O. subhilli		D. mammillatum 🛛 ु
	H. puzosiana	T	lter
Lower Albian	C. floridum		i i
	S. kitchini		indic
	L. regularis		ی L. regularis
	L.tardefurcata		L.tardefurcata
	L. germanica		L. germanica
	L. schrammeni		Micr.
U. Apt.	H. jacobi		H. jacobi 🔄 renil.