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## Reconsidering Carboniferous–Permian continental paleoenvironments in eastern equatorial Pangea: facies and sequence stratigraphy investigations in the Autun Basin (France)

Mathilde Mercuzot, Sylvie Bourquin, Pierre Pellenard, Laurent Beccaletto, Johann Schnyder, François Baudin, Céline Ducassou, Sylvain Garel, Georges Gand

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1        **Reconsidering Carboniferous–Permian continental paleoenvironments in eastern equatorial Pangea:**  
2        **facies and sequence stratigraphy investigations in the Autun Basin (France)**

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5        Mathilde Mercuzot<sup>a,b,\*</sup>, Sylvie Bourquin<sup>a</sup>, Pierre Pellenard<sup>b</sup>, Laurent Beccaletto<sup>c</sup>, Johann Schnyder<sup>d</sup>, François  
6        Baudin<sup>d</sup>, Céline Ducassou<sup>a</sup>, Sylvain Garel<sup>e,f</sup>, Georges Gand<sup>b</sup>

7  
8        <sup>a</sup>Univ Rennes, CNRS, Géosciences Rennes - UMR 6118, F-35000, Rennes, France.

9        \*mathilde.mercuzot@outlook.com

10        <sup>b</sup>Biogéosciences UMR uB/CNRS 6282, Université Bourgogne Franche-Comté, 21000 Dijon, France.

11        <sup>c</sup>BRGM, F-45060 Orléans, France.

12        <sup>d</sup>Institut des Sciences de la Terre de Paris (ISTeP), UMR 7193 CNRS, Sorbonne Université, F-75005 Paris,  
13        France.

14        <sup>e</sup>Energy and Geoscience Institute, The University of Utah, Salt Lake City, UT 84108, USA.

15        <sup>f</sup>CVA engineering, 6 Avenue Eiffel, 78420 Carrières-sur-Seine, France.

16  
17        \*corresponding author

18  
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26        **Abstract**

27        The late Carboniferous–early Permian represents a key period in the Phanerozoic history, given the major  
28        global geodynamic and climate modifications. The aim of this work is to better understand the context and  
29        characteristics of the sedimentation recorded in the continental environments of eastern equatorial Pangea at this  
30        time, through the example of the Autun Basin (northeastern Massif Central, France). The Autun Basin contains  
31        the historical stratotype of the Autunian continental stage, and its stratigraphy was recently improved by accurate  
32        numerical ages. This basin formed in an extensional tectonic context during the latest stages of the Variscan  
33        orogeny, and it is essential to study its paleoenvironmental evolution in order to provide new insights into the  
34        sedimentary evolution of contemporaneous surrounding basins. Using field and subsurface data, we propose a  
35        refined sedimentological model for the Autun Basin, relying on updated facies interpretations, organic matter  
36        content fluctuations, and sequence stratigraphy concepts and correlations. The continental environments of the  
37        lower sedimentary succession of the Autun Basin, previously considered to be fluvial and lacustrine, are herein re-  
38        interpreted as mainly lacustrine, comprising fine-grained organic matter-rich deposits, and supplied by coarser-  
39        grained deltaic siliciclastic sediments, without preservation of strict fluvial sedimentation. The determination of  
40        the sequence stratigraphy cycles, strengthened by the quantification of the organic matter content, and reflected by  
41        the temporal succession of progradational and retrogradational trends, is used to determine new correlations  
42        between several sections as well as to reconstruct the paleoenvironment evolution at the Carboniferous–Permian  
43        transition. This study provides evidence that the sedimentation area of the Autun Basin at the time of its filling  
44        was much larger than the preserved basin area, and suggests connections with contemporaneous neighboring  
45        French basins, pointing to a large sedimentary system in the northeastern Massif Central area rather than narrow  
46        and isolated basins.

47

48        **Keywords**

49        Gzhelian; Asselian; Continental delta environments; late-Variscan basin; paleoenvironment; paleogeography

50

51        **1. Introduction**

52        The late Carboniferous–early Permian (CP) is a key period in the Phanerozoic history, due to large-scale  
53        geodynamic modifications, including the latest Variscan orogeny stages and the onset of the breakup of Pangea  
54        (e.g., Ménard and Molnar 1988; Stampfli and Kozur 2006), as well as a major climate upheaval marked by the  
55        acme of the Late Paleozoic Ice Age (LPIA), constituting a turning point in the climate modes of the Paleozoic

56 (e.g., Gastaldo et al. 1996; Montañez et al. 2007). Given the presence of large tropical rainforests (Cleal and  
57 Thomas 2005) and the tremendous rates of organic carbon burial in sediments at that time (i.e., coal and black  
58 shale deposits), intertropical areas constituted a major atmospheric CO<sub>2</sub> sink. It is therefore of utmost importance  
59 to explore paleointertropical basins because their sensitivity to climate forcings has been underestimated in  
60 paleoclimate scenarios (e.g., Soreghan et al. 2020). At that time, intertropical latitudes are mainly considered as a  
61 mountainous region submitted to tropical weathering (e.g., Godd ris et al. 2017), and therefore mainly in  
62 erosion; active sedimentation areas are not fully considered in either the terrestrial paleogeography reconstructions  
63 or in the climate modelling. Continental sediments accumulated during the CP period are preserved in Western  
64 and Central Europe, in basins developed in an extensional tectonic setting, linked with the syn- to late-orogenic  
65 Variscan stages (e.g., Faure et al. 2009; Kroner and Romer 2013). In France, these sedimentary successions are  
66 considered as having been deposited in a multitude of small unconnected basins (e.g., Schneider and Scholze  
67 2018), such as those found in the northeastern part of the Massif Central (Aumance, Decize–La Machine, Blanzay–  
68 Le Creusot and Autun basins, Fig. 1), presenting roughly similar sedimentary patterns and hosting detrital  
69 sediments mostly derived from the erosion of the Variscan mountain belt (Vall  et al. 1988; Van den Driessche  
70 and Brun 1989; Burg et al. 1990; Malavieille et al. 1990; Faure and Becq-Giraudon 1993; Brun and van den  
71 Driessche 1994; Faure 1995; Becq-Giraudon et al. 1996; Genna et al. 1998).

72 Among these basins, the Autun Basin, containing the historical regional stratotype of the Autunian continental  
73 stage (Mayer-Eymar 1881; Gaudry 1883; Bergeron 1889; Munier-Chalmas and de Lapparent 1893), was mostly  
74 studied for its carbonaceous resources and outstanding paleontological record (e.g., Gaudry 1883; Sauvage 1890;  
75 Renault 1896; Landriot 1936; Doubinger 1970; Bouroz and Doubinger 1975; Elsass-Damon 1977; Gand et al.  
76 2011, 2012, 2014). This basin was recently dated using the U-Pb method on interbedded volcanic layers, allowing  
77 to precisely assign the Gzhelian and Asselian stages to the regional stratigraphy (Pellenard et al. 2017) and thereby  
78 enabling additional correlations with other Carboniferous-Permian basins and global events. However, few  
79 detailed sedimentological studies have been carried out since the seminal work of Marteau (1983), all arguing in  
80 favor of fluvial, palustrine and lacustrine depositional environments. More recent studies of neighboring CP basins,  
81 using modern concepts and analytical tools, including integrative sedimentological studies and sequence  
82 stratigraphy principles, along with well-log and seismic data as well as geochemical proxies, suggest that the  
83 depositional setting and environmental model of the northeastern Massif Central CP basins, including the Autun  
84 Basin, should be reconsidered (Aumance Basin, Mathis and Brulhet 1990; Decize–La Machine and Autun basins,  
85 Mercuzot et al. 2021a, b).

86 In a wider view, these northeastern Massif Central basins are in a key position between the Central European  
87 Permian Basin and the southern (e.g., Lodève, Saint-Affrique, Rodez, Brive or Pyrenean/South Alpine) basins.  
88 Therefore, reevaluated data from the Autun Basin would help to (i) accurately characterize the sedimentary  
89 dynamics and the nature of the sediments preserved in this equatorial continental system (i.e., through  
90 paleoenvironment reconstructions); (ii) specify the size of the initial sedimentation areas, allowing to thereafter  
91 integrate paleoenvironments into paleogeography reconstructions, something which has so far been challenging  
92 (e.g., Glennie et al. 2003; Roscher and Schneider 2006; Schneider and Scholze 2018); and lastly (iii) improve our  
93 knowledge on the dynamics of equatorial terrestrial systems during the CP period.

94 Therefore, we propose herein to re-evaluate the depositional model of the Autun Basin, based on modern  
95 sedimentological concepts including both facies and sequence stratigraphy analyses, performed on core and  
96 outcrop sections. Last, we aim to explain the variability of the lithological succession in terms of the  
97 paleoenvironmental evolution through time and space and to provide new constraints on the extent of the  
98 sedimentation areas during the CP period in the northeastern French Massif Central.

99

## 100 **2. Geological setting of the Autun Basin**

101 The CP Autun Basin is located in Burgundy (France), south of the Morvan Massif, in the northeastern part of  
102 the Massif Central (Fig. 1). It covers an area extending over ~250 km<sup>2</sup> and overlies a Devonian to Carboniferous  
103 magmatic/metamorphic and sedimentary substratum (Carrat 1969). It displays a sedimentary succession that is  
104 approximately 1.2 km thick, composed of alternating medium-to-coarse and fine-grained lithologies; the latter  
105 includes coal-bearing sequences and black-shale deposits, i.e., oil-shale beds (OSBs) (Marteau 1983). The  
106 depositional time frame has recently been constrained to a time period ranging from the late Ghzelian (latest  
107 Carboniferous) to the early Asselian (earliest Permian, Pellenard et al. 2017; Fig. 1c), using high resolution  
108 chemical abrasion – isotope dilution – thermal ionization mass spectrometry (CA-ID-TIMS) U–Pb ages from  
109 interbedded tonsteins, i.e., distal volcanic ash-fall layers deposited in continental environments, and altered in clay  
110 minerals, dominated by kaolinite (Spears 2012). The structure of the basin was described as a half-graben, later  
111 deformed due to an episode of tectonic flexure (e.g., Delafond 1889; Feys and Greber 1972; Marteau 1983;  
112 Châteauneuf and Farjanel 1989). Along the straight-lined southern margin, it is inferred that a brittle normal fault,  
113 named the Autun fault, partly controlled the CP subsidence of the basin (Marteau 1983; Choulet et al. 2012); today,  
114 it separates the sedimentary succession of the Autun Basin from a southerly Carboniferous (Westphalian) granitic  
115 pluton (Mesvres Granite, Fig. 2a). Along the northern basin's margin, Permian deposits unconformably overlie the

116 Viséan Lucenay-Lévêque Massif. To the east, the contact between the magmatic basement and the Paleozoic  
117 sedimentary units is partly covered by the Mesozoic series, and to the west, the basin is limited by the Saint-  
118 Honoré-les-Bains Massif (Marteau 1983, Fig. 2a).

119 The sedimentary succession of the Autun Basin (Fig. 1c) encompasses two continental regional stages, the  
120 Stephanian and the Autunian, originally defined by their floristic content, and separated by an unconformity (e.g.,  
121 Roche 1881; see Gand et al. 2017 for details). The Stephanian is represented by the Épinac Formation (Fm),  
122 including coal beds and OSBs, and is topped by the Mont Pelé Fm, immediately below the base of the Autunian  
123 series (Fig. 1c). The sedimentation area of the Stephanian Épinac Fm is restricted to the Épinac area, in the eastern  
124 part of the Autun Basin (Fig. 2a), whereas the Autunian deposits are preserved towards the center and the western  
125 part of the basin, where they directly lie on the magmatic substratum (Fig. 2). This Autunian succession is  
126 subdivided into the lower and upper Autunian, the latter being only preserved in the center of the basin (Pruvost  
127 1942; Marteau 1983; Gand et al. 2017). The lithostratigraphic units were first described by Delafond (1889),  
128 followed by Pruvost (1942) and Marteau (1983), who distinguished five units that are equivalent to the present-  
129 day formations: (i) the Igornay Fm (200 to 250 m thick, lower Autunian), composed of claystones and siltstones  
130 with organic matter (OM)-rich beds, i.e., the Moloy coal and the Igornay OSB, and topped by the sandy *Grès de*  
131 *Lally Inférieurs* Unit (Fig. 1c), (ii) the Muse Fm (300 to 400 m thick, lower Autunian), subdivided into the sandy  
132 *Grès de Lally Supérieurs* Unit, with the Lally OSB at its base and the Muse OSB at its top, and the *Grès et Schistes*  
133 *de Muse* Unit (Fig. 1c), (iii) the Surmoulin Fm (~250 m thick, upper Autunian), mainly fine-grained, with the  
134 Surmoulin OSB at the base and some dolomitic levels (Fig. 1c), (iv) the Millery Fm (~300 m thick, upper  
135 Autunian), composed of claystones with carbonate beds, some OM-rich deposits including the Les Télots OSBs  
136 and the pure algal-coal Boghead bed, as well as analcimolite beds in the upper part of the formation (Fig. 1c), and  
137 (v) the Curgy Fm (~100-150 m thick, uppermost Autunian), mainly composed of sandstones (Fig. 1c). The  
138 thickness of the upper Autunian is roughly estimated, as it is based only on descriptions of previous boreholes  
139 obtained from mining exploration, given that outcrops are very sparse and incomplete.

140 In Curgy Hill, in the center of the basin (Fig. 2), some Mesozoic sedimentary successions are preserved  
141 (Triassic and Lower Jurassic), lying above the CP succession (Courel 1970). Due to an erosional event between  
142 the Permian and Triassic (Bourquin et al. 2011), it is likely that upper Permian sediments were deposited in the  
143 Autun Basin but are no longer preserved.

144 The Autun Basin has been extensively investigated for its paleontological content (flora and fauna) and its  
145 mineral resources (coal, oil and uranium) since the 18<sup>th</sup> century, as described by Pruvost (1942), Elsass-Damon

146 (1977) and Marteau (1983). More recently, studies on OM have attempted to characterize the current alteration of  
147 fossil-bearing shales (Odin et al. 2015a, b), as well as to describe the types of OM found in the sediments, their  
148 variations in the stratigraphy, particularly in the main OM-rich levels of the basin, as well as the dynamics of the  
149 carbon and nitrogen cycles (Garel et al. 2017; Mercuzot et al. 2021b).

150 Sedimentologically-based paleoenvironmental reconstructions in the Autun Basin have mostly been carried  
151 out by Marteau (1983), who attributed the fine-grained laminated sediments and OSBs to palustrine/lacustrine  
152 environments based on "varve" features (i.e., seasonal alternations of dark and light-colored laminae), whereas the  
153 medium-to-coarse-grained sediments, including sandstones and conglomerates with trough-cross stratifications  
154 have been interpreted as strict fluvial systems.

155

### 156 **3. Material and methods**

#### 157 **3.1. Core and field sections of the Autun Basin**

158 Four unoriented cores drilled in the Autun Basin have been studied: the Chevrey (CHE-1), Varolles (VAR-1),  
159 Igornay (IG-1) and Muse (MU) cores (Fig. 2). The IG-1 core, drilled in 1965 by the Génie Rural (French rural  
160 engineering) in the village of Igornay (47°2'37.67"N, 4°22'48.70"E; 200 m thick), encompasses a large part of the  
161 Igornay Fm, from the Igornay OSB to the *Grès de Lally Inférieurs* Unit (Fig. 1c). The CHE-1 core (47°0'13.17"N,  
162 4°16'11.01"E; 366 m thick) and the VAR-1 core (47°0'0.31"N, 4°16'5.34"E; 266 m thick), located approximately  
163 10 km from the IG-1 well, were drilled in 1982 by the French Geological Survey (BRGM), with the original goal  
164 being to cross over the whole lower Autunian succession. The MU core (47°1'36.85"N, 4°22'54.56"E, 8 m thick)  
165 was drilled in the village of Muse to complete the observations on the historical Muse outcrop which has been  
166 excavated since 2010 for paleontological studies (Gand et al. 2011, 2014, 2015). It encompasses the uppermost  
167 part of the *Grès de Lally Supérieurs* Unit at the base of the well, and the totality of the Muse OSB.

168 Lastly, in order to complete the analysis of the core data, outcrops of the *Grès de Lally Inférieurs* Unit (Figs.  
169 1c, 2) have been studied at the former Les Chevrots (47°1'15.81"N, 4°26'25.81"E; 8 m thick) and Rigny quarries  
170 (47°1'14.35"N, 4°26'4.06"E; 15 m thick), and at the Arroux viaduct section (47°1'57.36"N, 4°21'52.86"E; 6 m  
171 thick). The Rigny and Chevrots sections have been previously studied by Marteau (1983), who assigned their  
172 medium to coarse-grained clastic sediments to a fluvial environment, either meandering or braided, as trough-cross  
173 stratifications are found together with beveled sedimentary geometries.

174

### 175 **3.2. Facies analysis to reconstruct the evolution of the depositional environment**

176 All of the studied sections (i.e., cores and outcrops) belong to the first half of the lower Autunian sedimentary  
177 succession (Igornay and Muse fms, Figs. 1c, 2), and have been described according to their granulometry and  
178 sedimentary features, at a scale of 1:50 for the MU, IG-1 and CHE-1 cores, and 1:100 for the VAR-1 core.

179 Each determined sedimentary facies corresponds to a depositional process, and the facies are grouped into  
180 facies associations, and are then ascribed to depositional environments, i.e., along the succession from a landward  
181 to a basinward position (Table 2).

182 All of the facies codes (Table 1) are largely based on the classifications provided by Miall (1978) and Postma  
183 (1990), established for fluvial and delta deposits, respectively. As some facies present in the Autun Basin were not  
184 described by these authors (because they are related to other depositional processes), these classifications have  
185 therefore been extended in this work, as already done in the works of Ducassou et al. (2019) and Mercuzot et al  
186 (2021a) in the neighboring Decize-La Machine CP Basin.

187 The granulometry is divided into three grain sizes: fine-grained facies with clays ( $< 4 \mu\text{m}$ , i.e., claystones) and  
188 silts ( $< 63 \mu\text{m}$ , i.e., siltstones), medium-grained facies with sands (fine sand  $< 0.25 \text{ mm}$   $<$  medium sand  $< 0.5 \text{ mm}$   
189  $<$  coarse sand  $< 2 \text{ mm}$ , i.e., sandstones), and coarse-grained facies, with gravels and some pebbles ( $< 2 \text{ cm}$  and  
190  $> 2 \text{ cm}$ , respectively, i.e., conglomerates). The grain size is indicated by a capital letter (F for fine-grained facies,  
191 S for sands, G for conglomerates; and two capital letters are used for heterolithic facies), preceded by an I when  
192 the sets are inclined, and followed by lowercase letters indicating the main sedimentary features or deformations  
193 (m for massive, mm for matrix supported, l for horizontal to sub-horizontal laminations, r for current ripples, w  
194 for wave ripples, t for trough cross-stratifications, mud for mudclasts, clast for clasts of various nature, i for  
195 injectites, and d for deformed structures). T and C represent the tonstein and carbonate levels, respectively.

### 197 **3.3. Organic matter characterization**

198 Claystone and siltstone samples from the IG-1 core (215 samples), CHE-1 core (331 samples) and MU core  
199 (36 samples) were analyzed using the Rock-Eval thermal analysis method described by Behar et al. (2001) at the  
200 IStEP laboratory (Sorbonne Université, Paris). Several measurements were obtained from the successive pyrolysis  
201 and oxidation of  $\sim 60 \text{ mg}$  of powder. Only the total organic carbon (TOC, expressed in wt.%), calculated as the  
202 sum of the pyrolyzed and residual organic carbon, is presented here, with an estimated uncertainty of  $\pm 0.05 \text{ wt.}\%$ .



### 204 **3.4. Sequence stratigraphy**

205 High-resolution sequence stratigraphy principles have been applied to the studied sedimentary succession of  
206 the Autun Basin, based on the observed stacking pattern of the smallest stratigraphic units, i.e., parasequences or  
207 genetic units (e.g., Cross 1988; Van Wagoner et al. 1988; Mitchum and Van Wagoner 1991; Cross et al. 1993). In  
208 continental sedimentary successions, genetic units are defined using a high-resolution reconstruction of the  
209 depositional environment evolution, i.e., by determining the position of the deposits along a landward–basinward  
210 transect. Therefore, it allows to identify larger-scale progradational–retrogradational cycles (i.e., stratigraphic  
211 cycles). These cycles are separated by the maximum regressive surface (MRS, lowest lake level, at the end of the  
212 progradational trend), and topped by the maximum flooding surfaces (MFS, highest lake level, at the end of the  
213 retrogradational trend, Wheeler 1964; Cross et al. 1993). Stratigraphic cycles depend on variations of the  
214 accommodation space ‘A’ combined with changes in sediment supply ‘S’, both of which are driven by climate  
215 (i.e., precipitation vs. evaporation rates, driving lake expansion/contraction phases) and deformation (tectonic  
216 processes, subsidence of the basin, e.g., Cross 1988; Jervey 1988; Galloway 1989; Galloway and Williams 1991;  
217 Mutto and Steel 2002; Péron et al. 2005; Bourquin et al. 2009); the trend is retrogradational when  $A/S > 1$  and  
218 progradational when  $A/S < 1$ .

219 In a mixed alluvial and lacustrine depositional environment, MFSs can reliably be used to recognize, delineate,  
220 and correlate genetic sequences (e.g., Bourquin et al. 1998), and the quantification of the OM content makes it  
221 easier to identify them. Sedimentary OM content (i.e., OM preservation, reflected by the TOC values), depending  
222 on OM production minus OM degradation, versus OM dilution (Bohacs 1990; Bohacs et al. 2000), is at its  
223 maximum in the most profundal lacustrine deposits (corresponding to MFSs) where the sedimentation rates are  
224 low, and where the sediments and the base of the water column remain dysoxic or anoxic, preventing the  
225 remineralization of OM. On the contrary, MRSs are defined where the most landward environments are observed,  
226 most of the time associated with low OM content due to effective oxidation.

## 228 **4. Re-evaluation of the paleoenvironments**

### 229 **4.1. Determination of the depositional environments from facies associations**

230 The sedimentary description of both the field sections and the cored wells of the Autun Basin has highlighted  
231 a total of 19 facies, detailed in Table 1 and pictured in Figures 3 to 6, ranging from fine-grained to coarse-grained  
232 facies, either homolithic or heterolithic, with a mean grain size of ~2-5 mm, and a maximum grain size of ~5 cm  
233 (rare levels). The observation of thin sections, taken from facies composed of fine sands to gravels, has provided

234 evidence for a wide diversity in detrital grains, dominated by rhyolitic quartz, feldspars and lithic fragments (Fig.  
235 4c, d, e). The grains are subangular to angular, therefore indicating immature material, moderate transport, and a  
236 sediment source that is likely quite close to the sedimentation area.

237 The facies are grouped into facies associations, used to interpret depositional environments (Table 2). The  
238 facies associations are named according to the lacustrine classification of Bohacs et al. (2000) that defines  
239 depositional environments based on the bathymetry of the deposits, depending on the subdivisions established for  
240 lacustrine water-column, i.e., epilimnion (superficial waters), thermocline (physical-chemical transition zone) and  
241 hypolimnion (bottom waters). Thus, this classification depends on the position of the deposits along a landward-  
242 to-basinward (i.e., proximal-distal) transect: the littoral lake (L) environment encompasses facies deposited at  
243 epilimnion-interval bathymetries, the sublittoral lake (SL) environment encompasses facies deposited at  
244 thermocline-interval bathymetries, and the profundal lake (P) environment includes facies deposited at  
245 hypolimnion-interval bathymetries. These positions were then subdivided by considering the sediment supply  
246 variations and the main depositional processes in each of them (Table 2), with a total of seven facies associations;  
247 these subdivisions are represented in the theoretical depositional model presented in Figure 7. The facies  
248 associations are described below, followed by the sedimentary descriptions of the field sections, where the facies,  
249 facies associations and their relationships (sedimentary architectures) are displayed; then, the facies associations  
250 in cored wells, and the related environmental evolution, are presented.

251

#### 252 **4.1.1. Facies association L1**

253 The L1 facies association, illustrated in Fig. 3, is dominated by medium-to-coarse-grained facies (i.e., coarse  
254 sands to pebbles), organized in beds that are one to several meters thick, either planar-laminated (GSl facies, Table  
255 1, Fig. 3b), with trough-cross stratifications (GSt facies, Table 1, Figs. 3 b), or massive (GSm facies, Table 1, Figs.  
256 3a, b). Given this range of granulometries, the planar bedding indicates high-energy tractive currents, and the  
257 trough-cross stratifications are interpreted as 3D megaripple migration. However, less common heterolithic facies,  
258 such as the SF facies (silt to coarse-sand m-thick levels, often lenticular and without marked contacts, Table 1),  
259 the St/F facies (medium-to-coarse-sand dm-thick levels with trough-cross stratifications, alternating with clayey  
260 to silty material, Table 1), and the GSmm/F facies (dm-thick coarse sands to gravels in a fine-grained matrix,  
261 alternating with fine-grained levels, Table 1), indicate more contrasted periods in terms of sediment fluxes, with  
262 calmer episodes allowing for the settling of the finest-grained particles. However, homolithic claystone and  
263 siltstone beds (F facies, Table 1) are scarce and relatively thin (dm-thick levels). Bioturbations can be found at the

264 top of some GSt-facies beds, indicating that this was a favorable environment for subaquatic life, and oxygenated  
265 waters, at least up to the water/sediment interface.

266 This facies association, showing high-energy current features, together with the dominant medium-to-coarse  
267 granulometries, and the frequent erosional surfaces, reflects high detrital inputs into the basin. A fluvial  
268 environment could be considered here, but the total absence of emersion evidence or pedogenic features (i.e., root  
269 traces, pedogenic nodules, slickensides, etc) instead suggests a strictly subaquatic, yet shallow environment, i.e.,  
270 a littoral lake environment (Fig. 7) with characteristics of deltaic topset deposits (e.g., Nemeč 1990; Postma 1990;  
271 Bhattacharya 2006; Rohais et al. 2008; Table 2).

272

#### 273 **4.1.2. Facies association L2**

274 The L2 facies association, represented in Fig. 3, is predominantly composed of fine to medium-grained facies,  
275 as well as carbonate deposits. The claystone to siltstone facies (F facies, several meters thick, Fig. 3a) are mostly  
276 massive, sometimes laminated, with an OM content up to 21 wt.%. These facies are associated with carbonate  
277 levels, either massive, likely diagenetic (cm-thick, Ca facies, Table 1), or they display very fine irregular laminae,  
278 sometimes encrusting remains of trunks, and are attributed to a microbial activity (Cs facies, dm-thick, Table 1,  
279 Fig. 3c). Some dm to m-thick levels present a coarser-grained lithology (fine to medium sand, rarely coarse),  
280 displaying wave-ripples (Sw facies, Fig. 3d), or forming lenticular bodies included in a silty material (SF facies),  
281 reflecting periods of sedimentary inputs, although very low. Only rare cm to dm-thick sandy beds, showing planar  
282 or trough-cross stratifications, indicate periods of deposition under a tractive current influence (GSI and GSt facies,  
283 fine to medium sand, Fig. 3a).

284 According to Burne and Moore (1987), Visscher et al. (1998) and Dupraz et al. (2009), microbial carbonate  
285 deposits are organomineralized structures formed by the association of benthic micro-organisms, some of which  
286 use photosynthetic metabolisms in most reported cases. Therefore, their presence implies a low water column  
287 (euphotic zone) with reduced sediment supply (no turbidity), allowing for chemical or biologically-induced  
288 carbonate precipitation when the concentration in carbonate and calcium ions is sufficient. Some carbonate  
289 microbial deposits have already been described in French CP basins, and assigned to shallow aquatic environments,  
290 either marginal lacustrine or fluvial, based on sedimentological evidence (features reflecting shallow  
291 environments, like mudcracks or root marks, oncoids or oolites) and biological evidence (photosynthetic  
292 metabolisms, e.g., Freytet et al. 1992, 1999, 2000; Gand et al. 1993; Stapf and Gand 1994).

293 The above-mentioned facies dominated by very low-energy deposits, in association with the microbial deposits,  
294 are thus attributed to a quiet littoral lake environment (Table 2), i.e., a shallow lake where the detrital sediment  
295 fluxes are minimal, either because of limited erosion in the watershed, or because they are located laterally from  
296 the main distributaries (Fig. 7). Some OM-rich levels preserved in the Autun Basin have already been attributed  
297 to such a shallow lake environment by Garel et al. (2017).

298

#### 299 **4.1.3. Facies association SL1**

300 The SL1 facies association, displayed in Fig. 4, is mainly composed of inclined facies, presenting a large range  
301 of granulometries, from claystones to pebbly conglomerates. The medium-to-coarse-grained facies are dominant,  
302 in dm to m-thick beds with erosive bases, either homolithic massive (IGSm facies, Table 1, Figs. 4a, c, 5a) or  
303 laminated (IGSl facies, Table 1, Figs. 4a, c, 5a), or heterolithic (IGSm/F facies, Table 1, Fig. 4c), sometimes  
304 matrix-supported (IGSmm/F facies, Table 1). These heterolithic facies are dominated by sandstones and  
305 conglomerates, organized in m-thick beds, and are topped by cm to dm-thick fine-grained beds (claystones to  
306 siltstones). Some fining-upward sandstone levels, sometimes beginning with gravels, followed by planar-  
307 lamination and ripple intervals, are interpreted as hyperconcentrated turbidite deposits, displaying parts of the  
308 Bouma sequence (GSB facies, with the Ta, Tb and Tc Bouma divisions, respectively, Bouma 1962, Table 1). Some  
309 matrix-supported coarse-grained lithologies, interbedded with fine-grained levels, are interpreted as debris flow  
310 deposits, alternating with calmer periods of settling of clays or silts (GSmm/F facies).

311 The inclination of the dominant facies of the SL1 facies association is attributed to a sedimentary dip rather  
312 than a tectonic tilting, given their association with numerous gravity-flow deposits, the absence of faults (either  
313 syn-sedimentary or post-depositional), and their observation at both the large (i.e., outcrops) and small scale (i.e.,  
314 cores). The sedimentary dip, together with the dominant facies reflecting high sedimentary fluxes alternating with  
315 phases of settling of fine-grained particles, and with the turbidite and the debris flow deposits, likely indicate  
316 deltaic foresets (e.g., Lowe 1982; Postma 1984; Colella et al. 1987; Kostaschuk and McCann 1989; Nemeč 1990;  
317 Massari 1996; Breda et al. 2007; Rubi et al. 2018) that are prograding into a sublittoral lake environment (Table  
318 2).

319

#### 320 **4.1.4. Facies association SL2**

321 The dominant facies of the SL2 facies association, represented in Fig. 5, are sandy to gravelly, dominated by  
322 dm to m-thick massive beds, with erosive or planar basal contacts (GSm facies, Fig. 5b), attributed either to

323 cohesive debris flows or to high-density turbidite deposits. Numerous dm to m-thick beds, with erosive bases and  
324 showing a vertical organization with fining-upward trends from gravels to coarse sands, planar bedding, current  
325 ripples and settling of fine-grained particle intervals are also displayed, attributed to the GSB facies, with the  
326 divisions of the Bouma sequence (Ta to Te, Bouma 1962, Fig. 5c). This facies indicates hyperconcentrated to low-  
327 density turbidity currents, here interpreted as relatively proximal along a landward-basinward transect, given their  
328 significant thickness and the medium-to-coarse-grained Ta division. Deformed beds measuring several meters  
329 thick, mixing fine-to-coarse-grained material and frequently showing folding structures (GSF<sub>d</sub> facies, Table 1),  
330 are interpreted as slump and slide deposits. Some sandstone to conglomerate beds, displaying planar laminations  
331 (GSI facies, Fig. 5a mostly dm-thick), or trough-cross stratifications (GSt facies, mostly m-thick), are included in  
332 this SL2 facies association, reflecting high-energy tractive currents. Other scarcer facies are also included,  
333 consisting in heterolithic alternations of medium-to-coarse-grained lithologies, sometimes matrix-supported, with  
334 fine-grained lithologies, reflected by the GS<sub>m</sub>m/F, Sm/F (Fig. 5b), F/Sm and FS facies (Table 1). Some periods of  
335 settling of fine-grained particles are also displayed, reflected by the F facies.

336 The GSt facies, associated with slumps, thick coarse-grained turbidites and heterolithic facies, is interpreted as  
337 hydraulic jump deposits formed at a slope break (e.g., Simons and Richardson 1963; Middleton 1965; Breda et al.  
338 2007). It reflects a delta toset geometry, i.e., the tangential transition from the deltaic foreset to the bottomset in  
339 a sublittoral lake environment, and/or gravelly bottomsets (i.e., Postma and Roep 1985; Rohais et al. 2008; Gobo  
340 et al. 2014; Rubi et al. 2018), therefore indicating prodelta deposits, i.e., the transition between the inclined foresets  
341 and the strict lacustrine environment.

342

#### 343 **4.1.5. Facies association SL3**

344 This facies association, illustrated in Fig. 5b, presents similarities with the facies association SL2, with  
345 numerous turbidite deposits reflected by the GS<sub>m</sub> and GSB facies (Fig. 5c), and tractive current influence reflected  
346 by the planar-laminated GSI facies. The main differences are: (i) the sandy-to-gravelly beds are thinner and scarcer  
347 on average (mostly dm-thick), in favor of more heterolithic facies, displaying thicker levels of fine-grained  
348 lithology, such as GS<sub>m</sub>m/F, Sm/F (Fig. 5b), F/Sm and FS facies, (ii) the basal granulometry of the coarser turbiditic  
349 levels (i.e., GS<sub>m</sub>, GSB) does not exceed the medium to coarse sands, and (iii) the Fl/Sr facies (Table 1), absent in  
350 the SL2 facies association, likely reflects alternations between periods of moderate tractive current (i.e., current  
351 ripple intervals) and of settling of fine-grained particles. Some relatively scarce dm to m-thick levels of matrix-  
352 supported conglomerates, constituted by large mudclasts (cm to dm-sized) floating in a fine-to medium-sand grey-

353 to-black matrix (Smud facies, Table 1, Fig. 5d), are interpreted as distal debris flows given that the eroded material  
354 partly comes from the fine-grained facies.

355 Accordingly, the SL3 facies association is characterized by more distal turbidite deposits than the SL2 facies  
356 association, that alternate with more significant calm periods of settling of fine-grained particles. Therefore, this  
357 facies association indicates fine-grained prodelta deposits (e.g., Postma and Roep 1985; Gilbert 1985; Rubi et al.  
358 2018), still in a sublittoral lake environment (Table 2, Fig. 7), but more distal than the SL2 facies association.

359

#### 360 **4.1.6. Facies association P1**

361 Facies association P1, detailed in Fig. 6, comprises both homolithic and heterolithic fine-grained facies. The  
362 homolithic F facies (Fig. 6a) dominates in intervals spanning several meters and is either massive or finely  
363 laminated (i.e., alternation of millimeter-thick clays, silts and siderite laminae); the latter is interpreted as varve  
364 deposits by Marteau (1983), yet without clear evidence of a seasonal control. It often contains fish fossils or  
365 remains (scales and coprolites), and sometimes presents OM enrichments. It alternates with the heterolithic F/Sm  
366 facies (cm-thick massive sandy levels interbedded in massive claystones to siltstones, Fig. 5b), and the laminated  
367 Fl/Sr facies (Fig. 6c), where the sandy levels contain current ripple marks (Figs. 6b, c). Tonstein levels (T facies)  
368 are frequently found embedded in the fine-grained beds. Some dm-thick medium-to-coarse-grained beds with  
369 erosive bases, either massive (facies GSm, Fig. 6a) or with large mudclasts (facies Smud), are intercalated in the  
370 fine-grained facies, and are interpreted as debris flows or grain flows; some dm-thick levels of GSB facies, mostly  
371 fine to medium-grained are also found and are interpreted as distal turbidites (Bouma sequence). Sometimes, some  
372 interbedded massive cm to dm-thick sandy levels in fine-grained intervals (claystones-siltstones) show injection  
373 patterns (SF<sub>i</sub> facies, Table 1), due to differential compaction, given the contrasted lithologies.

374 This facies association, dominated by fine-grained sediments deposited in a calm environment, yet presenting  
375 some gravity flow deposits (i.e., distal turbidites, debris flows and grain flows), is attributed to a profundal lake  
376 environment, with low sediment fluxes (Table 2, Fig. 7).

377

#### 378 **4.1.7. Facies association P2 and P2a**

379 Facies association P2, represented in Fig. 6, presents strong similarities with facies association P1. The fine-  
380 grained facies dominate, but the homolithic facies (F facies, Figs. 5d, 6d, e, f) are more present than the heterolithic  
381 facies. They are sometimes finely laminated (Fig. 6e), may contain scarce thin sandy lenses (Fig. 6d), and are very  
382 rich in fish remains (e.g., scales, coprolites, Fig. 6f), even containing selachian coprolites (freshwater sharks,

383 already found in Western European CP basins such as the Aumance, Blanzey–Le Creusot, Autun, or Saar-Nahe  
384 basins, Fischer et al. 2013; Schneider and Zajic 1994; Schneider et al. 2000; Luccisano et al. 2021). The heterolithic  
385 facies are constituted by massive claystones to siltstones alternating with fine to medium-grained sandstones,  
386 always massive (i.e., F/Sm facies), never showing current features, but sometimes showing bioturbations (Table 1).  
387 The coarsest levels are only represented by (i) the mm to cm-thick sandy levels of the F/Sm facies, the cm-thick  
388 fine to medium-grained sandy beds attributed to grain flows (GSm Facies) or to distal turbidites when showing  
389 Bouma sequence divisions (GSB facies), (ii) the rare m-thick dark siltstone beds, containing some mm-sized  
390 floating grains and interpreted as low-density tails of turbidity currents (Fclast facies, Te division of the Bouma  
391 sequence; Bouma 1962), and (iii) the rare dm-thick debris flows (Smud facies), thus indicating minimal sediment  
392 fluxes. This interpretation is also supported by the highest OM enrichment in the F facies with TOC values up to  
393 21.5 wt.%, reflecting periods of dysoxic to anoxic bottom waters and sediments under a sustained water-column  
394 stratification (chemocline/thermocline). Like for the P1 facies association (profundal lake environment with low  
395 sediment fluxes), tonstein layers (T facies) are observed since these low hydrodynamic environments are prone to  
396 fine-grained material preservation.

397 Therefore, this facies association is attributed to a profundal lake environment in its most distal part, with  
398 minimal sediment supply preventing the homogenization of the water column and favoring OM preservation when  
399 dysoxic to anoxic conditions are reached (P2a facies association, Table 2, Fig. 7), as evidenced by Mercuzot et al.  
400 (2021b).

401

## 402 **4.2. Architectures and depositional environment evolution based on field sections**

### 403 **4.2.1. The Chevrots section**

404 This outcrop section (Fig. 8), located above an OM-rich level attributed to the Igornay OSB, based on mining  
405 work and cartography (Fig. 2), represents the base of the *Grès de Lally Inférieurs* Unit (Fig. 1c), and displays a  
406 3D view with two E–W-oriented sections (Chevrots 1 and Chevrots 2; Fig. 8) and one WSW–ENE-oriented  
407 section. In the Chevrots 1 E–W section (Fig. 8), lenticular sandstone bodies are observed, with massive coarse-  
408 grained sands to gravels at the base (GSm facies) and with mudclasts highlighting horizontal bedding at the top  
409 (Smud facies, Fig. 8), alternating with planar laminated fine-grained lithologies (fine to medium sand, GSI facies,  
410 high-energy planar bedding). The top of the medium-to-coarse-grained levels is undulated to irregular (Fig. 8),  
411 indicating either an erosional event, the eroded material being deposited basinward, or a stasis in the sedimentation  
412 before the deposition of fine-grained lithologies filling the depressions. The coarse-grained layers also display

413 thickening-upward and coarsening-upward sequences. The WSW–ENE section shows downlap structures, with  
414 inclined laminated and massive facies (IGS1, IGSm facies, Fig. 8), and an evolution from fine-grained to coarse-  
415 grained lithologies is observed from the base to the top of the outcrop (Fig. 8). On the Chevrots 2 E-W section  
416 (Fig. 8), the beds become coarser towards the top, and the thickening-upward pattern of the strata reflects a  
417 progradational architecture. Altogether, the sedimentary features observed in the Chevrots section indicate a  
418 progradation of the sandstone bodies towards the WSW (almost parallel to the WSW–ENE section), also supported  
419 by a N200-oriented flute cast observed at the base of a coarse-grained bed in the Chevrots 1 section (Fig. 8c),  
420 rather than lateral accretion processes in a fluvial channel, as previously interpreted by Marteau (1983).

421 Although it is not possible to accurately restore the original sedimentary dip of these strata due to the  
422 subsequent moderate tectonic activity affecting the basin (i.e., post-early Permian faulting and tilting), all of the  
423 sedimentological characteristics observed on this outcrop indicate deltaic foreset deposits that can be attributed to  
424 a sublittoral lake SL1 environment (Table 2).

425

#### 426 **4.2.2. The Rigny section**

427 The Rigny section is located 450 m away from the Chevrots section and is representative of the same  
428 stratigraphic interval. This former quarry is suitable to observe the layer relationships and geometries, but cannot  
429 be used to provide a precise description of the facies as it is difficult to access the outcrop (height, vegetal cover).  
430 Although detailed sedimentary logs are not available, the strata displayed on the Rigny outcrop undoubtedly show  
431 a general coarsening-upward trend, from fine-grained sandstones at the base of the outcrop, to conglomerates at  
432 the top. The strata are thickening-upward and their general thickening towards the west, together with the inclined  
433 geometries, indicate progradational features (Fig. 9). Three major architectural characteristics are also observed:  
434 (i) onlap structures at the base of the prograding sets, interpreted as backset deposits, formed under a turbulent  
435 flow (hydraulic jump) in the deltaic toset (i.e., sublittoral lake SL2 environment, displayed on Fig. 5a), (ii)  
436 inclined strata towards the west, and (iii) an erosional surface filled by sandy material, attributed to a chute-fill  
437 structure eroding the underlying set. The two latter geometries indicate prograding deltaic sets, i.e., deltaic foreset  
438 deposits in the sublittoral lake SL1 environment, with a roughly WSW/SW flow direction, given that the outcrop  
439 is almost parallel to the prograding sets. Towards the top of the outcrop, the dip of the stratification is lower and  
440 the lithologies are dominated by conglomerates, likely massive with erosive bases. This interval can be attributed  
441 to deltaic topset deposits in a littoral lake L1 environment (Fig. 9).

442



#### 4.2.3. The Arroux section (ARR)

The base of the Arroux section (Fig. 10) is characterized by a massive m-thick coarse-sand level (GS<sub>m</sub> facies) containing trunk casts filled by sand and encrusted by microbial carbonate deposits (Cs facies, Figs. 3c, 10). Then, erosive sandy beds, fine to medium-grained, homolithic with planar laminations (GS<sub>l</sub> facies) or heterolithic (Sm/F facies), alternate with fine-grained facies (F facies, siltstones dominant) containing plant fragments. At the top of the section, another sandy level (very coarse sand, GS<sub>m</sub> facies) was found, associated with microbial deposits. Considered all together, the trunks preserved in living position, the wave ripples (Fig. 3d) in the sandy facies, and the associated microbial deposits indicate a marginal lake environment. Therefore, this facies succession corresponds to an alternation between a littoral lake environment, when sediment fluxes are minimal (fine-grained lithologies, protected lake environment L2), and a littoral lake L1, during periods of higher sediments fluxes (high-energy sandy facies).

#### 4.2.4. The Muse section and well (MU)

The Muse section is only composed of the Muse OSB, whereas the MU well encompasses the Muse OSB and the uppermost part of the *Grès de Lally Supérieurs* Unit (Fig. 1b). The well displays 3D megaripple structures (GS<sub>t</sub> facies, Table 1) at its base, indicating a littoral lake L1 environment (deltaic topsets, Fig. 11). Then, medium-to-coarse-grained planar laminated facies (GS<sub>l</sub> facies), rich in floating higher plant debris, indicate a sublittoral SL2/SL3 environment, and are followed by a littoral lake L2 environment, marked by massive fine-grained lithologies (i.e., claystones to very fine-grained sandstones), also rich in plant fragments. At the top of the core, the black shales (facies F) indicate a deeper lacustrine environment (P2) with a sustained water-column stratification, allowing for dysoxic/anoxic conditions at the base of the water column and in the sediments, as shown by the high TOC content (up to 28 wt.%). The coarse-grained lithologies in the MU well are oxidized, probably due to recent weathering as material from this core is close to the surface.

### 4.3. Evolution of the depositional environment inferred from subsurface data

#### 4.3.1. The Igornay core (IG-1)

The IG-1 core (Fig. 12) presents an overall trend from dominantly fine-grained to coarse-grained facies. The association of fine-grained facies, either homolithic, sometimes OM-rich, or heterolithic, with scarce medium-to-coarse-grained lithologies reflecting turbidites or debris flows, indicates intervals of profundal lake environments that are more or less distal (P2 to P1 environments, Table 2) depending on the frequency, thickness and

473 granulometry of the coarsest-grained levels. When displaying dysoxia to anoxia features (laminated OM-rich  
474 facies), the facies association is instead representative of the P2a environment (Table 2), as was the case at the  
475 base of the core and between 155 and 148 m (i.e., Igornay OSB, Figs. 1b, 12).

476 These profundal-lake facies associations are often interbedded with intervals of coarser-grained facies,  
477 occurring in dm-thick to several meters thick beds from sandstones to conglomerates, either thickening-upward  
478 (i.e., at the expense of the finest-grained facies) as shown at the base of the core, or thinning-upward above the  
479 Igornay OSB (Fig. 12). These intervals are composed of massive facies, sometimes matrix-supported or containing  
480 large mudclasts (i.e., debris flows), or displaying Bouma sequence divisions reflecting turbidite deposits, both of  
481 them indicating a sublittoral lake environment with significant or moderate sediment fluxes, reflecting prodelta  
482 deposits (SL2 and SL3 environments, respectively, Table 2). Some energetic medium-grained facies, with planar  
483 bedding and trough-cross stratifications, mark substantial flows and are interpreted as deposited in gravelly  
484 bottomsets or through hydraulic jumps occurring in deltaic toesets, respectively (SL2 environment, prodelta, Table  
485 2).

486 The coarsest lithologies of the IG-1 core (medium-to-coarse-grained facies) are located in the upper third of  
487 the core (Fig. 12). Some intervals display inclined facies with current features alternating with thin beds of finer-  
488 grained facies deposited during periods of fine-grained particle settling, as well as thickening-upward sequences  
489 and interbedded slump levels, thus indicating deltaic foreset progradations in a sublittoral lake environment (SL1,  
490 Table 2). Other intervals present planar-bedded facies or trough-cross stratifications, indicating maximal sediment  
491 fluxes and 3D-megaripple migration and therefore an even shallower environment, i.e., a sublittoral lake  
492 environment displaying deltaic topsets (L1 environment, Table 2). However, these facies are alternating with  
493 periods of very low-energy and sediment fluxes reflected by fine-grained levels, often OM-rich, sometimes  
494 bioturbated or containing some microbial carbonate deposits, marking a protected littoral lake environment (L2).

495

#### 496 **4.3.2. The Chevrey core (CHE-1)**

497 The lower half of the CHE-1 core displays an alternation between the fine-grained homolithic facies, containing  
498 some whitish tonstein levels and heterolithic facies (Fig. 13). Some dm-thick coarser-grained facies, reflecting  
499 distal turbidites or debris flows, are also displayed. The dominant fine-grained facies mostly indicate profundal  
500 lake P1 (when some detrital fluxes are deciphered by cm to dm-thick turbidite levels) and P2 environments, and  
501 sometimes P2a environments when dysoxic/anoxic conditions are reached (i.e., OM-rich deposits at ~330 m, Fig.  
502 13, Table 2). Several periods of slightly enhanced sediment fluxes (dm-thick sandstone beds with current features,

503 alternating with fine-grained lithologies, on 1 to 2 m thick intervals) indicate prodelta deposits in sublittoral lake  
504 SL2 and SL3 environments (Table 2). Embedded in this interval of dominantly profundal and sublittoral lake  
505 environment deposits, a ~30 m thick interval of mostly sandy to conglomeratic facies is found around 200 m,  
506 sometimes displaying trough-cross stratifications indicating 3D megaripple migrations in a littoral lake L1  
507 environment (major sediment supply in deltaic topsets), or sometimes with inclined facies, indicating a sublittoral  
508 lake SL1 environment (active deltaic foresets, Table 2).

509 The upper half part of the core begins with a ~25 m thick OM-rich interval composed of fine-grained facies  
510 attributed to the Lally OSB (Fig. 13), indicating a profundal lake P2a. Above, another alternation between deposits  
511 from profundal (fine-grained facies, from claystones to fine-grained sandstones) and sublittoral environments  
512 (frequent turbidites and grain flows, SL2 and SL3 prodelta deposits) is observed. However, the sandy to  
513 conglomeratic facies representing prodelta deposits are dominant over the fine-grained facies, with a thickening-  
514 upward trend. Two ~8 m thick intervals, dominated by coarse-grained facies with planar stratifications indicating  
515 high-energy currents, and reflecting deltaic topsets in a littoral lake L1 environment, are observed in this upper  
516 half part of the core.

517

#### 518 **4.3.3. The Varolles core (VAR-1)**

519 The depositional environment evolution in the VAR-1 core is displayed in Fig. 14. This core is dominated by  
520 an alternation between intervals of fine-grained facies, dominant at the base of the core, and intervals of medium-  
521 to-coarse-grained facies which, conversely, become dominant towards the top of the core.

522 The fine-grained facies are mostly characterized by laminated claystones to siltstones, sometimes finely  
523 laminated and OM-rich, reflecting a low-energy environment, assigned to a P2 profundal lake when the sediment  
524 fluxes are minimal (cm-thick fine to medium sandy levels), or to a P1 profundal lake environment when they are  
525 slightly more substantial, reflected by distal turbidites (heterolithic fine-grained facies, sometimes with Tb, Tc or  
526 Te divisions of the Bouma sequence) and scarce grain flows or debris flows. Close to the top of the core, a ~20 m  
527 thick interval composed of very fine-grained laminated black facies is displayed, with numerous fish remains, and  
528 is attributed to a dysoxic/anoxic profundal lake environment P2a, representing the Lally OSB according to Marteau  
529 (1983).

530 The second end-member, in terms of the facies association, is composed by ~5 m thick sets, either (i) dominated  
531 by fine-to-medium-grained heterolithic facies or homolithic facies, mainly massive or with planar bedding, and  
532 attributed to grain flows or turbidites deposited in a prodelta, in the sublittoral lake environment (SL2/SL3 facies

533 associations), or (iii) showing inclined medium-to-coarse-grained facies (grain flows and debris flows), sometimes  
534 deformed (i.e., slumps), reflecting deltaic foresets (sublittoral lake SL1 environment, Table 2), which have a much  
535 higher representation in the VAR-1 core compared to the IG-1 and CHE-1 cores.

536 Scarce plurimetric intervals displaying medium-to-coarse-grained facies, with high-energy planar bedding or  
537 trough-cross stratifications, are attributed to deltaic topsets (littoral lake L1 environment), and narrow intervals of  
538 fine-grained facies (claystones to siltstones), either finely laminated or massive, sometimes showing horizontal  
539 and vertical burrows, likely indicate a shallow low-energy environment, i.e., a protected littoral lake (L2  
540 environment; Fig. 14, Table 2). These most landward facies associations are only found in the lower third of the  
541 core.

542

## 543 **5. Basin-scale sequence stratigraphy correlations**

### 544 **5.1. Stratigraphic cycles based on the evolution of the depositional environments and OM** 545 **accumulation rates**

#### 546 **5.1.1. The Igornay well (IG-1)**

547 In IG-1, the TOC content values vary between 0.12 and 20.36 wt.% (Fig. 12), and the highest values can be  
548 used to determine the location of the MFSs in the sequence stratigraphy analysis. This core displays five intervals  
549 with very high TOC values: (i) at the base of the core (TOC ~15-17 wt.%), (ii) around 150 m, where the highest  
550 values are found (TOC up to 20 wt.%), (iii) around 85 m (TOC up to 12 wt.%); between 35 and 40 m (TOC up to  
551 16 wt.%) and around 22 m (TOC up to 13 wt.%). All of these intervals are associated with black fine-grained  
552 lithologies, mostly deposited in a profundal lake environment (P2 facies association, Fig. 12), or in a protected  
553 littoral lake environment (L2 facies association, Fig. 12).

554 Based on the depositional environment evolution described above and on these OM-content variations, four  
555 stratigraphic cycles have been identified in the IG-1 core (Fig. 12). The first one, from 200 to 152 m, encompasses  
556 a large progradational trend from a profundal dysoxic/anoxic lacustrine environment (P2a facies association) to a  
557 sublittoral lake environment (SL2 facies association, gravelly bottomsets in a prodelta), up to the MRS located at  
558 162 m. This trend is then reversed, with a retrogradational trend ending by a MFS at 152 m, within an  
559 anoxic/dysoxic profundal lake P2a environment, corresponding to the Igornay OSB (Marteau 1983). The second  
560 cycle, from 152 to 87 m, is progradational up to 128 m, from the previous profundal-dysoxic/anoxic lake P2a  
561 environment, to the sublittoral lake SL2 environment constituting the MRS. The retrogradational trend, up to 87 m,  
562 bounded by a MFS in a 1 m thick interval of profundal lake P2a deposits, is gradual and displays several

563 occurrences of sublittoral lake SL3 deposits (i.e., fine-grained prodelta deposits), between the profundal lake P1  
564 and the sublittoral lake SL2 (toesets/gravelly bottomsets in a prodelta) endmembers. The third cycle, from 87 to  
565 40 m, is progradational up to the MRS located at 53 m, corresponding to a littoral lake L1 environment (deltaic  
566 topset deposits), and then retrogradational, up to a dysoxic/anoxic protected littoral lake L2 environment. The  
567 fourth cycle, from 40 m to the top of the core, is only progradational, with increasing occurrences of coarse-grained  
568 littoral lake L1 deposits (deltaic topsets). Cycles 2 to 4 correspond to the *Grès de Lally Inférieurs* Unit (Fig. 12).

569

### 570 **5.1.2. The Chevrey well (CHE-1)**

571 The TOC values in the CHE-1 well range between 0.18 and 20.98 wt.% (Fig. 13). Intervals with significant  
572 TOC values are displayed around 325 m (TOC up to 10 wt.%) and between 130 and 155 m (TOC up to 21 wt.%),  
573 in the same dark and fine-grained facies as in the IG-1 core, and occasionally in very thin intervals interbedded in  
574 coarser lithologies (Fig. 13).

575 For the CHE-1 core, seven stratigraphic cycles have been identified (Fig. 13). The first one, from the base of  
576 the core to 324 m, shows a retrogradational trend, with the transition from a sublittoral lake environment (SL2 and  
577 SL3, prodelta deposits) to a profundal dysoxic/anoxic lake P2a environment comprising the MFS. The second  
578 cycle, from 324 to 228 m, displays high-frequency transitions between the profundal P1 and P2 and sublittoral  
579 SL3 lake environments, with a MRS characterized by a 2 m thick interval of sublittoral lake SL2 deposits, located  
580 at 245 m, and a MFS in OM-rich deposits (TOC of ~6 wt.%). The third cycle, from 228 to 176 m, is progradational  
581 up to a littoral lake L1 environment (deltaic topsets), with a MRS at 190 m, and retrogradational up to a profundal  
582 lake P2 environment (TOC values of 7 wt.%). The fourth cycle, from 176 to 140 m, is progradational up to a  
583 sublittoral lake SL2 environment at 162 m, constituting the MRS, and then retrogradational to a dysoxic/anoxic  
584 profundal lake P2a environment constituting a ~20 m thick interval with the highest OM content of the core (TOC  
585 up to 21 wt.%). The fifth cycle, from 140 to 96 m, is progradational up to 103 m, up to a littoral lake L1  
586 environment (deltaic topsets), and retrogradational up to another interval of dysoxic/anoxic profundal lake P2a  
587 environment (TOC values up to 5 wt.%). The sixth cycle, from 96 to 31 m, is only progradational, up to a littoral  
588 lake L1 environment, and is followed by the seventh cycle, also beginning by profundal lake P2 deposits, and  
589 progradational up to 21 m, followed by a retrogradational trend up to a profundal lake P1 environment at ~15 m.

590

### 5.1.3. The Varolles well (VAR-1)

591 In the VAR-1 core, no TOC values have been measured, making it impossible to precisely place the MFSs  
592 within the more distal deposit intervals at the end of the retrogradational trends. Five stratigraphic cycles have  
593 been identified based on sedimentological data (Fig. 14). The first one is progradational from the base of the core  
594 to 230 m with a transition from a profundal lake P2 environment to a sublittoral lake SL1 environment (deltaic  
595 foresets) constituting the MRS at 237 m, and then retrogradational up to a profundal lake P2 environment. The  
596 second cycle is from 230 to 149 m, with a progradational trend up to the littoral environments (L1, deltaic topsets,  
597 and L2, protected lake) and a retrogradational trend up to the profundal lake, probably dysoxic to anoxic given the  
598 very fine-grained black facies (P2a environment). The third cycle is from 149 to 102 m, with a progradational  
599 trend up to a sublittoral lake SL1 environment (deltaic foresets) at 130 m, and a retrogradational trend up to the  
600 profundal lake environment, again likely dysoxic/anoxic. The fourth cycle spans from 102 to 44 m, and displays  
601 the same depositional environments along its progradational/retrogradational trends than the previous cycle, with  
602 a MRS placed at 62 m, and a MFS in the middle of the 20 m thick interval, likely enriched in OM (very dark  
603 finely-laminated claystones comprising lot of fish remains, as observed in the IG-1 and CHE-1 OM-rich deposits).  
604 The fifth cycle, from 44 m to the top of the core, only displays a progradational trend, possibly incomplete, from  
605 the profundal lake P2a environment to the sublittoral SL2 environment (gravelly bottomsets in a prodelta).  
606

### 5.2. Correlations between deep cored wells

607  
608 Together with the present sequence stratigraphy analysis and some previous interpretations of Marteau (1983),  
609 it is possible to reliably make correlations between the three deep wells presented in Figure 15. The IG-1 core  
610 encompasses the Igornay OSB (from ~155 to 145 m, Fig. 12), with overlying deposits corresponding to the *Grès*  
611 *de Lally Inférieurs* Unit (Marteau 1983, Fig. 1c). No other significant OM-rich deposits are identified up to the top  
612 of the core, which means that the Lally OSB, located at the top of the *Grès de Lally Inférieurs* Unit, was not drilled.  
613 The CHE-1 core displays the *Grès de Lally Supérieurs* Unit at its top (Figs. 1c, 12), and the OM-rich interval  
614 between 130 and 155 m is attributed to the Lally OSB (Marteau 1983), thus indicating that the underlying deposits  
615 belong to the *Grès de Lally Inférieurs* Unit. Given the thickness between the Lally OSB and the OM-rich interval  
616 between 334 and 320 m (i.e., representing 165 m), these OM-rich deposits likely correspond to the Igornay OSB,  
617 since the maximum thickness of the *Grès de Lally Inférieurs* Unit throughout the Autun Basin is estimated to be  
618 ~150 m (Fig. 1c). Thus, it seems likely that the OM-rich intervals containing the MFSs, combined with the  
619 previously determined stratigraphic cycles, can be reliably used to provide accurate correlations between the IG-1  
620

621 and CHE-1 wells, as represented in Figure 15. The Igornay OSB comprises the MFS separating cycles 1 and 2 in  
622 these two wells, allowing to correlate the subsequent cycles as follows: the second major flooding located at 85 m  
623 in the IG-1 core corresponds to the flooding observed at 228 m in the CHE-1 core (top of cycle 2, Figs. 12, 13,  
624 15), and the MFS located at 40 m in the IG-1 core corresponds to the MFS at 176 m in the CHE-1 core (top of  
625 cycle 3, Figs. 12, 13, 15). In these two wells, profundal and sublittoral lake environments dominate at the base of  
626 the Igornay Fm, i.e., from the base to 80 m in the IG-1 core, and to 220 m in the CHE-1 core. The medium- to-  
627 coarse-grained lithologies between 40 and 90 m in the IG-1 core, attributed to sublittoral SL2 to littoral lake L1  
628 environments and assigned to the *Grès de Lally Inférieurs* Unit, can be correlated with the medium-to-coarse-  
629 grained facies of the CHE-1 core between ~190 and 220 m.

630 The CHE-1 and VAR-1 wells are located 850 m from each other (Fig. 2), at a similar altitude (310 m and 315  
631 m, respectively) and, according to Marteau (1983), the local dip of the series is  $2.5^\circ$  to the north, likely due to a  
632 local tectonic tilting, whereas the main regional dip is towards the south (Fig. 2b). The Lally OSB is well-identified  
633 in these two wells in the work of Marteau (1983), thus constituting an accurate correlating level (i.e., the MFS  
634 between cycles 4 and 5 in the two wells, Figs. 13–15). However, considering the short distance between the two  
635 wells and the slight local dip, the substantial depth of the Lally OSB in the CHE-1 core (i.e., 130 m, Figs. 13, 15)  
636 compared to the one in the VAR-1 core (i.e., 40 m, Figs. 14, 15), likely reflects a fault between the two wells.  
637 Despite the proximity of these two boreholes, the sedimentological descriptions also show that the VAR-1 facies  
638 are broadly coarser than the CHE-1 facies, possibly due to a higher sediment supply in the VAR-1 core location,  
639 and therefore indicating more proximal environments, with respect to the sediment sources. However, based on  
640 the recognition of the progradational–retrogradational cycles, it is possible to make correlations between these two  
641 wells (Fig. 15). Based on these new correlations, it is likely that the Igornay OSB has also been reached by the  
642 VAR-1 well, considering the dark laminated fine-grained facies deposited in a profundal lake P2 environment  
643 between 226 and 236 m; this hypothesis could be strengthened by additional TOC content analyses. Lastly,  
644 correlations between VAR-1 and CHE-1 are in agreement with some previous observations of Marteau (1983).

645

### 646 **5.3. Correlations between subsurface data and field sections**

647 Outcrop sections can be correlated to the three deep cores IG-1, CHE-1 and VAR-1, since the Chevrots and  
648 Rigny sections are stratigraphically located between the Igornay and Lally OSBs (i.e., in the *Grès de Lally*  
649 *Inférieurs* Unit), based on cartographic positions (Fig. 2). Moreover, based on field data, they are located only  
650 several meters above the Igornay OSB, indicating that the deltaic facies associations from topsets (L1 environment)

651 to gravelly bottomsets (SL2 environment, prodelta) of these outcropping sections correspond to the prodelta SL2  
652 to SL3 facies associations displayed in the IG-1 core. Based on the correlation between the cored wells, it also  
653 suggests that the Chevrots and Rigny sedimentary successions correspond to the profundal lake P1 and P2 facies  
654 associations in the CHE-1 core, and to either the marginal-lake (littoral lake L1) or distal (profundal lake) facies  
655 associations in the VAR-1 core, when considering a roughly constant thickness of the Igornay Fm throughout the  
656 basin (200-250 m, Fig. 1c).

657 The Arroux section, containing some alternations of medium-to-coarse and fine-grained lithologies, as well as  
658 microbial deposits, can be correlated with the interval showing microbial deposits in the IG-1 core (~37–28 m,  
659 i.e., the base of the progradational trend of cycle 4, Fig. 12). The MU core, encompassing the Muse OSB, is located  
660 higher up in the stratigraphic column (Muse Fm, Fig. 1c) and therefore cannot be correlated with any of the cores  
661 or outcrops.

662

## 663 **6. Discussion**

### 664 **6.1. Refining the paleoenvironments of the Autun Basin**

665 Sedimentological facies analyses suggest that the sediments of the Autun Basin were deposited in three  
666 positions along a landward–basinward transect, namely the littoral, sublittoral and profundal lakes (as defined by  
667 Bohacs et al. 2000). These positions are divided into seven depositional environments, depending on the  
668 sedimentary flux intensity, highlighting (i) periods dominated by high sediment supply in the basin, indicated by  
669 deltaic topset, foreset and prodelta deposits (toesets/bottomsets), and (ii) periods of low sediment supply, i.e.,  
670 reflected by fine-grained laminated sediments attributed either to profundal or shallow-protected littoral lacustrine  
671 deposits, depending on their association with low-water column sedimentary features (e.g., microbial deposits,  
672 trunks, wave ripples).

673 The two first stratigraphic cycles in the three deep cored wells (Figs. 12–15) present an evolution from a  
674 dominantly profundal lake to sublittoral lake environments (i.e., prodelta deposits), yet with some scarce sublittoral  
675 to littoral lake deposits in the VAR-1 core. In the lower part of the cores, the profundal lacustrine conditions are  
676 determined through the presence of OSBs (i.e., Igornay OSB) interbedded with turbidites, and the laminated fine-  
677 grained deposits containing alternations of dark, light and sometimes red laminae, possibly linked with seasonal  
678 physical and chemical modifications in the water column. The OSBs either indicate a decreased sediment supply  
679 in the basin, and/or a deepening of the lake, marked by a chemical or thermal stratification of the water column,  
680 leading to dysoxia/anoxia in the bottom waters.



681 The sedimentary architectures observed in the *Grès de Lally Inférieurs* Unit in the deep cores (IG–1, CHE–1  
682 and VAR–1 wells), and on the Chevrots and Rigny outcrops, together with the numerous rapid transitions between  
683 profundal lacustrine deposits (i.e., fine-grained lithologies and OSBs) and more proximal deposits with respect to  
684 the sediment source areas (i.e., coarse-grained sandstones to conglomerates), without pronounced unconformities,  
685 do not support transitions from a lacustrine to a strict fluvial environment, as suggested by several previous studies  
686 of the Autun Basin (e.g., Marteau 1983; Delfour et al. 1991; Delfour et al. 1995), but also in the Decize–La  
687 Machine Basin (Donsimoni 1990, 2006). Instead, the refined sedimentological data, with the coarsest-grained  
688 facies displaying deltaic features (e.g., inclined foresets, toeset and bottomsets deposits), paired with the use of  
689 sequence stratigraphy concepts, indicate deltaic progradations into a lacustrine environment, i.e., sedimentary  
690 succession dominated by subaquatic or lacustrine-marginal environments exclusively, rather than strictly fluvial  
691 vs. lacustrine environments. The fluvial or alluvial system feeding this delta-lake system is therefore not preserved  
692 in the parts of the basin or the sedimentary intervals studied here. These interpretations are also in line with the  
693 deltaic environments described in the recent studies of the neighboring Decize–La Machine Basin performed by  
694 Ducassou et al. (2019) and Mercuzot et al. (2021a), based on the core descriptions and seismic profiles, as well as  
695 in the study carried out by Mathis and Brulhet (1990) in the sedimentary succession of the Aumance Basin  
696 (location in Fig. 1b).

697 The Arroux section (ARR), close to the top of the *Grès de Lally Inférieurs* Unit (i.e., progradational trend of  
698 the cycle 4, Fig. 15), contains the most proximal facies observed in the studied lower Autunian, as indicated by  
699 the wave ripples and the trunks preserved in living position (Figs. 3c, d), reflecting periods of contraction of the  
700 lake and the lowest lake-level of the studied interval.

701 At the top of the IG–1 core (i.e., retrogradational trend of the third cycle and the whole fourth cycle, Fig. 15),  
702 thin OSBs are associated with some microbial deposits (Fig. 12), thus indicating a shallow water column in a  
703 littoral lake L2 environment protected from major sediment inputs. They are therefore different from the Igornay  
704 OSB, which is interpreted as profundal lake deposits. Two conditions are necessary to preserve such black shales  
705 in a shallow marginal part of the lake: (1) protection from sediment supply either due to the formation of a  
706 topographic or phytogenic barrier, or a quiet sedimentation taking place laterally from the main deltaic system  
707 (Fig. 7); and (2) stagnant water preventing the oxidation and remineralization of the OM.

708 Above the *Grès de Lally Supérieurs* Unit (i.e., the fifth, sixth and seventh stratigraphic cycles from the CHE-  
709 1 and VAR-1 cores; Fig. 15), up to the MU core deposits, the sedimentary succession, still belonging to *the Grès*  
710 *de Lally Supérieurs* Unit, is no longer available through surface or subsurface data. However, some silicified trunks

711 and roots (e.g., *Stigmaria flexuosa* and *Dadoxylon*) have been found in living position, indicating the presence of  
712 paleosols (Marguerier and Pacaud 1980; Renault 1988), and therefore other periods of low lake level in the Autun  
713 Basin, with the possibility of fluvial deposit preservation. In the uppermost sediments observed in the stratigraphy  
714 (i.e., the Muse section and MU core), the very high OM content found in the Muse OSB suggests a return to more  
715 distal environments, with profundal lacustrine facies deposited under dysoxic to anoxic conditions. The overlaying  
716 series are poorly known because of the lack of outcrops or core data (several tens of meters to hundreds of meters  
717 are possibly missing).

718 Lastly, when comparing the three deep cores (IG-1, CHE-1 and VAR-1 wells), the environments are generally  
719 more proximal in the IG-1 and VAR-1 cores than in the CHE-1 core, with respect to the sediment source areas.  
720 The more distal conditions recorded in the CHE-1 core may have prevented erosional events, resulting in a better  
721 preservation of the OM-rich fine-grained sediments of the Igornay OSB. This also indicates that the IG-1 core is  
722 located in a more proximal area of the basin than the CHE-1 core, and partly explains the absence of microbial  
723 deposits in the CHE-1 core.

724 To sum up, in the Autun Basin, the most profundal lacustrine environments are dominant in the late Gzhelian  
725 (cf. Fig. 1c), with identification of developed intervals of very finely and regularly laminated levels as well as  
726 OSBs, corresponding to periods of dysoxia/anoxia of the bottom waters and in the sediment. Then, these profundal  
727 lacustrine conditions evolve towards more proximal environments along a landward-to-basinward transect during  
728 the early Asselian, where deltaic systems are displayed, whereas the OM can still be preserved if the depositional  
729 environment is protected from the sediment supply. Lastly, the most proximal environments recorded in the studied  
730 sections, i.e., the closest to the sediment source areas, marked by carbonate-mineralized microbial deposits and  
731 trees, are described close to the Gzhelian/Asselian boundary (CP boundary, Fig. 1c).

732

## 733 **6.2. Basin-fill evolution**

734 A lake basin-type classification has been established by Bohacs et al. (2000) that distinguishes underfilled,  
735 balanced-fill and overfilled lake-basins, depending on the variations of the sediment supply and of the available  
736 accommodation space. Considering the characteristics listed above, three main intervals are displayed along the  
737 lower Autunian succession of the Autun Basin, and can be distinguished as per this classification (Fig. 15): (i) the  
738 two first stratigraphic cycles, dominated by sublittoral to profundal environments, thus displaying very low to  
739 moderate sediment fluxes, can be attributed to a balanced-fill lake-basin type, i.e., where the accommodation space  
740 exceeds the sediment supply, either induced by a climatically-driven high lake level or by high subsidence rates;

741 (ii) the third and fourth stratigraphic cycles, representing the most landward environments of the studied  
742 succession, with the highest sediment fluxes, are attributed to an overfilled lake-basin type, i.e., high sediment  
743 supply exceeding the accommodation rates; and (iii) the fifth to seventh stratigraphic cycles, displaying  
744 depositional environments comparable to the first two cycles, are also considered as periods of balanced-fill lake-  
745 basin type, either because of a decrease in the sediment fluxes and/or an increase in the subsidence.

746 This basin-fill evolution therefore reflects variations in the relative lake level over time, triggered either by  
747 climate or tectonic variations. Further work is required to determine the respective control of these two factors,  
748 notably through precise correlations with adjacent basins, which is only possible through the acquisition of precise  
749 radiometric ages.

750

### 751 **6.3. An isolated or connected lake system?**

752 The Autun Basin is one of four CP basins cropping out in the northeastern Massif Central, together with the  
753 Blanzay–Le Creusot, Aumance, and Decize–La Machine basins (Fig. 1b), formed and filled in a similar geodynamic  
754 setting. The tectono-sedimentary history of the Autun Basin is reconstructed in Figure 16. At the beginning of the  
755 basin filling, the deposition of CP sediments was driven by the Autun fault, and the distal facies extended further  
756 north (Fig. 16a). The subsequent tilting of the basin and the uplift of its borders then prevented the deposition of  
757 the post-early Permian and basal Triassic sediments (Fig. 16b). The currently preserved sediments are known from  
758 the Middle Triassic onwards – belonging to the Meso-Cenozoic cover of the Paris Basin – and are no longer  
759 controlled by any fault (i.e., regional subsidence, Fig. 16c). They were then partly eroded during the Late  
760 Cretaceous to Tertiary uplift phases (Fig. 16d). In the present day, erosion is still occurring, resulting in a Meso-  
761 Cenozoic succession that is almost totally eroded in the Autun Basin area (Fig. 16e). Thus, the present-day borders  
762 of the basin are erosive, and the observed deposits are partially preserved from the post-lower Permian uplifts and  
763 subsequent erosions because they were protected by the overlying Mesozoic sediments. This difference in  
764 position between the present-day northern border of the preserved sedimentary area and the initial border of the  
765 basin shows that the initial sedimentary area was much broader.

766 This is also observed in the Decize–La Machine Basin (Mercuzot et al. 2021a), where the most distal facies  
767 (i.e., profundal lacustrine facies) crop out near the present-day borders of the basin (Figs. 2, 16e), indicating that  
768 the shoreline of the lake at the time of sedimentation is not preserved. Furthermore, recent studies of this basin  
769 (Ducassou et al. 2019; Mercuzot et al. 2021a), also evidenced large deltaic systems prograding into a lacustrine  
770 environment, but highlighted more proximal depositional environments with respect to the sediment source areas

771 than in the Autun Basin, i.e., floodplain with coal deposits, coarse-grained alluvial fan or Gilbert-type deltaic  
772 lithologies, and an absence of varves and black shale deposits. On a landward-to-basinward depositional profile,  
773 these features indicate that the Decize–La Machine Basin is overall more proximal than the Autun Basin, and that  
774 its active sedimentation area was deepening towards the east, i.e., in the direction of the Autun Basin (cf. Fig. 1b),  
775 thus suggesting a possible connection between these two basins. This hypothesis is strengthened by the new age  
776 models of the Decize–La Machine and Autun basins, provided by Ducassou et al. (2019) and Pellenard et al.  
777 (2017), respectively, showing that the sedimentary successions of these two basins are contemporaneous (i.e.,  
778 centered around the CP boundary).

779 As suggested by Mercuzot et al. (2021a), the Decize–La Machine and Aumance basins could be part of a much  
780 larger basin, through connections with the subsurface Brécy, Contres and Arpheuilles basins, evidenced in the  
781 southern Paris Basin through seismic data by Beccaletto et al. (2015), and the Autun Basin would therefore be part  
782 of this larger system. This suggests a Permian basin spanning several hundreds of kilometers in length, with a  
783 roughly west-east extension, partly hidden beneath the Meso-Cenozoic sedimentary cover of the Paris Basin. This  
784 is also in agreement with paleobiogeography data, as highlighted by the studies performed by Schneider and Zajic  
785 (1994) and Schneider et al. (2000). During the uppermost Carboniferous (i.e., Gzhelian), some sharks, the fossils  
786 of which (e.g., teeth, coprolites) are found in the Autun and Aumance basins amongst others, had a uniform species  
787 association within the European basins (e.g., Puertollano Basin, Saar-Nahe Basin, Saale Basin and Central  
788 Bohemian Basin), implying connections between them.

789 It is therefore highly probable that the French CP basins of the northeastern Massif Central were connected at  
790 some point during their filling, likely with a shared drainage system with fluvial connections, rather than  
791 connections with the marine realm, as the paleoecology of the fossil sharks, investigated by Fischer et al. (2013)  
792 indicates a freshwater living environment for these species. This calls into question the use of the term of "basin",  
793 which would be not relevant anymore when mentioning French CP sedimentary successions or, more broadly,  
794 European CP successions, as each present-day individual basin could actually represent several distinct  
795 depocenters of larger former basins.

796

## 797 **7. Conclusion**

798 Based on sedimentological descriptions paired with sequence stratigraphy concepts, this study reveals that the  
799 lower Autun Basin sedimentary successions, previously ascribed to environments alternating between strictly  
800 fluvial and palustrine-lacustrine, correspond instead to an alternation of deltaic deposits prograding into a

801 lacustrine environment, without evidence of strict fluvial deposit preservation. It therefore provides evidence that  
802 during the late Carboniferous and the earliest Permian (~299 Ma), the Autun Basin was subjected to episodes of  
803 fluctuating accommodation space, either in response to climate or to subsidence variations, the respective roles of  
804 which still need to be determined.

805 During periods of high lake level (i.e., high accommodation space), the preservation of OM-rich sediments  
806 was favored by the development of dysoxic/anoxic conditions, also reached during episodes of low lake levels,  
807 when the depositional environment was protected from detrital supply. These conditions, when coupled with low  
808 water turbidity, also made efficient microbial photosynthesis possible, and thus the mineralization of microbial  
809 mats. Moreover, the presence of trees in living position and evidence of paleosols indicate that parts of the basin  
810 were occasionally emerged, notably close to the Gzhelian/Asselian boundary.

811 Lastly, the presence of profundal lacustrine deposits cropping out along the present-day borders of the Autun  
812 Basin, together with the missing lateral transition between the delta-lake system and the areas in erosion, indicate  
813 that these borders are only erosive, and thus do not correspond to the initial limits of the basin at the time of its  
814 infill. This implies that the Carboniferous–Permian basins of the northeastern Massif Central were broader than  
815 the present-day preserved sedimentary areas, and that they might have been connected to form a larger basin, as  
816 also supported by seismic data and paleobiogeography. It highlights a potential underestimation of the extent and  
817 thickness of sedimentary systems in eastern equatorial Pangea during the late Carboniferous and the early Permian.  
818 As these areas likely constituted a considerable atmospheric CO<sub>2</sub> sink through the storage of organic carbon in  
819 sediments, they would have constituted a major driving factor on the climate, especially at that time (e.g.,  
820 Montañez et al. 2016; Richey et al. 2020). Given the sensitivity of the equatorial continental areas to climate  
821 forcing (e.g., Soreghan et al. 2020), these results and their implications should help constrain future paleoclimate  
822 reconstructions.

823

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### 1130 **Tables**

1131 Table 1. Description of facies observed in the studied sections with their lithologies, sedimentary features and  
1132 depositional processes.

1133

1134 Table 2. Facies associations observed in the studied sections, corresponding to depositional environments. For the  
1135 facies descriptions, see Table 1.

1136

### 1137 **Figures**

1138 Fig. 1 a Map of Western Europe showing the main Variscan tectonic structures and the surface and subsurface  
1139 Permian basins (modified from Beccaletto et al. 2015 and Schneider and Scholze 2018). b Geological map of the  
1140 northeastern Massif Central, France, with the location of the late Carboniferous to early Permian basins. Modified  
1141 from Elsass-Damon 1977. c Synthetic sedimentary succession and stratigraphy of the Autun Basin including the  
1142 radiometric ages reported by Pellenard et al. (2017), the lithostratigraphic divisions (formations and units), the  
1143 major oil-shale beds, and the studied sections. SNB: Saar-Nahe Basin, AB: Autun Basin, BCB: Blanzey–Le Creusot  
1144 Basin, AuB: Aumance Basin, LB: Lodève Basin, Ste.: Stephanian, OSB: Oil-shale bed, OM: Organic matter, M-  
1145 P Fm: Mont-Pelé Formation.

1146

1147 Fig. 2 a Geological map of the Autun Basin including the lithostratigraphic divisions (same Fm colors as in Fig.  
1148 1c) and the studied subsurface and outcrop sections. Modified from Gand et al. (2007). b Cross-section of the  
1149 Autun Basin displaying the lithostratigraphic divisions and the studied wells and section. The VAR–1, CHE–1,  
1150 Rigny and Chevrots sections are projected given their approximate position in the stratigraphy. IG-1: Igornay well,  
1151 CHE-1: Chevrey well, VAR-1: Varolles well, MU: Muse cored well and section.

1152

1153 Fig. 3 Illustration of the facies associations corresponding to the littoral lake environments (L1 and L2 facies  
1154 associations; see Table 1 for the facies codes). a Outcrop of the Arroux section displaying fine-grained facies (F



1155 facies, low sedimentary fluxes) alternating with medium-to-coarse-grained facies, massive or with trough-cross  
1156 stratifications (GS<sub>m</sub> and GS<sub>t</sub> facies, high sedimentary fluxes), and attributed to the succession of shallow and  
1157 protected lake and deltaic topset deposits, in a littoral lake environment. The white arrow indicates centimetric  
1158 gravels. b Interval from the CHE-1 core (located at ~186 m, Fig. 13) displaying sandy facies, massive (GS<sub>m</sub>),  
1159 laminated (GS<sub>l</sub>) with fining-upward trends and erosional bases (white arrow) and with trough-cross stratifications  
1160 (GS<sub>t</sub>), representing deltaic topset deposits in a littoral lake environment (L1 facies association, Fig. 13). c  
1161 Transversal section of microbial carbonates (Cs facies) encrusting a trunk (dashed line - tilted) near the Arroux  
1162 section. d Reworked fragment of a sandstone bed with wave ripples (Sw facies, found at the base of the cliff of the  
1163 Arroux section, Fig. 10).

1164

1165 Fig. 4 Illustration of the SL1 facies association (sublittoral lake environment, deltaic foresets; see Table 1 for the  
1166 facies codes). a Chevrots section (cf. map location in Fig. 2b and location on the outcrop in Fig. 8): zoom on  
1167 inclined facies, massive (IGS<sub>m</sub>) and laminated (IGS<sub>l</sub>), the latter presenting downlap geometries (white arrows).  
1168 The current direction is indicated by the red arrow. b Photograph of a similar interval, taken perpendicularly to the  
1169 current (red arrow; cf. location on the outcrop in Fig. 8). c Illustration of inclined homolithic and heterolithic facies  
1170 of the CHE-1 core (located at ~194 m, Fig. 13) attributed to the SL1 environment, and topped with the GS<sub>t</sub> facies  
1171 (trough-cross stratifications) characterizing the L1 facies association, i.e., littoral lake environment with deltaic  
1172 topsets. The white arrow highlights an erosional surface. d, e, f Thin sections illustrating various facies of the IG-  
1173 1 core, showing immature sandstones (i.e., litharenites) with subangular to angular grains of quartz, feldspars and  
1174 lithic fragments. d Poorly-sorted GS<sub>l</sub> facies presenting small lithic fragments (lf), sometimes of volcanic origin  
1175 (vlf, altered rhyolites), and large rhyolitic quartz grains (rqz) displaying typical corrosion gulfs. e GS<sub>m</sub> facies  
1176 presenting a better sorting, containing lithic fragments, rhyolitic quartz grains and some micas (muscovite, m). f  
1177 Thin section of a fine-sand levels from the heterolithic Sm/F facies, with a poorly sorting, angular grains, including  
1178 detrital quartz (qz), feldspars (fds) and muscovite (m).

1179

1180 Fig. 5 Illustration of the facies associations (SL1 to SL3 environments, see Table 1 for the facies codes)  
1181 corresponding to the sublittoral lake environments (prodelta). a Rigny section (see map location in Fig. 2b and  
1182 location on the outcrop in Fig. 9): zoom on an alternation of inclined facies attributed to deltaic foresets (SL1  
1183 facies association) with sandy prodelta deposits (SL2 facies association), characterized by the horizontal GS<sub>l</sub> facies  
1184 onlapping the IGS<sub>m</sub> facies of the deltaic foreset. b Interval from the IG-1 core (located at ~135 m, Fig. 12)

1185 displaying facies from the profundal lake environment (P1 facies association) at the base, followed by the  
1186 sublittoral prodelta SL3 facies association, and by profundal lake deposits (P2 facies association, dominated by  
1187 organic-rich claystones) and prodelta deposits (SL2 facies association) towards the top. The SL3 prodelta deposits  
1188 (Sm/F) are broadly finer-grained than the SL2 prodelta deposits, with a higher proportion of fine-grained  
1189 granulometries; in the prodelta SL2 facies association, the sandy beds (Sm/F and GSm facies) are thicker. c Zoom  
1190 on a sandy to clayey turbiditic level of the IG-1 core, displaying four terms of the Bouma sequence, i.e., Ta  
1191 (massive and fining-upward sand), Tb (medium to fine sand, high-energy planar laminae), Tc (ripple bedding) and  
1192 Td (low-energy planar laminae composed of clay to silt material). The white arrow shows the erosive surface at  
1193 the base as well as fluid escape features. d Photograph of the Smud facies of the CHE-1 core, attributed to debris  
1194 flow deposits in rather profundal environments (sublittoral lake SL3, or sometimes profundal lake P1  
1195 environments). Pluricentimetric rip-up clasts of various facies and mudclasts are contained in a coarse-sand matrix,  
1196 sometimes very dark. Fluid escape (white arrow) or injectite features are often observed.

1197

1198 Fig. 6 Illustration of deposits corresponding to the profundal lake environments (P1 and P2 facies associations, see  
1199 Table 1 for the facies codes). a Photograph of a small section located in the Saint-Léger-du-Bois village, ~800 m  
1200 from the Chevrots and Rigny sections (Fig. 2a) displaying the Igornay oil-shale beds, that are also reached by the  
1201 IG-1 well (Fig. 12). Fine-grained OM-rich deposits (F facies) alternate with coarser-grained levels (GSm facies),  
1202 indicating a profundal lake environment, yet including clastic sediment supply events (P1 facies association). b  
1203 Current ripples in fine sandstone from the Fl/Sr facies (zoom of Fig. 6c), reworking millimetric phytoclasts (black  
1204 laminae). c Heterolithic fine-grained facies Fl/Sr from the IG-1 core (~100 m), showing alternation of organic  
1205 matter-rich clayey deposits and thin fine-grained sandy turbidites attributed to the profundal lake environment (P1  
1206 facies association). d Fine-grained facies, laminated and OM-rich (F facies), with minor sedimentary fluxes  
1207 represented as centimetric fine-sand lenses, attributed to the most distal lacustrine environment (P2 facies  
1208 association, Saint-Léger-du-Bois outcrop). e, f Examples of the F facies in the IG-1 core. e F facies with colored  
1209 millimetric laminae (clays, silts and very fine sand, located at 179.50 m, Fig. 12). f OM-rich F facies with very  
1210 thin black laminations in the IG-1 core (located at 182.50 m, Fig. 12). The white arrows indicate phosphate-fish  
1211 coprolites.

1212

1213 Fig. 7 Conceptual model of the Autun Basin showing the depositional environments determined from the  
1214 subsurface and outcrop data. This model does not represent a snapshot of the basin but rather a combination of all  
1215 the depositional environments found through time. See Table 2 for the facies association codes.

1216

1217 Fig. 8 Les Chevrots section (see Figs. 1c and 2 for the position in the stratigraphy and location on a map, and Table  
1218 1 for the facies codes). a Top-view of the Chevrot quarry showing the orientations of the available outcrops and  
1219 two sections used for detailed logs. b Sedimentary logs of the E-W sections, correlated together (see Fig. 10 for  
1220 the log caption; the colors of the sedimentary geometries are the same as those used in Fig. 8c). C: claystone, Si:  
1221 siltstone, Fs: fine sand, Ms: medium sand, Cs: coarse sand, Gr: gravel. The sedimentary features display  
1222 coarsening-upward beds and the sedimentary architecture displays downlap and progradational structures. c E-W,  
1223 ENE-WSW and E-W views of the outcrop (from the left to the right), showing the deltaic geometries. The ENE-  
1224 WSW view is approximately parallel to the flow. The red arrow on the right E-W section indicates the N200-  
1225 oriented flute cast.

1226

1227 Fig. 9 a Photograph of the Rigny section (see Figs. 1c and 2 for the position in the stratigraphy and location on a  
1228 map, and Table 1 for the facies codes), oriented W-E. b Interpretation of the photograph highlighting deltaic  
1229 architectures, notably with chute-fill and backset features, reflecting foreset and prodelta (toeset/bottomset)  
1230 environments, respectively, and overlain by a conglomeratic topset.

1231

1232 Fig. 10 Sedimentary log of the Arroux section (see Figs. 1c and 2 for the position in the stratigraphy and location  
1233 on a map, and Table 1 for the facies codes) showing the evolution of the depositional environments.

1234

1235 Fig. 11 Sedimentary log of the MU core (see Figs. 1c and 2 for the position in the stratigraphy and location on the  
1236 map, Fig. 10 for the log caption, and Table 2 for the facies association codes) showing the evolution of the  
1237 depositional environments. The TOC content has been measured for the Muse OSB only. TOC: Total Organic  
1238 Carbon

1239

1240 Fig. 12 Sedimentary log of the IG-1 well (see Figs. 1c and 2 for the position in the stratigraphy and location on a  
1241 map, Fig. 10 for the log caption, and Table 2 for the facies association codes), evolution of the depositional

1242 environment, stratigraphic cycles and OM content (Total Organic Carbon, TOC) variation through time. OSB:  
1243 Oil-shale bed, a: anoxia.

1244

1245 Fig. 13 Sedimentary log of the CHE–1 well (see Figs. 1c and 2 for the position in the stratigraphy and location on  
1246 the map, Fig. 10 for the log caption, and Table 2 for the facies association codes), evolution of the depositional  
1247 environments, stratigraphic cycles and evolution of the TOC content. TOC: Total Organic Carbon.

1248

1249 Fig. 14 Sedimentary log of the VAR–1 well (see Figs. 1c and 2 for the position in the stratigraphy and location on  
1250 the map, Fig. 10 for the log caption, and Table 2 for the facies association codes), depositional environment  
1251 evolution and stratigraphic cycles.

1252

1253 Fig. 15 Correlations between the IG–1, CHE–1 and VAR–1 wells. The Arroux, Chevrots and Rigny sections have  
1254 been replaced at the base and top of the *Grès de Lally Inférieurs* Unit, respectively. The MU core is not figured as  
1255 this section is stratigraphically above the *Grès de Lally Inférieurs* Unit (i.e., Muse OSB, not reached by the three  
1256 wells). See Fig. 2 for the location of the wells and sections on a map, and Fig. 10 for the log caption. OSB: Oil-  
1257 shale bed; MFS: Maximum Flooding Surface; MRS: Maximum Regressive Surface.

1258

1259 Fig. 16 Simplified tectono-sedimentary history of the Autun Basin through time. a Filling of the basin during the  
1260 late Carboniferous and the early Permian, driven by the Autun fault activity. b Tilting of the basin, uplift of its  
1261 borders, erosion. c Meso-Cenozoic sedimentation, no longer controlled by the Autun fault. d Tertiary regional  
1262 uplift and erosion, with a probable reactivation of the Autun fault. e Present-day configuration, with erosion.

1263