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

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Abstract

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

Keywords

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

1. Introduction

The late Carboniferous–early Permian (CP) is a key period in the Phanerozoic history, due to large-scale geodynamic modifications, including the latest Variscan orogeny stages and the onset of the breakup of Pangea (e.g., Ménard and Molnar 1988; Stampfli and Kozur 2006), as well as a major climate upheaval marked by the acme of the Late Paleozoic Ice Age (LPIA), constituting a turning point in the climate modes of the Paleozoic (e.g., Gastaldo et al. 1996; Montañez et al. 2007). Given the presence of large tropical rainforests (Cleal and Thomas 2005) and the tremendous rates of organic carbon burial in sediments at that time (i.e., coal and black shale deposits), intertropical areas constituted a major atmospheric CO_2 sink. It is therefore of utmost importance to explore paleointertropical basins because their sensitivity to climate forcings has been underestimated in paleoclimate scenarios (e.g., Soreghan et al. 2020). At that time, intertropical latitudes are mainly considered as a mountainous region submitted to tropical weathering (e.g., Goddéris et al. 2017), and therefore mainly in erosion;active sedimentation areas are not fully considered in either the terrestrial paleogeography reconstructions or in the climate modelling. Continental sediments accumulated during the CP period are preserved in Western and Central Europe, in basins developed in an extensional tectonic setting, linked with the syn- to late-orogenic Variscan stages (e.g., Faure et al. 2009; Kroner and Romer 2013). In France, these sedimentary successions are considered as having been deposited in a multitude of small unconnected basins (e.g., Schneider and Scholze 2018), such as those found in the northeastern part of the Massif Central (Aumance, Decize–La Machine, Blanzy–Le Creusot and Autun basins, Fig. 1), presenting roughly similar sedimentary patterns and hosting detrital sediments mostly derived from the erosion of the Variscan mountain belt (Vallé et al. 1988; Van den Driessche and Brun 1989; Burg et al. 1990; Malavieille et al. 1990; Faure and Becq-Giraudon 1993; Brun and van den Driessche 1994; Faure 1995; Becq-Giraudon et al. 1996; Genna et al. 1998).

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

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

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

2. Geological setting of the Autun Basin

The CP Autun Basin is located in Burgundy (France), south of the Morvan Massif, in the northeastern part of the Massif Central (Fig. 1). It covers an area extending over ~250 km² and overlies a Devonian to Carboniferous magmatic/metamorphic and sedimentary substratum (Carrat 1969). It displays a sedimentary succession that is approximately 1.2 km thick, composed of alternating medium-to-coarse and fine-grained lithologies; the latter includes coal-bearing sequences and black-shale deposits, i.e., oil-shale beds (OSBs) (Marteau 1983). The depositional time frame has recently been constrained to a time period ranging from the late Ghzelian (latest Carboniferous) to the early Asselian (earliest Permian, Pellenard et al. 2017; Fig. 1c), using high resolution chemical abrasion – isotope dilution – thermal ionization mass spectrometry (CA-ID-TIMS) U–Pb ages from interbedded tonsteins, i.e., distal volcanic ash-fall layers deposited in continental environments, and altered in clay minerals, dominated by kaolinite (Spears 2012). The structure of the basin was described as a half-graben, later deformed due to an episode of tectonic flexure (e.g., Delafond 1889; Feys and Greber 1972; Marteau 1983; Châteauneuf and Farjanel 1989). Along the straight-lined southern margin, it is inferred that a brittle normal fault, named the Autun fault, partly controlled the CP subsidence of the basin (Marteau 1983; Choulet et al. 2012); today, it separates the sedimentary succession of the Autun Basin from a southerly Carboniferous (Westphalian) granitic pluton (Mesvres Granite, Fig. 2a). Along the northern basin's margin, Permian deposits unconformably overlie the

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

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

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

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

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

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

3. Material and methods

3.1. Core and field sections of the Autun Basin

Four unoriented cores drilled in the Autun Basin have been studied: the Chevrey (CHE-1), Varolles (VAR-1), Igornay (IG-1) and Muse (MU) cores (Fig. 2). The IG-1 core, drilled in 1965 by the Génie Rural (French rural 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 Igornay Fm, from the Igornay OSB to the *Grès de Lally Inférieurs* Unit (Fig. 1c). The CHE-1 core (47°0'13.17"N, 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 10 km from the IG–1 well, were drilled in 1982 by the French Geological Survey (BRGM), with the original goal 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) was drilled in the village of Muse to complete the observations on the historical Muse outcrop which has been excavated since 2010 for paleontological studies (Gand et al. 2011, 2014, 2015). It encompasses the uppermost part of the *Grès de Lally Supérieurs* Unit at the base of the well, and the totality of the Muse OSB.

Lastly, in order to complete the analysis of the core data, outcrops of the *Grès de Lally Inférieurs* Unit (Figs. 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 (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 thick). The Rigny and Chevrots sections have been previously studied by Marteau (1983), who assigned their medium to coarse-grained clastic sediments to a fluvial environment, either meandering or braided, as trough-cross stratifications are found together with beveled sedimentary geometries.

3.2. Facies analysis to reconstruct the evolution of the depositional environment

All of the studied sections (i.e., cores and outcrops) belong to the first half of the lower Autunian sedimentary succession (Igornay and Muse fms, Figs. 1c, 2), and have been described according to their granulometry and 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.

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

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

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

3.3. Organic matter characterization

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

3.4. Sequence stratigraphy

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

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

4. Re-evaluation of the paleoenvironments

4.1. Determination of the depositional environments from facies associations

The sedimentary description of both the field sections and the cored wells of the Autun Basin has highlighted a total of 19 facies, detailed in Table 1 and pictured in Figures 3 to 6, ranging from fine-grained to coarse-grained facies, either homolithic or heterolithic, with a mean grain size of ~2-5 mm, and a maximum grain size of ~5 cm (rare levels). The observation of thin sections, taken from facies composed of fine sands to gravels, has provided evidence for a wide diversity in detrital grains, dominated by rhyolitic quartz, feldspars and lithic fragments (Fig. 4c, d, e). The grains are subangular to angular, therefore indicating immature material, moderate transport, and a sediment source that is likely quite close to the sedimentation area.

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

4.1.1. Facies association L1

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

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

4.1.2. Facies association L2

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

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

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

4.1.3. Facies association SL1

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

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

4.1.4. Facies association SL2

The dominant facies of the SL2 facies association, represented in Fig. 5, are sandy to gravelly, dominated by dm to m-thick massive beds, with erosive or planar basal contacts (GSm facies, Fig. 5b), attributed either to cohesive debris flows or to high-density turbidite deposits. Numerous dm to m-thick beds, with erosive bases and showing a vertical organization with fining-upward trends from gravels to coarse sands, planar bedding, current ripples and settling of fine-grained particle intervals are also displayed, attributed to the GSB facies, with the divisions of the Bouma sequence (Ta to Te, Bouma 1962, Fig. 5c). This facies indicates hyperconcentrated to low-density turbidity currents, here interpreted as relatively proximal along a landward-basinward transect, given their significant thickness and the medium-to-coarse-grained Ta division. Deformed beds measuring several meters thick, mixing fine-to-coarse-grained material and frequently showing folding structures (GSFd facies, Table 1), are interpreted as slump and slide deposits. Some sandstone to conglomerate beds, displaying planar laminations (GSl facies, Fig. 5a mostly dm-thick), or trough-cross stratifications (GSt facies, mostly m-thick), are included in this SL2 facies association, reflecting high-energy tractive currents. Other scarcer facies are also included, consisting in heterolithic alternations of medium-to-coarse-grained lithologies, sometimes matrix-supported, with fine-grained lithologies, reflected by the GSmm/F, Sm/F (Fig. 5b), F/Sm and FS facies (Table 1). Some periods of settling of fine-grained particles are also displayed, reflected by the F facies.

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

4.1.5. Facies association SL3

This facies association, illustrated in Fig. 5b, presents similarities with the facies association SL2, with numerous turbidite deposits reflected by the GSm and GSB facies (Fig. 5c), and tractive current influence reflected by the planar-laminated GSl facies. The main differences are: (i) the sandy-to-gravelly beds are thinner and scarcer on average (mostly dm-thick), in favor of more heterolithic facies, displaying thicker levels of fine-grained lithology, such as GSmm/F, Sm/F (Fig. 5b), F/Sm and FS facies, (ii) the basal granulometry of the coarser turbiditic levels (i.e., GSm, GSB) does not exceed the medium to coarse sands, and (iii) the Fl/Sr facies (Table 1), absent in the SL2 facies association, likely reflects alternations between periods of moderate tractive current (i.e., current ripple intervals) and of settling of fine-grained particles. Some relatively scarce dm to m-thick levels of matrix-supported conglomerates, constituted by large mudclasts (cm to dm-sized) floating in a fine-to medium-sand greyto-black matrix (Smud facies, Table 1, Fig. 5d), are interpreted as distal debris flows given that the eroded material partly comes from the fine-grained facies.

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

4.1.6. Facies association P1

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

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

4.1.7. Facies association P2 and P2a

Facies association P2, represented in Fig. 6, presents strong similarities with facies association P1. The fine-grained facies dominate, but the homolithic facies (F facies, Figs. 5d, 6d, e, f) are more present than the heterolithic facies. They are sometimes finely laminated (Fig. 6e), may contain scarce thin sandy lenses (Fig. 6d), and are very rich in fish remains (e.g., scales, coprolites, Fig. 6f), even containing selachian coprolites (freshwater sharks, already found in Western European CP basins such as the Aumance, Blanzy–Le Creusot, Autun, or Saar-Nahe basins, Fischer et al. 2013; Schneider and Zajic 1994; Schneider et al. 2000; Luccisano et al. 2021). The heterolithic facies are constituted by massive claystones to siltstones alternating with fine to medium-grained sandstones, always massive (i.e., F/Sm facies), never showing current features, but sometimes showing bioturbations (Table 1). The coarsest levels are only represented by (i) the mm to cm-thick sandy levels of the F/Sm facies, the cm-thick fine to medium-grained sandy beds attributed to grain flows (GSm Facies) or to distal turbidites when showing Bouma sequence divisions (GSB facies), (ii) the rare m-thick dark siltstone beds, containing some mm-sized floating grains and interpreted as low-density tails of turbidity currents (Fclast facies, Te division of the Bouma sequence; Bouma 1962), and (iii) the rare dm-thick debris flows (Smud facies), thus indicating minimal sediment fluxes. This interpretation is also supported by the highest OM enrichment in the F facies with TOC values up to 21.5 wt.%, reflecting periods of dysoxic to anoxic bottom waters and sediments under a sustained water-column stratification (chemocline/thermocline). Like for the P1 facies association (profundal lake environment with low sediment fluxes), tonstein layers (T facies) are observed since these low hydrodynamic environments are prone to fine-grained material preservation.

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

4.2. Architectures and depositional environment evolution based on field sections

4.2.1. The Chevrots section

This outcrop section (Fig. 8), located above an OM-rich level attributed to the Igornay OSB, based on mining work and cartography (Fig. 2), represents the base of the *Grès de Lally Inférieurs* Unit (Fig. 1c), and displays a 3D view with two E–W-oriented sections (Chevrots 1 and Chevrots 2; Fig. 8) and one WSW–ENE-oriented section. In the Chevrots 1 E–W section (Fig. 8), lenticular sandstone bodies are observed, with massive coarse-grained sands to gravels at the base (GSm facies) and with mudclasts highlighting horizontal bedding at the top (Smud facies, Fig. 8), alternating with planar laminated fine-grained lithologies (fine to medium sand, GSl facies, high-energy planar bedding). The top of the medium-to-coarse-grained levels is undulated to irregular (Fig. 8), indicating either an erosional event, the eroded material being deposited basinward, or a stasis in the sedimentation before the deposition of fine-grained lithologies filling the depressions. The coarse-grained layers also display thickening-upward and coarsening-upward sequences. The WSW–ENE section shows downlap structures, with inclined laminated and massive facies (IGSl, IGSm facies, Fig. 8), and an evolution from fine-grained to coarse-grained lithologies is observed from the base to the top of the outcrop (Fig. 8). On the Chevrots 2 E-W section (Fig. 8), the beds become coarser towards the top, and the thickening-upward pattern of the strata reflects a progradational architecture. Altogether, the sedimentary features observed in the Chevrots section indicate a progradation of the sandstone bodies towards the WSW (almost parallel to the WSW–ENE section), also supported by a N200-oriented flute cast observed at the base of a coarse-grained bed in the Chevrots 1 section (Fig. 8c), rather than lateral accretion processes in a fluvial channel, as previously interpreted by Marteau (1983).

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

4.2.2. The Rigny section

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

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 (GSm 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 (GSl 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, GSm 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 (GSt facies, Table 1) at its base, indicating a littoral lake L1 environment (deltaic topsets, Fig. 11). Then, medium-to-coarse-grained planar laminated facies (GSl 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 granulometry of the coarsest-grained levels. When displaying dysoxia to anoxia features (laminated OM-rich facies), the facies association is instead representative of the P2a environment (Table 2), as was the case at the base of the core and between 155 and 148 m (i.e., Igornay OSB, Figs. 1b, 12).

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

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

4.3.2. The Chevrey core (CHE–1)

The lower half of the CHE-1 core displays an alternation between the fine-grained homolithic facies, containing some whitish tonstein levels and heterolithic facies (Fig. 13). Some dm-thick coarser-grained facies, reflecting distal turbidites or debris flows, are also displayed. The dominant fine-grained facies mostly indicate profundal lake P1 (when some detrital fluxes are deciphered by cm to dm-thick turbidite levels) and P2 environments, and sometimes P2a environments when dysoxic/anoxic conditions are reached (i.e., OM-rich deposits at ~330 m, Fig. 13, Table 2). Several periods of slightly enhanced sediment fluxes (dm-thick sandstone beds with current features, alternating with fine-grained lithologies, on 1 to 2 m thick intervals) indicate prodelta deposits in sublittoral lake SL2 and SL3 environments (Table 2). Embedded in this interval of dominantly profundal and sublittoral lake environment deposits, a ~30 m thick interval of mostly sandy to conglomeratic facies is found around 200 m, sometimes displaying trough-cross stratifications indicating 3D megaripple migrations in a littoral lake L1 environment (major sediment supply in deltaic topsets), or sometimes with inclined facies, indicating a sublittoral lake SL1 environment (active deltaic foresets, Table 2).

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

4.3.3. The Varolles core (VAR–1)

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

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

The second end-member, in terms of the facies association, is composed by ~5 m thick sets, either (i) dominated by fine-to-medium-grained heterolithic facies or homolithic facies, mainly massive or with planar bedding, and attributed to grain flows or turbidites deposited in a prodelta, in the sublittoral lake environment (SL2/SL3 facies associations), or (iii) showing inclined medium-to-coarse-grained facies (grain flows and debris flows), sometimes deformed (i.e., slumps), reflecting deltaic foresets (sublittoral lake SL1 environment, Table 2), which have a much higher representation in the VAR-1 core compared to the IG-1 and CHE-1 cores.

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

5. Basin-scale sequence stratigraphy correlations

5.1. Stratigraphic cycles based on the evolution of the depositional environments and OM accumulation rates

5.1.1. The Igornay well (IG-1)

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

Based on the depositional environment evolution described above and on these OM-content variations, four stratigraphic cycles have been identified in the IG–1 core (Fig. 12). The first one, from 200 to 152 m, encompasses a large progradational trend from a profundal dysoxic/anoxic lacustrine environment (P2a facies association) to a sublittoral lake environment (SL2 facies association, gravelly bottomsets in a prodelta), up to the MRS located at 162 m. This trend is then reversed, with a retrogradational trend ending by a MFS at 152 m, within an anoxic/dysoxic profundal lake P2a environment, corresponding to the Igornay OSB (Marteau 1983). The second cycle, from 152 to 87 m, is progradational up to 128 m, from the previous profundal–dysoxic/anoxic lake P2a environment, to the sublittoral lake SL2 environment constituting the MRS. The retrogradational trend, up to 87 m, bounded by a MFS in a 1 m thick interval of profundal lake P2a deposits, is gradual and displays several occurrences of sublittoral lake SL3 deposits (i.e., fine-grained prodelta deposits), between the profundal lake P1 and the sublittoral lake SL2 (toesets/gravelly bottomsets in a prodelta) endmembers. The third cycle, from 87 to 40 m, is progradational up to the MRS located at 53 m, corresponding to a littoral lake L1 environment (deltaic topset deposits), and then retrogradational, up to a dysoxic/anoxic protected littoral lake L2 environment. The fourth cycle, from 40 m to the top of the core, is only progradational, with increasing occurrences of coarse-grained littoral lake L1 deposits (deltaic topsets). Cycles 2 to 4 correspond to the *Grès de Lally Inférieurs* Unit (Fig. 12).

5.1.2. The Chevrey well (CHE-1)

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

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

5.1.3. The Varolles well (VAR-1)

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

5.2. Correlations between deep cored wells

Together with the present sequence stratigraphy analysis and some previous interpretations of Marteau (1983), it is possible to reliably make correlations between the three deep wells presented in Figure 15. The IG–1 core encompasses the Igornay OSB (from ~155 to 145 m, Fig. 12), with overlying deposits corresponding to the *Grès de Lally Inférieurs* Unit (Marteau 1983, Fig. 1c). No other significant OM-rich deposits are identified up to the top of the core, which means that the Lally OSB, located at the top of the *Grès de Lally Inférieurs* Unit, was not drilled. The CHE–1 core displays the *Grès de Lally Supérieurs* Unit at its top (Figs. 1c, 12), and the OM-rich interval between 130 and 155 m is attributed to the Lally OSB (Marteau 1983), thus indicating that the underlying deposits belong to the *Grès de Lally Inférieurs* Unit. Given the thickness between the Lally OSB and the OM-rich interval between 334 and 320 m (i.e., representing 165 m), these OM-rich deposits likely correspond to the Igornay OSB, since the maximum thickness of the *Grès de Lally Inférieurs* Unit throughout the Autun Basin is estimated to be ~150 m (Fig. 1c). Thus, it seems likely that the OM-rich intervals containing the MFSs, combined with the previously determined stratigraphic cycles, can be reliably used to provide accurate correlations between the IG-1 and CHE-1 wells, as represented in Figure 15. The Igornay OSB comprises the MFS separating cycles 1 and 2 in these two wells, allowing to correlate the subsequent cycles as follows: the second major flooding located at 85 m 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, 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 cycle 3, Figs. 12, 13, 15). In these two wells, profundal and sublittoral lake environments dominate at the base of 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-coarse-grained lithologies between 40 and 90 m in the IG–1 core, attributed to sublittoral SL2 to littoral lake L1 environments and assigned to the *Grès de Lally Inférieurs* Unit, can be correlated with the medium-to-coarse-grained facies of the CHE–1 core between ~190 and 220 m.

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

5.3. Correlations between subsurface data and field sections

Outcrop sections can be correlated to the three deep cores IG–1, CHE–1 and VAR–1, since the Chevrots and Rigny sections are stratigraphically located between the Igornay and Lally OSBs (i.e., in the *Grès de Lally Inférieurs* Unit), based on cartographic positions (Fig. 2). Moreover, based on field data, they are located only several meters above the Igornay OSB, indicating that the deltaic facies associations from topsets (L1 environment) to gravelly bottomsets (SL2 environment, prodelta) of these outcropping sections correspond to the prodelta SL2 to SL3 facies associations displayed in the IG-1 core. Based on the correlation between the cored wells, it also suggests that the Chevrots and Rigny sedimentary successions correspond to the profundal lake P1 and P2 facies associations in the CHE-1 core, and to either the marginal-lake (littoral lake L1) or distal (profundal lake) facies associations in the VAR-1 core, when considering a roughly constant thickness of the Igornay Fm throughout the basin (200-250 m, Fig. 1c).

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

6. Discussion

6.1. Refining the paleoenvironments of the Autun Basin

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

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

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

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

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

Above the *Grès de Lally Supérieurs* Unit (i.e., the fifth, sixth and seventh stratigraphic cycles from the CHE-1 and VAR-1 cores; Fig. 15), up to the MU core deposits, the sedimentary succession, still belonging to *the Grès de Lally Supérieurs* Unit, is no longer available through surface or subsurface data. However, some silicified trunks and roots (e.g., *Stigmaria flexuosa* and *Dadoxylon*) have been found in living position, indicating the presence of paleosols (Marguerier and Pacaud 1980; Renault 1988), and therefore other periods of low lake level in the Autun Basin, with the possibility of fluvial deposit preservation. In the uppermost sediments observed in the stratigraphy (i.e., the Muse section and MU core), the very high OM content found in the Muse OSB suggests a return to more distal environments, with profundal lacustrine facies deposited under dysoxic to anoxic conditions. The overlaying series are poorly known because of the lack of outcrops or core data (several tens of meters to hundreds of meters are possibly missing).

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

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

6.2. Basin-fill evolution

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

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

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

6.3. An isolated or connected lake system?

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

This is also observed in the Decize–La Machine Basin (Mercuzot et al. 2021a), where the most distal facies (i.e., profundal lacustrine facies) crop out near the present-day borders of the basin (Figs. 2, 16e), indicating that the shoreline of the lake at the time of sedimentation is not preserved. Furthermore, recent studies of this basin (Ducassou et al. 2019; Mercuzot et al. 2021a), also evidenced large deltaic systems prograding into a lacustrine environment, but highlighted more proximal depositional environments with respect to the sediment source areas than in the Autun Basin, i.e., floodplain with coal deposits, coarse-grained alluvial fan or Gilbert-type deltaic lithologies, and an absence of varves and black shale deposits. On a landward-to-basinward depositional profile, these features indicate that the Decize–La Machine Basin is overall more proximal than the Autun Basin, and that its active sedimentation area was deepening towards the east, i.e., in the direction of the Autun Basin (cf. Fig. 1b), thus suggesting a possible connection between these two basins. This hypothesis is strengthened by the new age models of the Decize–La Machine and Autun basins, provided by Ducassou et al. (2019) and Pellenard et al. (2017), respectively, showing that the sedimentary successions of these two basins are contemporaneous (i.e., centered around the CP boundary).

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

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

7. Conclusion

Based on sedimentological descriptions paired with sequence stratigraphy concepts, this study reveals that the lower Autun Basin sedimentary successions, previously ascribed to environments alternating between strictly fluvial and palustrine-lacustrine, correspond instead to an alternation of deltaic deposits prograding into a lacustrine environment, without evidence of strict fluvial deposit preservation. It therefore provides evidence that during the late Carboniferous and the earliest Permian (~299 Ma), the Autun Basin was subjected to episodes of fluctuating accommodation space, either in response to climate or to subsidence variations,the respective roles of which still need to be determined.

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

Lastly, the presence of profundal lacustrine deposits cropping out along the present-day borders of the Autun Basin, together with the missing lateral transition between the delta-lake system and the areas in erosion, indicate that these borders are only erosive, and thus do not correspond to the initial limits of the basin at the time of its infill. This implies that the Carboniferous–Permian basins of the northeastern Massif Central were broader than the present-day preserved sedimentary areas, and that they might have been connected to form a larger basin, as also supported by seismic data and paleobiogeography. It highlights a potential underestimation of the extent and thickness of sedimentary systems in eastern equatorial Pangea during the late Carboniferous and the early Permian. As these areas likely constituted a considerable atmospheric CO_2 sink through the storage of organic carbon in sediments, they would have constituted a major driving factor on the climate, especially at that time (e.g., Montañez et al. 2016; Richey et al. 2020). Given the sensitivity of the equatorial continental areas to climate forcing (e.g., Soreghan et al. 2020), these results and their implications should help constrain future paleoclimate reconstructions.

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Tables

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

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

Figures

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

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

Fig. 3 Illustration of the facies associations corresponding to the littoral lake environments (L1 and L2 facies associations; see Table 1 for the facies codes). a Outcrop of the Arroux section displaying fine-grained facies (F facies, low sedimentary fluxes) alternating with medium-to-coarse-grained facies, massive or with trough-cross stratifications (GSm and GSt facies, high sedimentary fluxes), and attributed to the succession of shallow and protected lake and deltaic topset deposits, in a littoral lake environment. The white arrow indicates centimetric gravels. b Interval from the CHE-1 core (located at ~186 m, Fig. 13) displaying sandy facies, massive (GSm), laminated (GSl) with fining-upward trends and erosional bases (white arrow) and with trough-cross stratifications (GSt), representing deltaic topset deposits in a littoral lake environment (L1 facies association, Fig. 13). c Transversal section of microbial carbonates (Cs facies) encrusting a trunk (dashed line - tilted) near the Arroux section. d Reworked fragment of a sandstone bed with wave ripples (Sw facies, found at the base of the cliff of the Arroux section, Fig. 10).

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

Fig. 5 Illustration of the facies associations (SL1 to SL3 environments, see Table 1 for the facies codes) corresponding to the sublittoral lake environments (prodelta). a Rigny section (see map location in Fig. 2b and location on the outcrop in Fig. 9): zoom on an alternation of inclined facies attributed to deltaic foresets (SL1 facies association) with sandy prodelta deposits (SL2 facies association), characterized by the horizontal GSl facies onlapping the IGSm facies of the deltaic foreset. b Interval from the IG-1 core (located at ~135 m, Fig. 12) displaying facies from the profundal lake environment (P1 facies association) at the base, followed by the sublittoral prodelta SL3 facies association, and by profundal lake deposits (P2 facies association, dominated by organic-rich claystones) and prodelta deposits (SL2 facies association) towards the top. The SL3 prodelta deposits (Sm/F) are broadly finer-grained than the SL2 prodelta deposits, with a higher proportion of fine-grained granulometries; in the prodelta SL2 facies association, the sandy beds (Sm/F and GSm facies) are thicker. c Zoom on a sandy to clayey turbiditic level of the IG-1 core, displaying four terms of the Bouma sequence, i.e., Ta (massive and fining-upward sand), Tb (medium to fine sand, high-energy planar laminae), Tc (ripple bedding) and Td (low-energy planar laminae composed of clay to silt material). The white arrow shows the erosive surface at the base as well as fluid escape features. d Photograph of the Smud facies of the CHE-1 core, attributed to debris flow deposits in rather profundal environments (sublittoral lake SL3, or sometimes profundal lake P1 environments). Pluricentimetric rip-up clasts of various facies and mudclasts are contained in a coarse-sand matrix, sometimes very dark. Fluid escape (white arrow) or injectite features are often observed.

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

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

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

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

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

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

Fig. 12 Sedimentary log of the IG–1 well (see Figs. 1c and 2 for the position in the stratigraphy and location on a map, Fig. 10 for the log caption, and Table 2 for the facies association codes), evolution of the depositional environment, stratigraphic cycles and OM content (Total Organic Carbon, TOC) variation through time. OSB: Oil-shale bed, a: anoxia.

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

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

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

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