

Transgressive-regressive cycles in saline lake margin oolites: paleogeographic implications (Priabonian, Vistrenque basin, SE France)

Nazim Semmani¹, François Fournier^{1,*}, Philippe Léonide¹, Monique Feist², Sarah Boularand³ and Jean Borgomano¹

¹ Aix-Marseille Univ, CNRS, IRD, Coll France, CEREGE, 3, place Victor Hugo, Case 67, 13331, Marseille cedex 03, France

² Université de Montpellier, Institut des sciences de l'évolution (ISEM), Campus Triolet, CC065, 34095 Montpellier cedex 5, France

³ Fédération de recherche sciences chimiques Marseille FR 1739, Pôle PRATIM, 13331 Marseille cedex 03, France

Received: 7 January 2022 / Accepted: 10 June 2022 / Publishing online: 28 July 2022

Abstract – The integrative analysis of a lacustrine carbonate succession from Butte Iouton hill (Vistrenque basin, SE France) brings new insights into depositional models and stacking patterns of oolitic saline lake margins and provides new details regarding the late Eocene paleogeography of southeast France. Depositional facies analysis and paleoenvironmental reconstructions allow reconstructing an oolitic lacustrine ramp model, displaying from the proximal to the distal areas: (1) shallow marginal saline lake domain with deposition of planar microbial laminites, and molluscan-ostracodal wackestone, (2) a more distal and open lacustrine environments with low to moderate energy characterized by the deposition of peloidal grainstones and (3) a domain of higher energy with accumulation of ooids mixed with peloids in the vicinity of the area of ooid production. Lake margin carbonate sedimentation dominantly occurred during stages of lake transgression while subaerial exposure surfaces developed during periods of negative inflow-evaporation balance (forced regression). Carbon and oxygen isotopes together with vertical trends in salinity inferred from molluscan associations show that lake transgression does not result from increasingly positive freshwater-evaporation balance volume but from the combination of subsidence and outflow from neighbouring saline waterbodies. The Butte Iouton carbonate margin is part of a set of interconnected saline lakes, occupying continental basins from Languedoc and Rhodanian region during the Priabonian, with a siliciclastic-dominated sedimentation in the southern margin, sourced by erosion of Pyrenean reliefs, and a carbonate-dominated northern margin with significant oolitic sedimentation in high-energy nearshore area.

Keywords: lacustrine carbonates / oolite / saline lakes / paleogeography / Eocene

Résumé – Cycles de transgression-régression sur une marge oolithique de lac salin : implications paléogéographiques (Priabonien, Bassin de la Vistrenque, Sud-Est de la France). L'étude intégrée d'une butte-témoin de carbonates lacustres (Butte Iouton) a permis d'établir un modèle de dépôt détaillé d'une marge carbonatée oolithique de lac salin, de mettre en évidence des cycles de transgression-régression et d'apporter des éléments de reconstitution paléogéographique des bassins lacustres priaboniens du sud-est de la France. Un modèle de rampe carbonatée lacustre a été mis en évidence, présentant du pôle proximal au pôle distal : (1) un domaine interne à laminites microbiennes et wackestones à ostracodes et mollusques, (2) un domaine plus ouvert, d'énergie modérée à sédimentation granulaire péloïdale et (3) un environnement externe de plus haute énergie à accumulation d'ooïdes et de péloïdes. La sédimentation carbonatée de bordure de lac se produit principalement pendant des phases de transgression lacustre contrôlées par la subsidence alors que les surfaces d'émersion marquent des périodes de bilan hydrique déficitaire et d'assèchement du lac (régression forcée). Les signatures isotopiques (carbone et oxygène) des carbonates ainsi que les tendances d'évolution verticale de la salinité estimées par les assemblages de mollusques suggèrent que les transgressions lacustres ne sont pas associées à un bilan hydrologique excédentaire, mais à des connexions avec des masses d'eau salées adjacentes dans un contexte subsident. Les sédiments carbonatés de la Butte Iouton se sont déposés sur les marges d'un système de lacs salins interconnectés de

*Corresponding author: fournier@cerege.fr

grande dimension, occupant différents sous-bassins du Languedoc et de la Vallée du Rhône. La marge sud de ce système lacustre était à sédimentation silicoclastique dominante, alimentée par l'érosion des reliefs pyrénéens, alors que la marge nord était carbonatée avec un développement significatif de corps oolithiques.

Mots clés : carbonates lacustres / oolithe / lacs salins / paléogéographie / Eocène

1 Introduction

The European Cenozoic Rift System (ECRIS) (Ziegler, 1992; Dèzes *et al.*, 2004) is a NE-SW system of continental lake basins formed during the upper Eocene in the Alpine foreland. These basins are characterized by thick siliciclastic, carbonate and evaporite deposits (*e.g.* Rouchy, 1997). In southeast France, the onset of saline lakes occurred as early as the early Priabonian in the Saint-Chaptes basin (Lettéron *et al.*, 2018) and then developed on a larger scale during the middle to late Priabonian in the Alès (Lettéron *et al.*, 2018), Issirac (Lettéron *et al.*, 2017), Mormoiron-Carpentras (Triat and Truc, 1974; Truc, 1978), Manosque-Forcalquier (Lesueur, 1991) basins and further north in the Valence graben (Dromart and Dumas, 1997) (Fig. 1A). Despite detailed studies on individual basins or connected lake systems (*e.g.* ASCI lake system: Lettéron *et al.*, 2022; Apt-Manosque-Forcalquier lake system: Lesueur, 1991), there are still unresolved questions, debates and controversies on the paleogeography of western Europe during the late Eocene – lower Oligocene times, the origin of the salinity in the lakes and the connections between the lakes and the oceanic realm (*e.g.* Fontes *et al.*, 1991; Rouchy, 1997; Briot and Poidevin, 1998; Bodergat *et al.*, 1999; Rouchy and Blanc-Valleron, 2009; Lettéron *et al.*, 2017; Lettéron *et al.*, 2018). For instance, Lettéron *et al.* (2017, 2018) found that the ASCI lacustrine system was connected to neighbouring saline water bodies whose location and source are not formally established. According to these authors, saline water feeding is presumably from the leaching of northern Triassic diapirs *via* Mormoiron-Carpentras throughs and/or marine domain through the Vistrenque area. The latter is poorly documented since the Paleogene deposits are almost entirely buried beneath the Rhône delta sediments.

Another major issue for the reconstruction of paleogeographic and tectonic evolution of Paleogene basins from southeast France is the availability and quality of chronostratigraphic constraints (Séranne *et al.*, 2021). East of the Nîmes fault, the Cenozoic Vistrenque graben is known only through subsurface studies and has been assigned to the Oligocene Gulf of Lion margin (Valette and Benedicto, 1995; Benedicto *et al.*, 1996), while Cavelier (1984) suggested that the Vistrenque graben initiated during the Priabonian coevally with the neighbouring Languedoc basins such as the north-Montpellier, Sommières, Saint-Chaptes, Alès and Issirac basins (Séranne *et al.*, 2021; Lettéron *et al.*, 2022). To date, the paucity of chronostratigraphic data from the basal filling of the graben (*Série grise* siliciclastic unit, *e.g.* Valette and Benedicto, 1995) does not allow this hypothesis to be validated. However, the northern part of the basin offers the possibility to study on outcrops carbonate successions assumed to be upper Eocene in age (Roman, 1910) and thus provides clues to address the question.

In the present work, we carry out a detailed petrographic, sedimentological and geochemical analysis of a carbonate succession, which outcrops on a residual hill (Butte Iouton,

Beaucaire) located east of the Nîmes fault on the northern margin of the Vistrenque graben and that is characterized by the dominance of oolitic deposits (Figs. 1A and 3A). The main objectives of this study are 1) to document the existence of a salt lake carbonate sedimentation during the Priabonian in the north of the Vistrenque basin and provide new constraints to the chronostratigraphic framework 2) to reconstruct the depositional environments for a Cenozoic oolitic saline lake margin 3) to discuss the control of tectonics and paleohydrological changes onto the vertical facies stacking pattern and depositional sequence development and 4) to provide new insights into the paleogeography of the southeast France by investigating the possible relationships between the saline lake basins of the ECRIS.

2 Geological setting

2.1 The Vistrenque Cenozoic basin: regional tectonic setting and stratigraphy

The Vistrenque basin is a NE-SW trending Cenozoic basin located in the western part of the Camargue region (SE France). The basin extends over 50*30 km² and is assumed to be the deepest Cenozoic basin in the SE of France (Benedicto *et al.*, 1996), it is linked to the Northeast with the Pujaut trough and is separated from the neighbouring Vaccarès (Petit-Rhône) basin by the Albaron structural high (Fig. 1A).

The Nîmes fault is a major low angle-ramp that bounds the Vistrenque and Pujaut basins to the NW and was active during the Oligo-Aquitainian rifting of the Gulf of Lion margin that preceded the oceanic accretion in the Liguro-Provençal basin during the Burdigalian (Gorini *et al.*, 1993; Séranne *et al.*, 1995; Valette and Benedicto, 1995; Benedicto *et al.*, 1996).

Prior to the Oligo-Miocene rifting, strike-slip deformation regime led to the development of many continental sedimentary basins (*e.g.* Alès–Saint-Chaptes–Issirac basin, Lettéron *et al.*, 2022) during the Priabonian (late Eocene) in Languedoc area within a NE trending sinistral strike-slip shear zone, located between the Cévennes and Nîmes faults (Séranne *et al.*, 2021). The Eocene and Oligocene basins of the Languedoc area have well constrained chronostratigraphic frameworks and their depositional and structural settings are well documented (Benedicto *et al.*, 1996; Séranne *et al.*, 2021; Lettéron *et al.*, 2022). The Nîmes and Cévennes sinistral strike-slip faults have accommodated simultaneously the E-W extension of the Western European rifting in the north and the Pyrenean compression from the south (Séranne *et al.*, 2021). In the Camargue region located southern to the Languedoc, Eocene deposits are only known from the Jonquières high (Fig. 1A), and no evidence can be provided to confirm the presence of upper Eocene deposits in the Camargue basins (*e.g.* Vistrenque basin) since their chronostratigraphic framework is not constrained (Benedicto *et al.*, 1996).

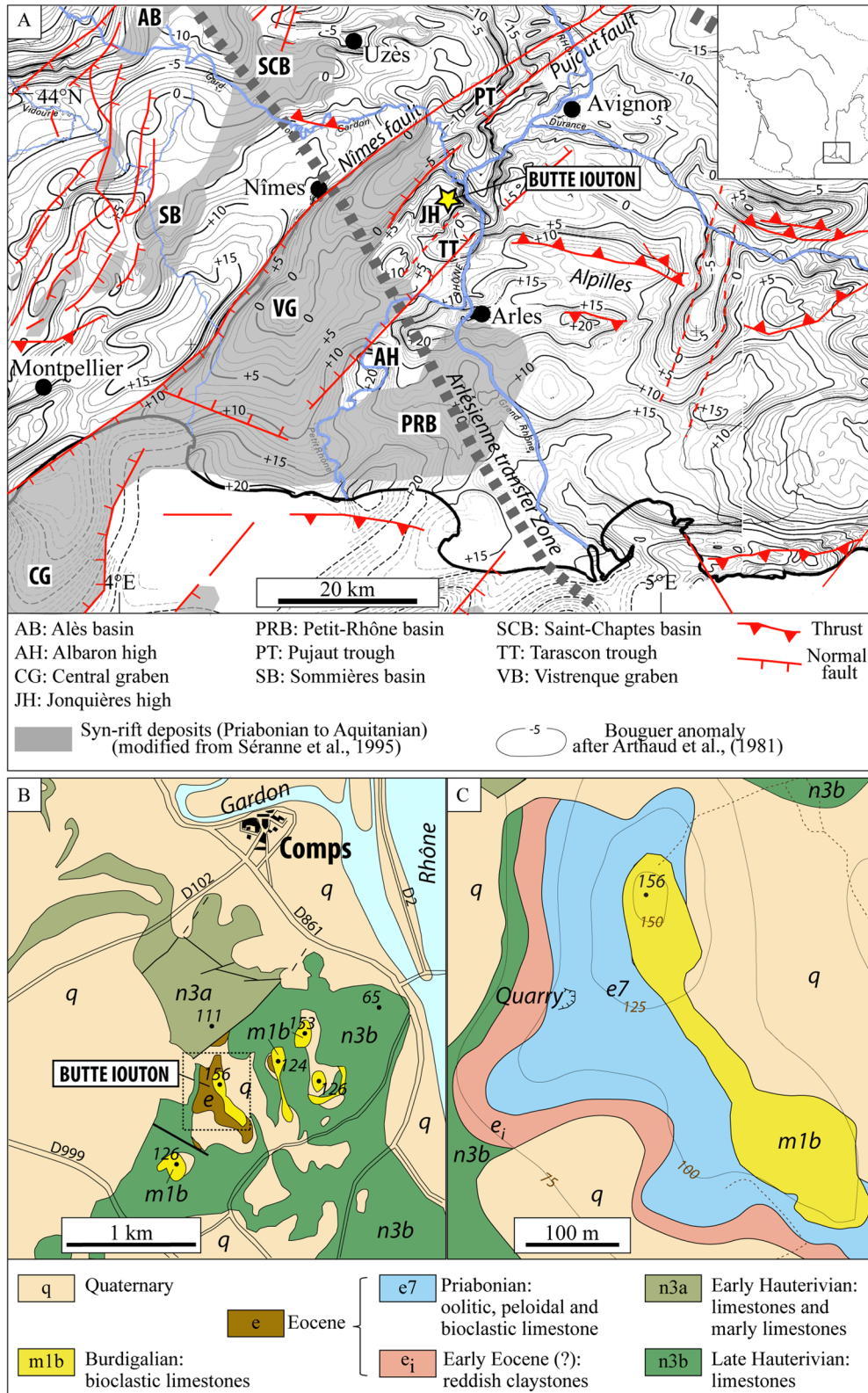


Fig. 1. A) Simplified structural map of Languedoc and southern Rhône valley (SE France) (after Séranne *et al.*, 2021; Mauffret and Gorini, 1996): the grey shaded areas indicate late Eocene to Aquitanian deposits (after Séranne *et al.*, 1995; Séranne *et al.*, 2021) and the background map displays the Bouguer anomaly (after Arthaud *et al.*, 1981). B) Geological map of the Comps and Butte Iouton area, modified from the BRGM geological map, Nîmes sheet 1/50000 (Ménillet, 1973): the map shows the Eocene to Miocene outcrops and the Cretaceous substratum of the Jonquières high. C) Detailed geological map displaying the close-up view of the box around the butte Iouton hill in B).

Stratigraphically, the Eocene (?) to Aquitanian sedimentary succession of the Vistrenque basin exceeds 3000 m in thickness and is subdivided in the depocentre of the basin into three main units, from bottom to top: *Série grise* (more than 2000 m thick), *Série Rouge* (~200 m) and *Série Calcaréo-salifère* (900 m) formations (Benedicto *et al.*, 1996). The lowermost *Série grise* unit consists mainly of deep-lake non-fossiliferous mixed siliciclastic-carbonate detrital sediments and their attribution to the beginning of the Oligo-Miocene gulf of Lion rifting (Benedicto, 1996) or to the late Eocene development of continental basins is an open question. The upper *Série Calcaréo-Salifère* unit is made essentially of evaporite deposits that were assigned to the Upper Oligocene (Valette, 1991). According to Cavelier (1984), the similarity of the sedimentation pattern between the Languedoc grabens and Vistrenque basin (*i.e.* dominant siliciclastic sedimentation to south and carbonate lacustrine margin to the north) would suggest that the deposition of the lowermost *Série grise* unit or at least the basal intervals of this unit was coeval with the widespread Priabonian continental sedimentation in the Issirac, Alès, Saint-Chaptes and Sommières basins.

2.2 The Jonquières high: stratigraphy of the Priabonian lacustrine margin

The Jonquières high is about 5–6 km wide and represents a NE-SW horst structure bordering the Vistrenque basin to the north and located southeast to the Pujaut trough and northwest to the Tarascon trough (Fig. 1A). The high is constituted essentially of the Lower Cretaceous substratum; the Eocene to Miocene cover is limited to a few small residual hills between the villages of Comps and Beaucaire (Fig. 1B). Resting on the Hauterivian marine limestones and marly limestones, the Eocene deposits from these hills (*e.g.* butte Iouton) consist essentially of a ~30 m thick lacustrine limestone succession resting on variegated clays and silts (about 20 m thick interval) attributed by Pellat and Allard (1895) to the early Eocene on the basis of regional facies analogy without any paleontological evidence. These Eocene lacustrine limestones are unconformably overlain by Burdigalian (early Miocene) transgressive coralline algal marine limestones (Pellat and Allard, 1895; Roman, 1903) (Fig. 1C).

The lacustrine limestones from Butte Iouton include oolitic intervals that have been exploited since the Middle Ages as a statuary stone (Dumas, 1876). They yielded a rich molluscan fauna that has attracted the attention of geologists since the first half of the 19th century (De Roys, 1846). The first detailed section of the Butte Iouton hill was carried out by Pellat and Allard (1895) who identified 9 main fossiliferous carbonate layers and mentioned a preliminary list of fossil molluscs. Roman (1910) took charge of the detailed study of fossil molluscs from the regional “Sannoisian” formations and has drawn up a comprehensive inventory that consists of 30 taxa including eight holotypes (hosted in the collections of the University of Lyon) of gastropod species.

3 Material and methods

The 50 m-thick Cenozoic succession of the Butte Iouton hill has been mapped (Fig. 1B). Most of the carbonate section

is quarried on the western flank of the hill (see location in Fig. 1C) thus enabling a continuous and detailed observation of the rock succession. Data on sedimentary structures, depositional textures, biological content, and diagenetic features are compiled in the detailed sedimentary log (Fig. 2).

3.1 Depositional facies and petrographic characterization

A total of 28 thin sections have been prepared to perform detailed microfacies characterization and to determine the petrographic features of the grains using a conventional transmitted polarized light microscope. Carbonate depositional facies have been defined on both macroscopic descriptions and microscopic observations using the Dunham classification of carbonates (Dunham, 1962) expanded by Embry and Klovan (1971). Point-counting (300 points) performed with the JMicroVision software allows to quantify the allochem proportions in thin sections (Roduit, 2007). SEM observations conducted at Pôle PRATIM (Plateforme de Recherche Analytique Technologique et Imagerie, Aix-Marseille University, FSCM) using a Philips XL30 ESEM (environmental scanning electron microscope) enable to investigate in more detail the internal microstructure of some carbonate grains.

3.2 Biological assemblages and chronostratigraphic framework

Particular attention was paid to the examination of the quarry's fossiliferous layers to determine the fossil assemblages, namely the molluscs (gastropods and bivalves) and the remains of characean algae (Fig. 3). Molluscan assemblages provide key indication for paleoecological reconstructions (*e.g.* Lettéron *et al.*, 2017) and contribute to a lesser extent to constrain the chronostratigraphic framework (Cavelier *et al.*, 1984). Charophyte gyrogonites constitute an essential tool to better constrain the age of the deposition of fresh and brackish water carbonates and will therefore be used for the biostratigraphic review of the studied succession from the butte Iouton hill. Molluscan shells and charophyte gyrogonites are often well preserved and are easily extracted. In few horizons, the shells are totally dissolved and only the external moulds remain. Casts have been made by injecting silicone resin into the moulds and the resulting casts allow a detailed examination of the external ornamentation of the molluscan shell casts. The identification of the molluscan taxa is carried out in accordance with the diagnoses documented in Fontannes (1884) and in Roman (1910). The fossil collection of Pierre de Brun, hosted in the Museum of Paleontology of the Aix-Marseille University, that catalogues most of the molluscs found in the butte Iouton have been also consulted.

The chronostratigraphic framework of the butte Iouton limestones has been therefore established using: (1) characean gyrogonites and (2) key molluscan taxa with significant stratigraphic value.

3.3 Carbon and oxygen stable isotopes

A total of 58 powdered samples (average spacing = 50 cm) were extracted from the limestones using a Dremel micro-drill

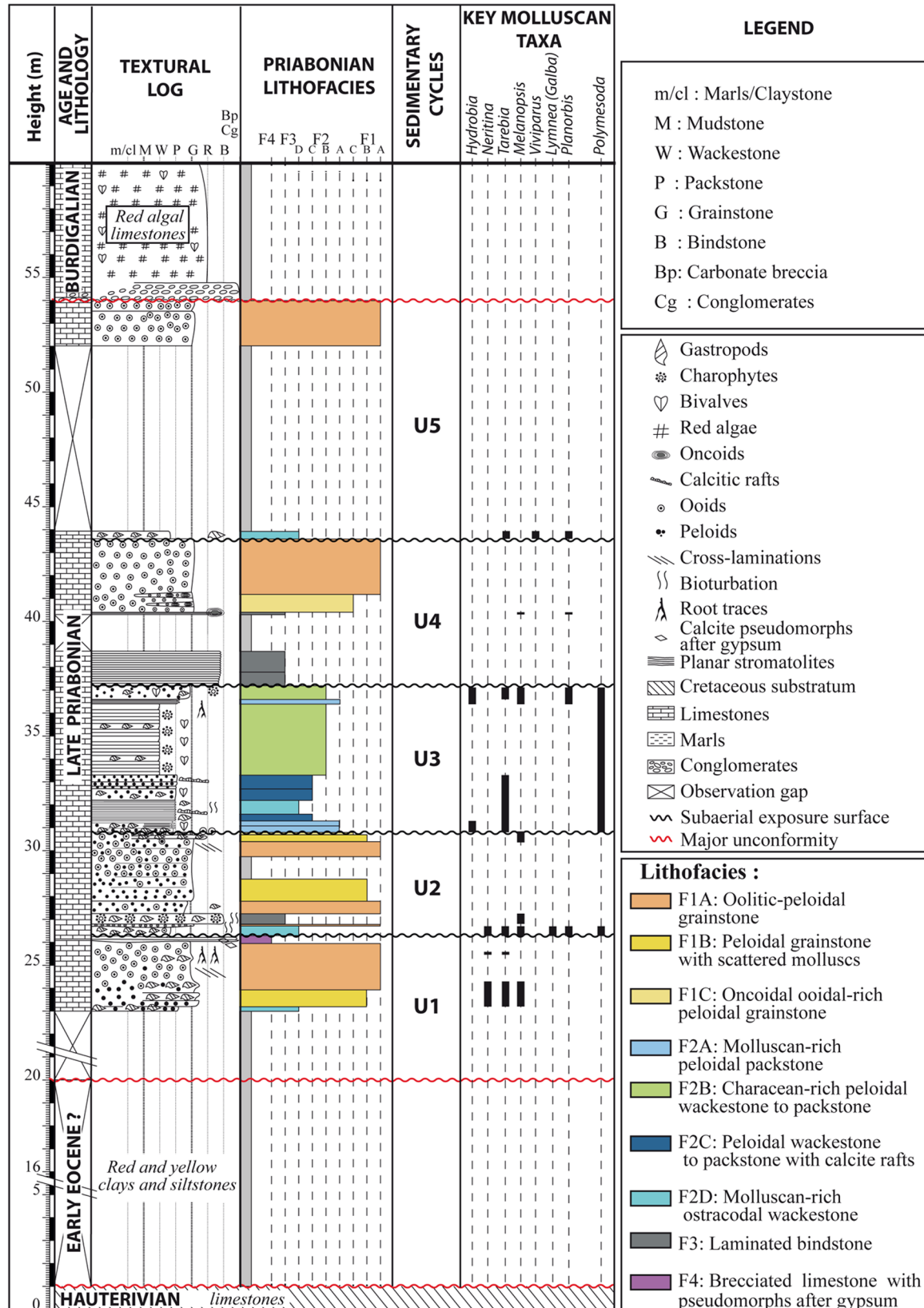


Fig. 2. Detailed sedimentary log of the butte Iouton succession and main molluscan taxa identified on field. Most of the section is measured on the quarry (see location in Fig. 1C). See text for the definition of lithofacies and sedimentary cycles.

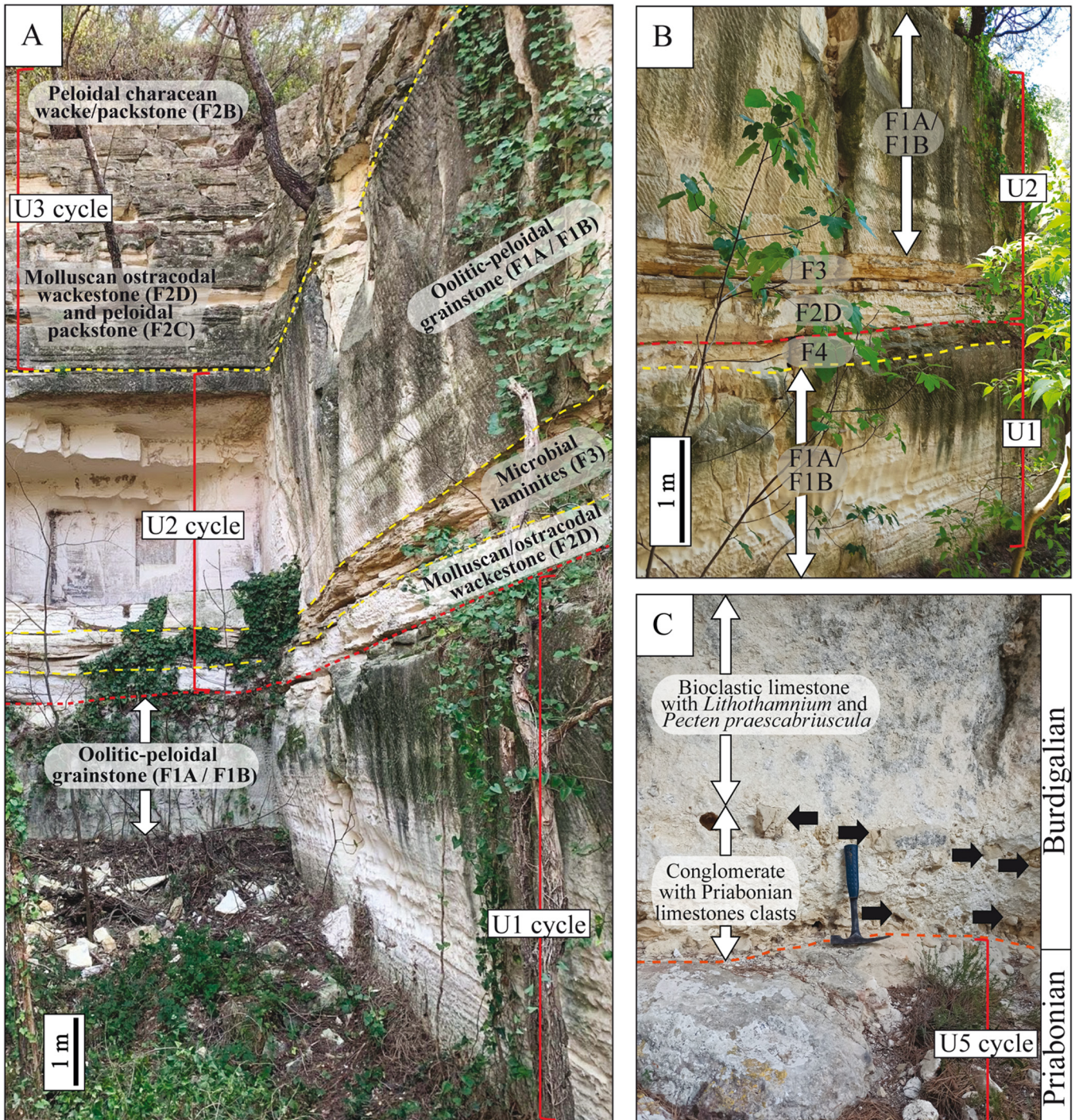


Fig. 3. Field photographs from the Butte Iouton quarry. A) Stratal succession from U1 to U3 cycles showing the thick and horizontally layered oolitic-peloidal grainstone beds. B) Close view on stratal succession from U1 and U2 cycles C) Erosional contact between Priabonian lacustrine oolitic grainstones and overlying Burdigalian bioclastic limestones. Priabonian limestone clasts are reworked within the Burdigalian deposits (black arrows).

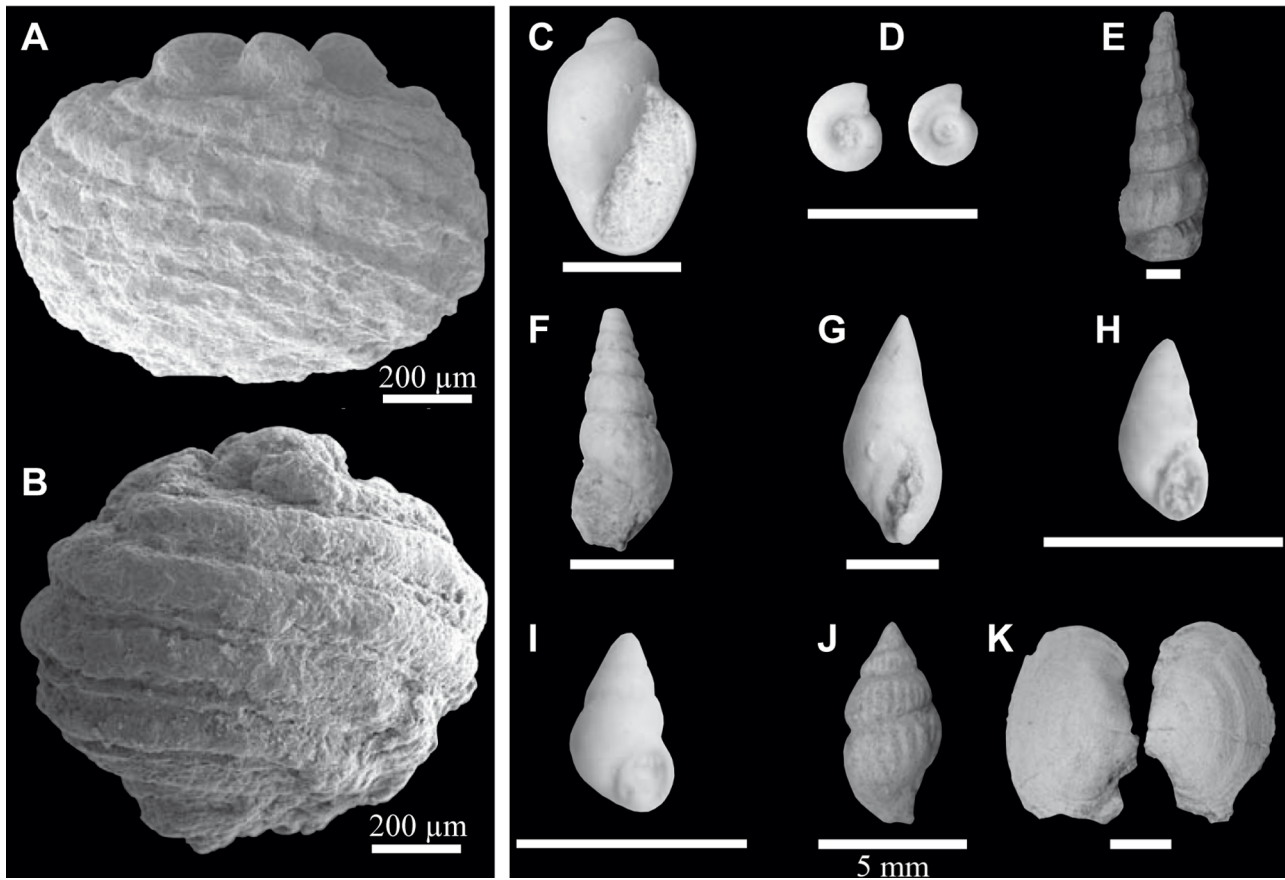


Fig. 4. Charophyte gyrogonites and key gastropods and bivalves from the butte Iouton limestones. A–B: SEM photographs of characean gyrogonites from the lowermost characean-rich microbial laminites. A) *Gyrogonia caelata* (Reid and Groves, 1921), lateral view. B) *Gyrogonia* aff. *lemanii capitata* (Grambast and Grambast-Fessard, 1981) lateral view. C–K: Common molluscan taxa. C) *Lymnea ioutensis* (Roman, 1910). D) *Planorbis stenocyclotus* (Fontannes, 1884). E) *Brotia Albigensis* (Noulet, 1854). F) *Tarebia barjacensis* (Fontannes, 1884). G) *Melanopsis acrolepta* (Fontannes, 1884). H) *Hydrobia celasensis* (Fontannes, 1884). I) *Assiminea nicolasi* (Roman, 1910). J) *Nystia plicata* (d'Archiac and de Verneuil, 1845). K) *Polymesoda dumasi* (de Serres, 1827). Scale bar is 5 mm.

tool. Bulk-rock stable carbon and oxygen isotope analyses were performed at the GeoZentrum Nordbayern department, Friedrich-Alexander-Universität Erlangen-Nürnberg (Germany) in order to detect potential diagenetic overprints (*e.g.* pedogenesis at exposure surfaces) and/or to provide insights into lake paleohydrology. The analysis technique employed consists in the reaction of the powders with 100% phosphoric acid at 70°C using a Gasbench II connected to a Thermo Fisher Scientific DELTA V Plus mass spectrometer. All values are reported in per mil relative to V-PDB. Reproducibility and accuracy were monitored by replicate analysis of laboratory standards calibrated by assigning $\delta^{13}\text{C}$ values of +1.95‰ to NBS19 and –47.3‰ to IAEA-CO9 and $\delta^{18}\text{O}$ values of –2.20‰ to NBS19 and –23.2‰ to NBS18. Reproducibility for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ was ± 0.04 and ± 0.03 (1 standard deviation), respectively.

4 Results and interpretations

4.1 Biostratigraphy

The Butte Iouton quarry yields two taxa from the genus *Gyrogonia* and some specimens are catalogued in the

collections of the University of Montpellier under the number CF.3088.

4.1.1 *Gyrogonia caelata* Ried and Groves, 1921 (Fig. 4A)

This species is largely dominant in the charophyte assemblage. The general morphology as well as the dimensions of the examined samples are consistent with the definition given by Grambast and Grambast-Fessard (1981). *G. caelata* is widespread in the European area and occurs within the charophytes biozones ranging from *Maedleriella embergeri* zone to *Stephanochara vectensis* zone (Riveline *et al.*, 1996). These biozones encompass the upper Lutetian – Priabonian interval.

4.1.2 *Gyrogonia* aff. *lemanii capitata* Grambast and Grambast-Fessard, 1981 (Fig. 4B)

This species is uncommon in the butte Iouton deposit and only a couple of specimens have been identified. The specimens meet the morphological criteria given by Grambast and Grambast-Fessard (1981) although their dimensions are found to be slightly smaller. This taxon is reported from many

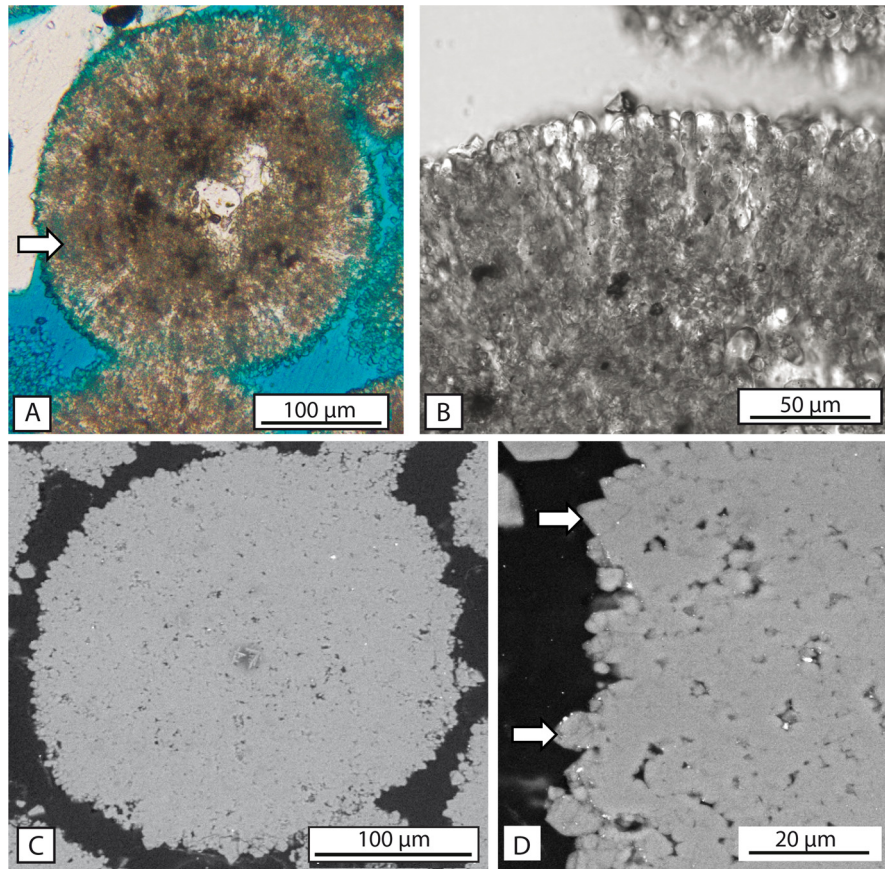


Fig. 5. Microstructure of ooids. A) Thin-section microphotograph under polarized-light microscopy showing the variably preserved radiaxial microstructure within the cortex and the occurrence of micritized areas (arrows). The inner part of the ooid is pervasively micritized and the nucleus consists of a quartz grain. B) Detail of the radiaxial microstructure of ooid cortex under reflected-light microscopy. C) SEM photograph of a thin-sectioned micritized ooid showing the euhedral to subhedral micrite probably replacing the initially radiaxial microstructure and the presence of significant inter-crystalline microporosity. D) Close-up on the outer cortex of a micritized ooid under SEM showing microrhombic calcite overgrowths (arrow).

areas in Western Europe, such as the Paris Basin, Campbon Basin (southern Brittany), Upper Rhine Basin (Bouxwiller site) and southwestern Languedoc (Causse-et-Veyran site) (Riveline, 1986). *G. lemani capitata* appears, together with the whole species of the genus *Gyrogona*, within the *Maedleriella embergeri* biozone and has a lesser range than *G. caelata* (Riveline *et al.*, 1996). The former extends only up to the *Psilochara repanda* biozone, thus suggesting an age ranging from the Lutetian to the upper Bartonian. The difference in dimensions with the holotype raises uncertainties about the taxonomic attribution of the two specimens to *G. lemani capitata*, hence the insertion of the complement aff. (*species affinis*). The insufficient amount of material makes it difficult any attempt to define a new species. Because of such a taxonomic uncertainty, these two specimens were not considered for constraining biostratigraphic ages.

The molluscan taxa identified on the butte Iouton outcrops are illustrated in Figure 4 and fall within the list of taxa compiled by Roman (1910) (Fig. 4C–K). Out of a total of the 30 molluscan taxa described by the same author in this site, 15 species are also documented from the molluscan associations of the middle to upper Priabonian successions from the Alès and Issirac basins (Fontannes, 1884; Lettéron *et al.*,

2017). Among the mollusc taxa of the butte Iouton, some fossils are considered to have a reliable regional stratigraphic value and are therefore used as key-stratigraphic markers in continental settings (Cavelier *et al.*, 1984; Fauré, 2007). For instance, *Nystia plicata* (d'Archiac and de Verneuil, 1845) extends from the late Priabonian to the Rupelian while *Viviparus soricinensis* (Noulet, 1854) has a much wider range since it is known from middle Priabonian up to Rupelian deposits. However, the bivalve *Polymesoda dumasi* (de Serres, 1827) has a narrow range since it occurs only from the middle to upper Priabonian and has never been reported in the Oligocene successions. Along with the previously discussed stratigraphic implications of the charophyte flora, the molluscan assemblage especially the occurrence of the taxa *N. plicata* and *P. dumasi* provides strong evidence to assign a late Priabonian age to the Butte Iouton limestones.

4.2 Carbonate petrography and diagenetic features

Petrography and SEM observations of thin sections from the butte Iouton limestones help to identify five grain types, namely ooids, peloids, aggregate grains, reworked sparitic crusts and miscellaneous skeletal grains including molluscans

(both bivalves and gastropods) and ostracods, and charophyte remains.

Ooids are the dominant grain type and are generally small, averaging 300 microns in diameter (medium sand) (Figs. 5A and 6A–B). These small ooids display various cortex fabrics: thin cortices are found in superficial ooids while radial fibrous or concentric micritic cortices define radial (Fig. 5A–B) and micritized ooids (Fig. 5C–D) respectively. The ooids have either peloid, bioclast or fine quartz grain nuclei and show different stages of micritization obliterating the original microstructure. Other coated grains include coarse ooids and/or oncoids (=coated grains whose cortex is formed by cyanobacterial laminae) (Fig. 6G), their sizes range between 600 microns and may reach up to 2 mm and most of them display concentric laminae cortices.

Peloids are frequent in the butte Iouton limestones and show various shapes and sizes (Figs. 5A–6E–6E–F). Peloids are in general sub-rounded to elongated, range between 80 and 200 microns in size and display dark and homogeneous micritic internal structure. Aggregate grains from the butte Iouton section are very irregular in shape and are recognized based on the characteristic lobate to rounded outlines (Fig. 6E). These aggregate grains have a wide range of sizes from 0.5 mm to several mm and the original separate grains may either be peloids or micritized ooids; their smooth outlines allow to consider them as lumps according to the description provided by Tucker and Wright (1990). Reworked sparitic crusts are flattened and are thin sheets formed by calcite crystals arranged side by side. The sparry crystals are equigranular, dogteeth shaped, and each is between 40 and 50 μm in size (Fig. 7F). Calcite crystals line up in one or more rows and this may reflect single or multiple generations of crystal growth from an initial surface, possibly a microbial film and have been reworked and re-deposited without any particular orientation.

The molluscs from the butte Iouton limestones consist mainly of freshwater to oligo-mesohaline taxa. Gastropods and bivalves may be found in the form of entirely micritized calcitic shells (Fig. 6E–F) or recognized by their external moulds if they are completely dissolved, especially in case of formerly aragonitic shells (Fig. 7A, D, G–H). Ostracods (Fig. 7G) and characean gyrogonites (Fig. 8C) are preserved owing to their original calcite mineralogy.

The main diagenetic processes observed are: a) compaction (ooids, shells, characean remains), b) micritization of molluscan shells and ooid cortices, c) selective mouldic dissolution of aragonite grains (mainly molluscs), d) cementation (calcite spar: Fig. 8E), e) pedogenesis (soil formation, brecciation), and f) calcite pseudomorphs after gypsum (Fig. 8E).

Petrographic observations show preferential dissolution of the aragonite shells of molluscs and the preservation of the ooids cortices that may point to different original mineralogies of these grains, while some samples display strong micritization of both molluscan shells and ooids. The original mineralogy of the ooids is difficult to establish since both radial and micritized layers can coexist and since petrographic observations show evidences of severe neomorphic processes. The mineralogy of ooids and their fabric, in particular those formed in freshwater and extreme environments is still a matter of debate (e.g. Kahle, 1974; Sandberg, 1975; 1980; Swirydzuk and Wilkinson, 1979).

4.3 Depositional facies and paleoenvironmental interpretations

Based on depositional texture (Dunham classification), sedimentary structures, biotic composition, and the petrographic character of the allochems, nine depositional facies have been defined and summarized in Table 1.

4.3.1 F1A. Oolitic-peloidal grainstone

This facies consists of moderately to well-sorted grainstones composed of a mixture of ooids and peloids in variable proportions: ooids (~ 300 microns in size) are dominant and their proportion ranges from 50% (bimodal distribution) to 95% (unimodal distribution) (Fig. 6A). Some ooids exhibit preserved superficial and radial internal structures although most of them are strongly micritized. The peloids are predominantly small and have different morphologies, their dimensions range between 100 and 200 microns; other allochems include few aggregate grains ($<1\%$). Molluscan shells and fragments can accumulate in the form of fossiliferous gravelly lenses interbedded with the ooidal-peloidal sand levels (Fig. 6C). The gravelly lenses are about 10 cm thick and few metres wide, and most of the fossils are complete or slightly broken. The molluscan assemblage is dominated by *Melanopsis*, *Tarebia* and *Neritina* together with the peloidal grainstones (see description hereinafter), the oolitic-peloidal grainstones form subhorizontal beds with thicknesses varying from 2 m to 3 m (Figs. 3B–6C–6C). Cross-stratifications are seldom visible on outcrop and when observed (e.g. Fig. 6D) they may form 10–50 cm height sets that are bounded at base and top by planar nearly horizontal surfaces (“planar cross-stratifications”). The scarce apparent paleocurrent directions measured on the quarry faces are toward the south-west.

Interpretation: The moderately to good sorting of these grainstones and the winnowing of the micrite suggest high energy depositional conditions. Though seldom observable, the occurrence of planar cross-stratifications within the oolitic beds may reflect sandwaves or dunes migration related to high energy currents (Dalrymple, 1992). Ooids are generally produced in shallow nearshore shoals subject to high hydrodynamic conditions and form very well sorted sediments. Thus, the mixture of ooids and peloids in F1A facies suggests deposition in the vicinity of these shoals where ooids are remobilized by waves and currents. In lacustrine environments, well sorted oolitic sediments are essentially reported from shallow lake margin shoreface (e.g. Williamson and Picard, 1974; Tānavsuu-Milkeviciene *et al.*, 2017; Gallois *et al.*, 2018; Deschamps *et al.*, 2020) and foreshore settings (Swirydzuk *et al.*, 1980; Milroy and Wright, 2002). The relative scarcity of sedimentary structures in most oolitic beds may result from significant burrowing of a stable substrate in a low to moderate energy environment in backshoal setting as reported from shallow marine environments (Pomar *et al.*, 2015). The molluscan-rich gravelly lenses are also indicative of moderate to high energy at least intermittently to make fossil accumulations possible. Gastropod *Tarebia* is known to thrive preferentially in oligo-mesohaline waters (e.g. Plaziat and Younis, 2005; Esu and Girotti, 2010; Miranda *et al.*, 2010) while *Melanopsis* is mostly indicative of freshwater to

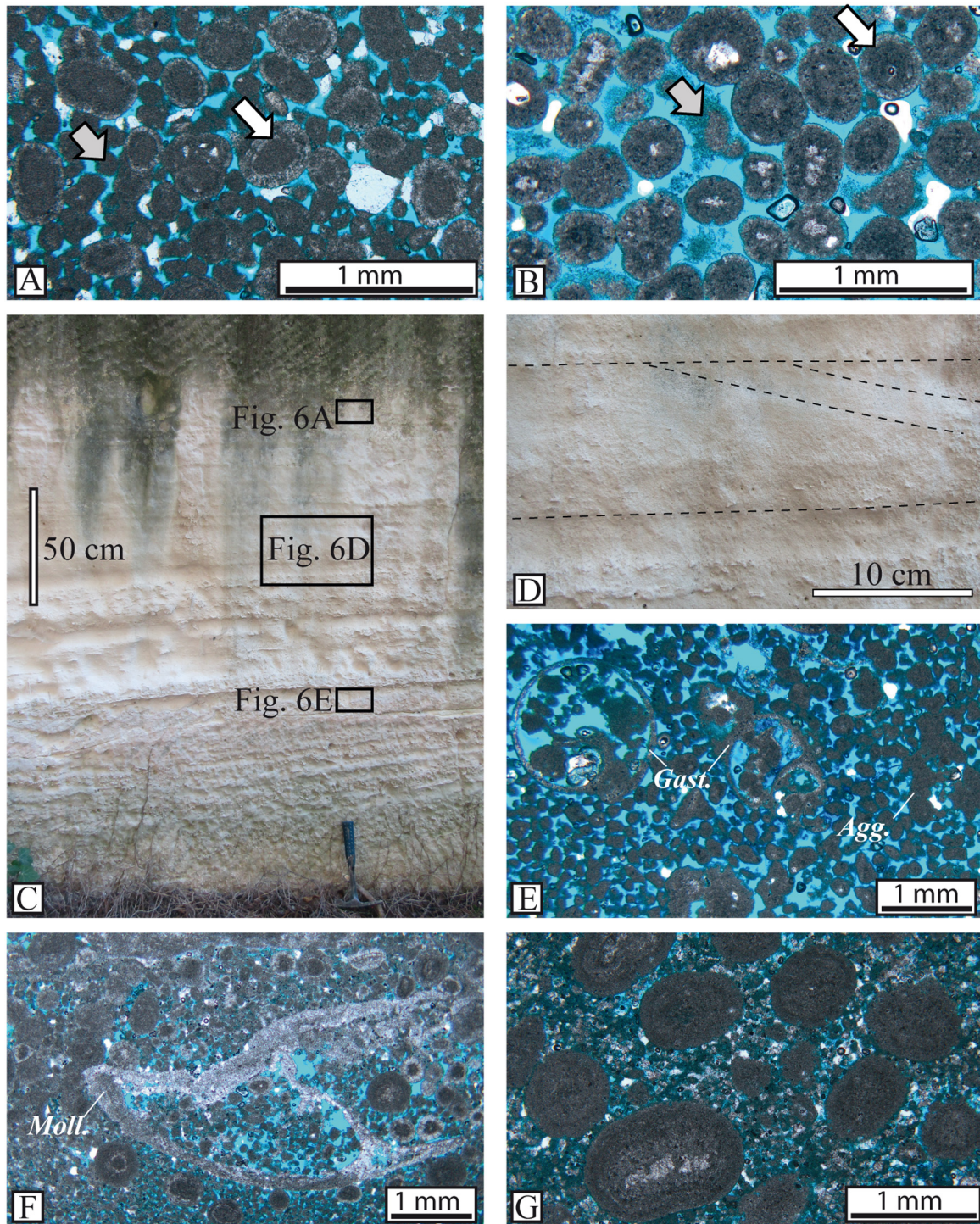


Fig. 6. Oolitic-peloidal and peloidal grainstones facies (F1). A-B-E-F-G) Thin section microphotographs under plane polarized light; C-D: Field photographs. A) Oolitic-peloidal grainstone (Facies F1A) showing a mixture of ooids (white arrow) and peloids (grey arrow). Note the bimodal distribution of grains: the medium-sized grains include superficial, radiaxial and strongly micritized ooids while the peloids are the finer (around 0.1–0.2 mm size) and structureless grains. The nuclei of the ooids are essentially made of peloids. B) Well-sorted oolitic-peloidal grainstone displays abundant radiaxial ooids (white arrow) and few peloids (grey arrow). The nuclei of the ooids consist of quartz grains or bioclasts. Note the high amount of intergranular porosity and the almost lack of compaction features. C) Field photograph of the southern face of the quarry showing a massive bed of oolitic peloidal grainstones with decimetre-thick, gravelly fossiliferous lenses. Cross-stratifications are seldom visible (see Fig. 6D). D) Close-up view of sub-planar cross-stratification from the oolitic-peloidal grainstones indicated by the dotted lines. The cross-beddings heights range between 10 and 50 cm. E) Peloidal grainstones with scattered molluscs (F1B facies) displaying slightly elongated peloids, micritized molluscan shells (mainly gastropods: *Gast.*) and few aggregate grains (*Agg.*). F) Oncooidal-oidal rich peloidal grainstones (F1C facies) are poorly sorted sands consisting of a mixture of peloids and coarse grains (coated grains and molluscs). Note the strong micritization of the molluscan shells (*Moll.*). G) F1C facies displays bimodal distribution made of millimetric coated grains (ooids and/or oncoids) floating in a peloidal sand matrix: F1C facies occurs generally within few centimetres thick lenses.

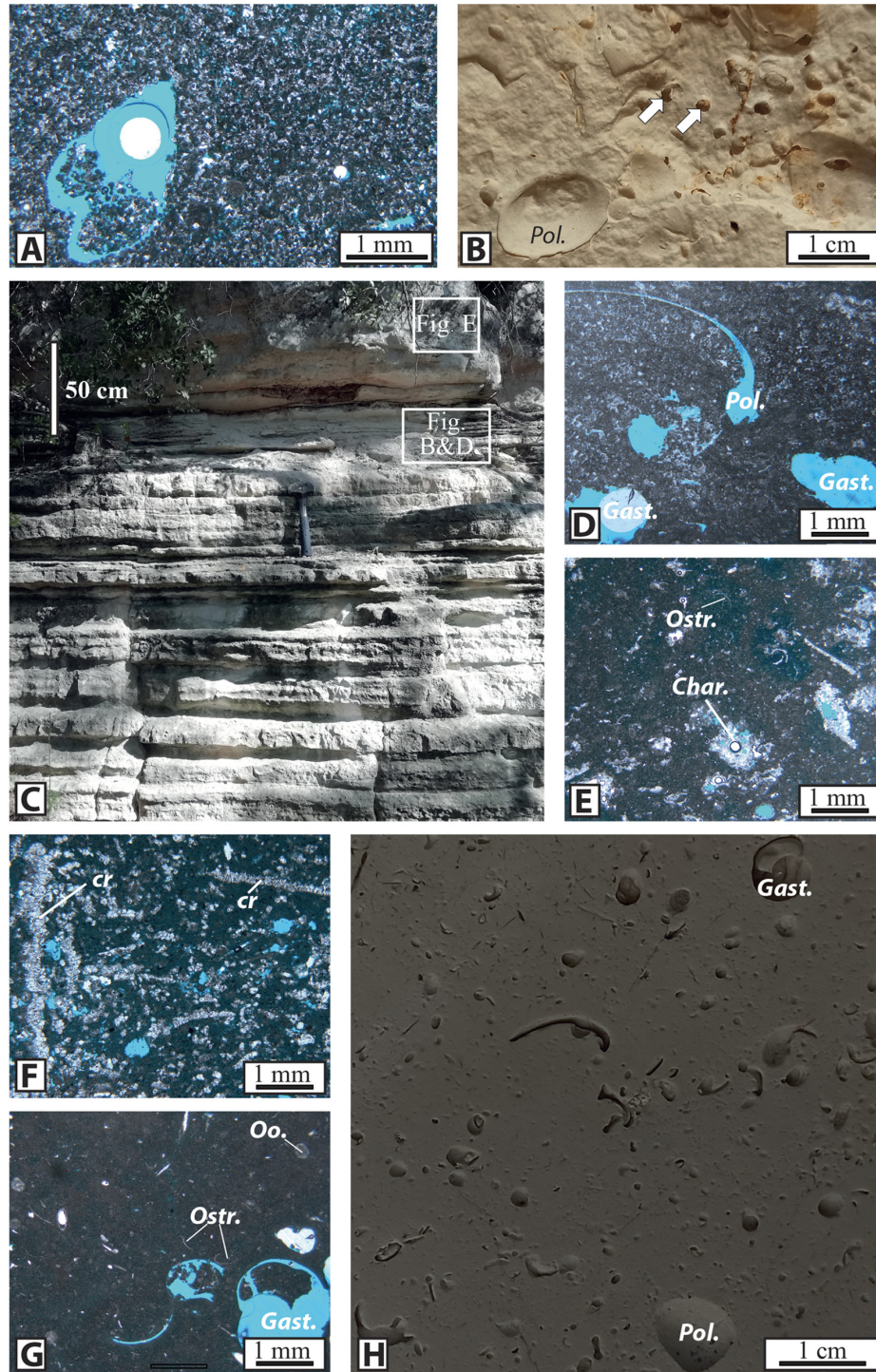


Fig. 7. Mud-dominated facies F2. A) Molluscan-rich peloidal packstones (F2A facies) The thin section shows dissolution of a gastropod and the abundance of microspar cement (PPL; plane polarized). B) Hand sample image showing the accumulation of molluscs in the facies F2A. The molluscan assemblage is dominated by *Polymesoda* sp. (**Pol.**) and small hydrobids (white arrow). C) Outcrop photograph showing the decimetre thick tabular beds of the mud-dominated facies (F2). D) Thin section of the facies F2A exhibits a mould after *Polymesoda* sp. (**Pol.**) in the upper quarters of the picture and small gastropod moulds (**Gast.**) in the lower left and right-hand quarters and abundant microspar cementation (PPL). E) Thin section of Characean-rich peloidal wackestone to packstone (F2B facies) displaying abundant characean cortical cells and stems (**Char.**) and ostracods (**Ostr.**). The matrix is made of densely packed peloids. F) Peloidal wackestone to packstones with reworked calcitic rafts (**cr**) (F2C facies). G) Thin section (under PPL) of the facies F2D showing abundant ostracods (**Ostr.**), molds of gastropods (**Gast.**) and (reworked?) ooids (**Oo.**). The micrite is inhomogeneous suggesting burrowing and bioturbation. H) Hand sample image displaying molluscan-rich ostracod wackestone (F2D facies): the molluscan shells are preserved as moulds. The assemblage is dominated by gastropods (**Gast.**) and by the bivalve *Polymesoda* (**Pol.**).

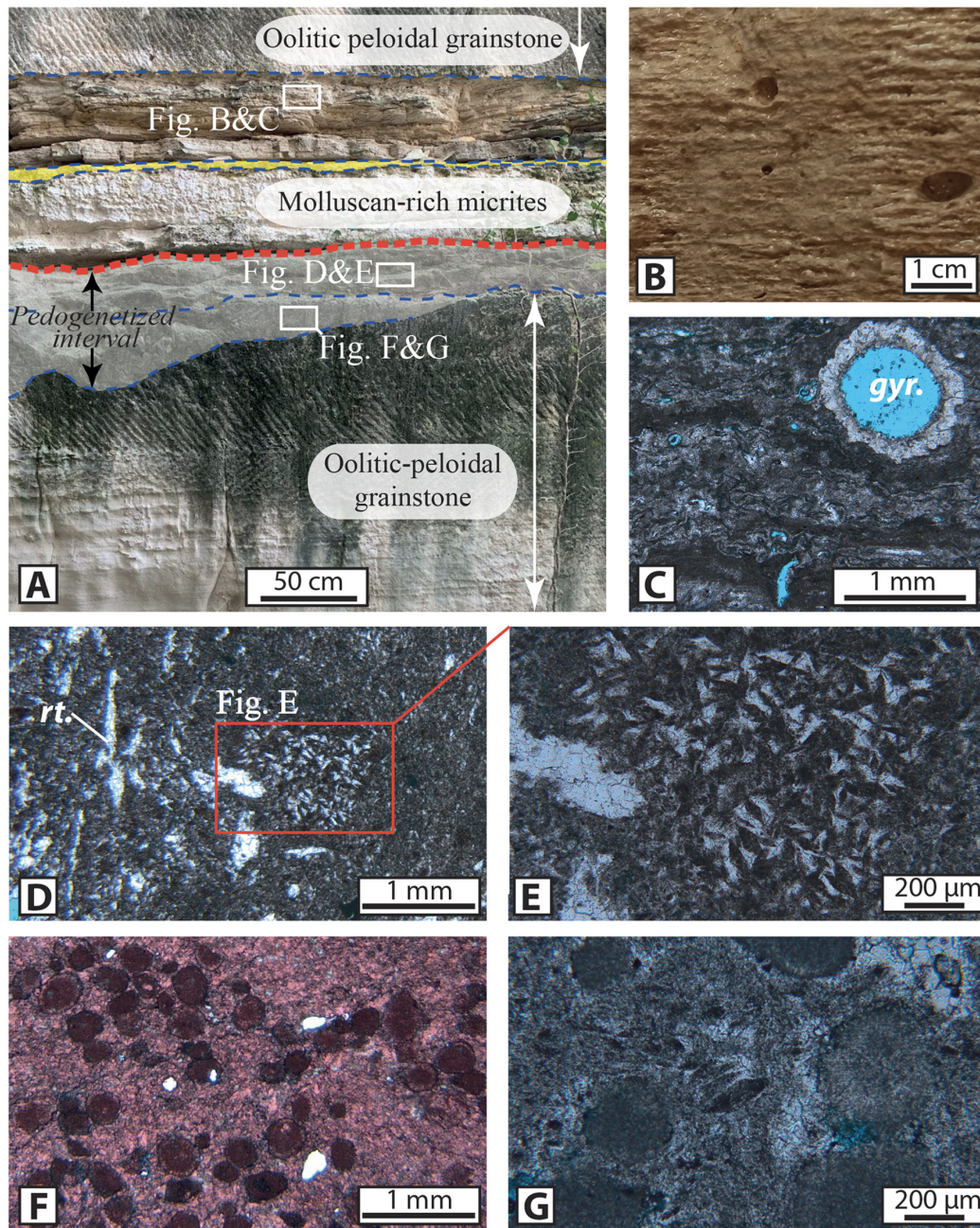


Fig. 8. Planar-laminated bindstones (F3 facies) and pedogenic carbonate breccia (F4 facies). A) Field photograph of the southern face of the quarry displaying the vertical evolution from the oolitic peloidal grainstones (lower white double arrow) to the brecciated interval (dark double arrow). The red thick dashed line indicates a subaerial exposure surface, and the yellow interval indicates few centimetres-thick oolitic grainstone. The laminated bindstones occur in the upper part of the picture (see Fig. 8B and 8C). (B) Close-up view of the planar-laminated bindstone. Infra-centimetric pores are moulds after *Melanopsis* gastropod dissolution. (C) Thin section under plane polarized light of F3 facies displaying alternations of dark (micrite) and light (accumulation of characean cortical cells fragments and calcite microspar) crinkled to wavy laminae, with characean gyrogonite (*gyr.*). D-E) Microphotographs under plane polarized light of brecciated limestones. (D) Thin section showing vertical and curved cracks (root trace: *rt*) filled with calcite. White box indicates a dissolution vug filled with calcitic pseudomorphs after gypsum. (E) Close-up view of the box in B) showing relicts of the tabular to microlenticular gypsum and the replacing calcitic micrite to microspar. (F) Thin section showing the intrasediment growth of gypsum within the oolitic-peloidal grainstone. The similarity in petrographic characters with the underlying F1B facies (see Fig. 8A) and the grain contact points to post-depositional gypsum growth after lake evaporation. The Alizarine Red staining in red colors indicates calcite mineralogy (plane polarized light). (G) close-up view showing calcite pseudomorphs after gypsum that occupy the inter-oolidal space.

Table 1. Facies classification of the Butte louton limestones: biological contents, sedimentary and diagenetic features, and their paleoenvironmental interpretations.

Facies	Dominant biota	Sedimentary structures	Stratal pattern	Diagenetic features	Paleoenvironmental interpretation
F1A Oolitic-peloidal grainstone	Gastropods: <i>Melanopsis</i> , <i>Tarebia</i> , <i>Neritina</i>	Seldom visible cross-stratifications. Good sorting (unimodal) to bimodal distribution	Massive, can form up to 2–3 metres thick units with peloidal rich grainstones (F1B)	– Micritization of shells and ooids cortices – Intragranular microporosity development – Microhombic micrite overgrowths – Minor compaction features at grain contact	Moderate to high energy, shallow, oligo-mesohaline, perennial lake environments, at the vicinity of oolitic shoals
F1B Peloidal grainstone	Gastropods: <i>Melanopsis</i> , <i>Tarebia</i> , <i>Neritina</i>	Seldom visible cross-stratifications. Bimodal distribution of the grains	Massive, can form up to 2–3 metres thick units with oolitic-rich grainstones (F1A)	– Micritization of shells and ooids cortices – Intragranular microporosity development – Minor compaction features at grain contact	Moderate energy, shallow, oligo-mesohaline, perennial lake environments, in backshoal setting
F1C Oncoidal-oolitic-peloidal grainstone	Scarce gastropods	Gravel lenses of coarse-sized grains	Centimetre-thick strata	– Micritization of shells and ooids cortices – Intragranular microporosity development – Minor compaction features at grain contact	Moderate to high energy, shallow, oligo-mesohaline, perennial lake environments
F2A Mollusk-rich peloidal packstone-grainstone	Bivalves (Polymesoda), gastropods (Hydrobids, <i>Tarebia</i>), ostracods, scarce charophytes	Structureless	Few centimetres to decimetre tabular beds	– Microsparry and sparry calcite cements – Dissolution of molluscan shells	Shallow, oligo-mesohaline lake with low to moderate water energy
F2B Characean-rich peloidal wackestone-packstone	Characean gyrogonites and stems, ostracods, mollusks (<i>Polymesoda</i> , <i>Tarebia</i> , hydrobids)	Structureless	Centimeter-thick tabular to nearly horizontal beds forming up to 4 m thick set of platelets limestones	– Dissolution of aragonitic shells – Microsparry to sparry calcite cements in molds	Shallow, perennial oligo-mesohaline lake with Characean meadows
F2C Peloidal wackestone to packstone with calcitic rafts	Bivalves (<i>Polymesoda</i>), gastropods (<i>Tarebia</i>)	Structureless	Decimetre tabular beds	– Dissolution of aragonitic shells	Shallow, perennial oligo-mesohaline lake, within or at vicinity of unpreserved macrophyte meadows
F2D Molluscan-ostracodal wackestone	Ostracods, gastropods (<i>Lymnaea</i> , <i>Viviparus</i> , <i>Planorbis</i> , <i>Tarebia</i>)	Inhomogeneous micrite, burrowing and bioturbation	Decimetre tabular beds to metre beds	– Dissolution of aragonitic shells – Microsparry to sparry calcite cements in molds	Low energy, shallow freshwater to oligohaline pools and sheltered areas of the lake margin
F3 Planar-laminated bindstone	Characean gyrogonites and stems, ostracods, gastropods (mainly <i>Melanopsis</i>)	Alternation of subhorizontal to wavy and crinkled millimeter-thick micritic and microsparitic laminae	Up to 2 m-thick intervals of massive to platy limestones	– Dissolution of aragonitic shells – Microsparry to sparry calcite cements in molds	Low energy, very shallow freshwater to oligohaline lake margin
F4 Carbonate breccia with pseudomorphs after gypsum	No preserved biota	Structureless	Decimetre thick tightly cemented and irregularly bedded limestone. Gradual transition with underlying oolitic grainstone	– Circumgranular cracks – Dissolution vug and conduits formations – Root traces – Intrasediment growth of microlenticular gypsum – Calcite pseudomorphs after gypsum – Sparry calcite cements	Paleosol in evaporitic setting

oligohaline settings (Velasco *et al.*, 2006). Plaziat and Younis (2005) found that smooth morphologies of *Melanopsis*, such as evidenced in Butte Iouton specimens, prefer brackish-water environments. The oolitic-peloidal grainstones and gravelly lenses are therefore interpreted to form within and/or at the vicinity of shallow nearshore oolitic shoals, in low to moderate salinity (from oligo- to mesohaline) and moderate to intermittently high energy waters.

4.3.2 F1B: Peloidal grainstone with scattered molluscs

F1B facies consists of a moderately to well-sorted grainstones composed mainly of peloids with proportions ranging between 75% and 90% and molluscan shells (<20%) with few aggregate grains and ooids (Fig. 6E). The peloids occur in a wide range of morphologies and are between 0.05 and 0.2 mm in size. The aggregate grains (Fig. 6E) are large with dimensions comprised between 0.5 mm and few millimetres and are often lumps formed by peloids and few micritized ooids bound together by microbial cement. Gastropods are the dominant organisms found in these facies and their association is similar to that described previously from the oolitic-peloidal grainstones, among others *Melanopsis* and *Tarebia*: the shells are found to be entirely micritized. Together with the previously described oolitic-peloidal sands (F1A) and the gravelly fossiliferous lenses, these peloidal grainstones are organized into massive (2–3 m thick) and subhorizontal, structureless beds.

Interpretation: Like in the F1A facies, the lack of mud matrix and the good sorting of the grains suggest that F1B facies are deposited in moderate to high energy settings. In addition, the occurrence of F1B facies together with F1A facies and the presence of minor proportion of ooids in the peloidal sands strongly indicate nearby depositional environments. The good sorting and the low variation in shape of peloids suggest they are likely to be mostly produced by organisms (*i.e.*, faecal pellets) like gastropods and ostracods. Molluscan-rich accumulations probably result from transportation and deposition of molluscan shells during higher energy episodes. Similarly to F1A, the molluscan assemblage indicates oligo-mesohaline shallow waters probably of less than 10 m in depth (*e.g.* Lettéron *et al.*, 2017 and references therein). Furthermore, the absence of subaerial exposure features within these facies indicates perennial lake conditions. Consequently, F1B facies is interpreted to form in the shallow parts of a perennial lake close to the oolitic shoals with moderate to high energy levels.

4.3.3 F1C: Oncoidal-oidal rich peloidal grainstone

F1C facies is a peloidal grainstone comprising large proportions of oncoids and coarse ooids, and molluscan shells (Fig. 6F–G). This facies has been only encountered within centimetre to few centimetres thick lenses, interbedded within F1B peloidal grainstones at top of U2 and in U4 cycle. Peloids are predominant (50%) and the coated grains (20–40%) consist either of coarse ooids (~600–900 microns) or oncoids (up to 2 mm in size), their grain distribution exhibits floating coarse grains in a peloidal matrix. The molluscan shells are less frequent and are strongly micritized.

Interpretation: The scarcity of mud matrix in these grainstones indicates at least intermittent water turbulence allowing the winnowing of fines. In addition, the poor sorting and the presence of coarse coated grains reflect sporadic high energy events such as fluvial floods. The peloids from F1C facies resemble those of F1B facies in which they are intercalated, and therefore may form in the same perennial shallow lake settings with moderate to high water energy. Oncoid-rich grainstones have been found to form as a result of fluvial overbank in lacustrine and floodplain environments (Schäfer and Stapf, 1978; Arenas *et al.*, 2007; Lettéron *et al.*, 2018), but are also common along the shoreline of various modern and ancient lakes (*e.g.* Plio-Pleistocene from Lake Turkana: Hargrave *et al.*, 2014; Nutz *et al.*, 2020; Lake Geneva: Davaud and Girardclos, 2001). Therefore, the F1C facies is interpreted to form in a shallow nearshore environment of a perennial lake, similar to that of F1B depositional environments, the oncoids perhaps deriving from the shoreline or from a nearby mouth of an oncoïd-producing river.

4.3.4 F2A: Molluscan-rich peloidal packstone-grainstone

This facies consists of limestones containing large amounts of small peloids mixed with frequent molluscs, few ostracods and scarce small ooids set in micrite to microspar matrix (Fig. 7A–D). The peloids are densely packed, irregular in shape and are very small (80–200 microns in size). The molluscan shells are dissolved, and the organisms are identified only from their external moulds, the biological association comprises mainly *Polymesoda*, *Hydrobia* and *Tarebia* (Fig. 7B). These peloidal-dominated packstones are found in the form of decimetre thick beds and are devoid of sedimentary structures (Fig. 7C).

Interpretation: The occurrence but relative scarcity of micrite matrix suggests relatively calm environments but with transient periods of higher energy. The abundance of peloids in the matrix and their regular shape and comparable size (50–100 µm) may be interpreted as faecal pellets and likely results from the presence of abundant molluscan and crustacean communities. The molluscan assemblage dominated by *Polymesoda* and *Hydrobia* and *Tarebia* is indicative of warm, shallow and oligo-mesohaline waters (Daley, 1972; Morton, 1983; Fretter and Graham, 1978; Lettéron *et al.*, 2017). Extant *Polymesoda* bivalves are found in a variety of variable salinity shallow environments (Reichenbacher *et al.*, 2004; Harris *et al.*, 2015) and their optimal depth is lower than 1 m (Tabb and Moore, 1971) even though these may be found at depths of 10 m (Morton, 1983; Lettéron *et al.*, 2017). *Polymesoda* are found both valves connected thus indicating deposition in their living environment. Extant *Hydrobia acuta neglecta* are found in coastal lagoons where salinity ranges between 10 and 24‰ (Fretter and Graham, 1978). Thus, the biological community of F2A facies, particularly through the presence of *Hydrobia*, exhibits the greatest tolerance to salinity elevation compared to the freshwater to oligo-mesohaline gastropods and charophytes found in the overlying and underlying levels (F2B and F2D facies, see descriptive sections hereinafter). The lack of subaerial exposure features indicates deposition in perennial waters. The facies F2A is therefore interpreted to form in shallow, warm, and brackish lake with low to moderate water energy.

4.3.5 F2B: Characean-rich peloidal wackestone to packstone

This facies consists of a mixture of densely packed peloids of very small size (50–100 microns) with frequent characean cortical cells, stems and gyrogonites, and numerous ostracods, occasional molluscs and few ooids (Fig. 7C–E). The charophytes remains are preserved and are slightly compacted. Molluscan shells are either entirely leached or completely micritized and their association is dominated by *Polymesoda*, *Tarebia* and hydrobids. F2B facies occurs in several centimetres to decimetre thick tabular to nearly horizontal beds and form together with F2A peloidal packstones an approximately 4 m high package of platelets limestones (Fig. 7C).

Interpretation: The mud-supported texture results from the trapping of micrite and peloids and indicates low water energy which limits the winnowing of fine particles. The abundance of characean remains reflects the development of macrophyte meadows in shallow lake margin environments which act like a natural barrier against hydrodynamic energy. Charophytes colonize lacustrine substrates and may cover large areas but are limited by light penetration and their maximum depth does not exceed 12 m (Garcia, 1994; Garcia and Chivas, 2006) thus supporting the shallow water column during the deposition of the F2B facies. Charophytes thrive in freshwater lakes, but some taxa tolerate brackish waters and withstand changes in salinity (Garcia, 1994; Van Den Berg *et al.*, 1998; Lett  ron *et al.*, 2017). In addition, the molluscan assemblages found in these wackestones indicate warm, shallow and fresh to oligo-mesohaline waters. Finally, the F2B facies reflects deposition within calcifying and non-calcifying charophyte meadows in shallow, freshwater to oligo-mesohaline lake settings.

4.3.6 F2C: Peloidal wackestone to packstone with calcitic rafts

This facies occurs in decimetre tabular beds formed by densely packed peloids similar to those from facies F2A and F2B and comprises various proportions of crystalline flakes (calcitic rafts), few ostracods and scarce small gastropods and ooids (Fig. 7F). The peloids are very small (120–200 microns in size) and may be of faecal origin. Calcite rafts, described early as reworked sparitic crusts, are fragmented into pieces of various size (0.1 to 5 mm) or even as individual spar crystal. Gastropod shells are entirely leached. Faunal content is poor and molluscan assemblage is dominated by *Polymesoda* and *Tarebia*. These facies are found close to the F2A and F2B tabular beds and arranged together within the platelets limestones package.

Interpretation: The abundance of mud matrix in these facies suggests deposition in low-energy areas. However, the breakage of the calcite rafts and the abundance of peloids indicate intermittent hydrodynamic conditions. Features resembling those crystalline flakes are documented in the literature and many hypotheses have been considered to explain their origin. Many authors described these structures in various depositional settings and referred to them as calcite rafts, paper thin rafts and floating mats (see review in Lett  ron *et al.*, 2018 and references therein). The abundance of peloids

may indicate abundant gastropods and crustacean communities. The presence of small gastropods is indicative of shallow lake conditions probably of less than 10 m while the molluscan assemblage is indicative of brackish water environments. The close occurrence of this facies with F2A and F2B facies indicate nearby depositional settings. Therefore, the peloidal wackestones to packstones with calcite rafts facies reflect deposition in calm waters, supersaturated for CaCO₃ precipitation at the water-air interface (calcite rafts), with intermittent moderate water energy in the shallow sheltered areas of the lake in the vicinity of non-calcifying macrophyte meadows.

4.3.7 F2D: Molluscan-rich ostracod wackestone

This facies consists of limestones that contain sparse to loosely packed allochems including numerous ostracods and mollusc shells as well as few ooids and peloids (Fig. 7G–H). These wackestones occur in beds of several centimetres to few tens of centimetres (Fig. 8A). Ostracods are small (around 0.5 mm) and thin-shelled and their valves may be found either articulated or disarticulated. Gastropods are often leached but their complete external moulds allow easy identification (Fig. 7G). The molluscan assemblage is widely diversified, and the community comprises essentially terrestrial and freshwater to oligo-mesohaline water taxa, among them *Lymnea* (*Galba*), *Planorbis*, *Tarebia*, *Viviparus* and *Polymesoda*.

Interpretation: The molluscan-rich ostracod wackestones are formed in low energy environments as suggested by the high micrite content of the facies. The matrix of these wackestones consists of inhomogeneous micrite and this likely results from ostracod burrowing and bioturbation. Burrowing and bioturbation indicate intense biological activity in very well oxygenated conditions. In addition, the molluscan assemblage, reflecting various ranges of salinity mostly freshwater for *Lymnea*, *Planorbis* and *Viviparus* and oligo-mesohaline for *Polymesoda*, indicates shallow and variable salinity settings, potentially marginal pools close to emerged wetlands or a saline lake margin at the vicinity of freshwater springs. Charophyte remains are not found thus excluding the development of calcifying meadows although non calcifying subaqueous prairies could have developed. The presence of significant amount of small ooids in F2D wackestones indicates the vicinity of oolitic bodies from which the ooids are sporadically exported into the sheltered areas. Moreover, these molluscan-rich ostracod wackestones are sharply overlain by high energy oolitic deposits (F1A) and this suggests lateral migration of the oolitic sand bodies. Finally, F2D facies is interpreted to form in low energy and shallow freshwater to brackish pools and sheltered areas of the lake margin.

4.3.8 F3: Planar-laminated bindstones (microbial laminites)

Microbial laminites are made of an alternation of subhorizontal to wavy and crinkled dark clotted and peloidal micrite laminae (100 microns to 1 mm thick) and light thin laminae (0.5 to 1 mm) constituted of the accumulation of crushed charophyte stems and cortical cells with fine calcite spar cement (Fig. 8B–C). This facies exhibits a bindstone fabric (*sensu* Embry and Klovan, 1971) and is formed by

micrite stabilization and binding of various skeletal grains including gastropod and ostracod shells as well as characean gyrogonites (Fig. 8B–C). The molluscan assemblage is dominated by the gastropod *Melanopsis acrolepta* the shells of which are entirely dissolved (Fig. 8B). The laminated bindstones show very little fenestral porosity and the presence of small-scale undulations and corrugations in the laminae may point to a microbial origin of the micrite. This facies occurs in centimetre tight beds and may form up to metre intervals of laminated limestones (Fig. 8A).

Interpretation: Planar laminated stromatolites from Tertiary basins of SE France are interpreted to form in very shallow water lacustrine environments that may experience occasional short-term emersions (e.g. Wattine *et al.*, 2003; Lettéron *et al.*, 2017). The shallow-water conditions prevailing for the deposition of facies F3 are supported by the abundance of characean gyrogonites and stems, and by the bathymetric range of the bound molluscs (*Melanopsis*). The presence of charophyte gyrogonites indicates colonization of the lake substrate by charophyte algae in the nearby areas and suggests freshwater to slightly brackish water conditions. While stromatolites are euryhaline and tolerate a wide range of salinities (e.g. Talbot and Allen, 1996), the biological content points to freshwater to oligohaline conditions. Extant *Melanopsis* are found to live in coastal streams and freshwater to oligohaline lake waters under Mediterranean and semi-arid climates (Plaziat and Younis, 2005; Velasco *et al.*, 2006). In the Priabonian lacustrine deposits from the Issirac basin (SE France), planar stromatolites are interpreted to form in the shallowest parts of the lake margin while the charophytes are considered to thrive at depths comprised between 0.5 m and 10 m (Lettéron *et al.*, 2017). However, it has been documented that the development of either photosynthetic (e.g. charophytes) or microbial communities is presumably driven by changes in trophic conditions regardless of the depositional depth (Lettéron, 2018). The microbial communities can adapt to trophic changes (oligotrophic conditions) as evidence by the trapping of characean gyrogonites by the microbial binding organisms, the charophyte meadows likely occupying the deeper areas of the lake. Finally, facies F3 is interpreted to form in very shallow lake conditions under freshwater to oligo-mesohaline conditions within perennial lake body.

4.3.9 F4. Carbonate breccia with pseudomorphs after gypsum

The facies F4 is found only in one bed (0.50 m) from the butte Iouton succession (Fig. 8A). It consists of a carbonate breccia displaying vertical changes in texture and diagenetic features. The lower part of the bed is made of a fractured, tight oosparite whose ooids appear to be floating within sparry calcite pseudomorphs after gypsum (Fig. 8F–G). The mechanical contact between ooids argue for subsequent displacement of the grains in the initial grainstone sediment during the formation and growth of gypsum crystals. The upper part of the breccia interval is characterized by the occurrence of 1) Root traces and curved cracks (Fig. 8D) occluded by microsparite and sparite cements and 2) gypsum crystals, replaced by calcitic micrite, infilling cavities (Fig. 7D–E). These tight limestones have a total thickness

of around 50 cm and are irregularly bedded and capped by an uneven surface. Furthermore, these brecciated limestones are overlain by an interval of few centimetres thick of mottled vivid red clays (Fig. 8A).

Interpretation: the development of curved cracks and root marks affecting the initial oolitic-peloidal grainstones (F1A facies) suggests pedogenic processes during a stage of subaerial exposition (Freytet and Plaziat, 1982; Alonso-Zarza, 2003). Grain displacement during gypsum growth indicate that sulfate precipitation occurred shortly after ooid deposition, before compaction. The presence of calcite pseudomorphs after gypsum would indicate hypersaline conditions within the paleosoil and the enrichment of water in sulphate solutes. Evaporative concentration of solutes and thereby gypsum formation necessarily reflect climate aridity and negative water inflow/evaporation. The F4 succession is therefore interpreted as representing a paleosoil horizon developed during a stage of saline lake drying.

4.4 Vertical evolution of facies

The Priabonian carbonate succession from the butte Iouton is approximately 30 m thick and is characterized by the dominance of oolitic and peloidal grainstone facies (F1 facies) organized in the form of massive, horizontally bedded intervals associated with fossiliferous muds (F2 facies) and stromatolite levels (F3 facies) found in the form of platelets limestones (Fig. 3). Four massive intervals of oolitic grainstones (F1A facies) and peloidal grainstones (F1B facies) have been identified in the sedimentary succession and have a maximum individual thickness of about 3 m. In addition, the succession records episodic high-energy sedimentation as indicated by the regular occurrence of thin gravelly lenses and coarse-sized sands (F1C facies). Such grain-supported massive intervals are interbedded within thinly-layered limestones of wackestone to packstone texture (Facies F2A, F2B, F2C and F2D) or microbial laminites (Facies F3). The alternation of wackestone-packstone and microbial laminites with massive grainstone intervals allows the definition of 5 depositional cycles, U1 to U5, despite large masked parts (Fig. 2). Within the butte Iouton quarry, the lowermost cycle U1 (3.30 m thick) overlies the lower Eocene variegated clays and silts and displays the transition from thinly layered molluscan-rich ostracod wackestones (F2D facies) to massively bedded peloidal grainstones (F1B facies) and oolitic-peloidal grainstones (F1A facies) with scarce planar cross-stratifications: the base of the massive bed is sharp and contains gravelly-sized fossil shells accumulations (Fig. 3A–B). The oolitic interval is capped by a subaerial exposure surface as illustrated by the development of brecciated limestones (F4 facies) and overlying paleosol horizon (Fig. 8A).

Cycle U2 (4.50 m thick) starts with mud-supported facies (Fig. 3A–B) dominated by freshwater to oligo-mesohaline molluscan (F2D facies) that pass upwards into oolitic grainstones deposits (F1A facies). Above the thin oolitic bed (Fig. 7A), a 50 cm thick interval of characean-rich laminated bindstones (F3 facies) is overlain by massively bedded peloidal and oolitic grainstones (F1A and F1B facies). These grainstones become coarser and gravelly toward the top and are capped by a thin interval of oncoidal-oidal grainstone (F1C).

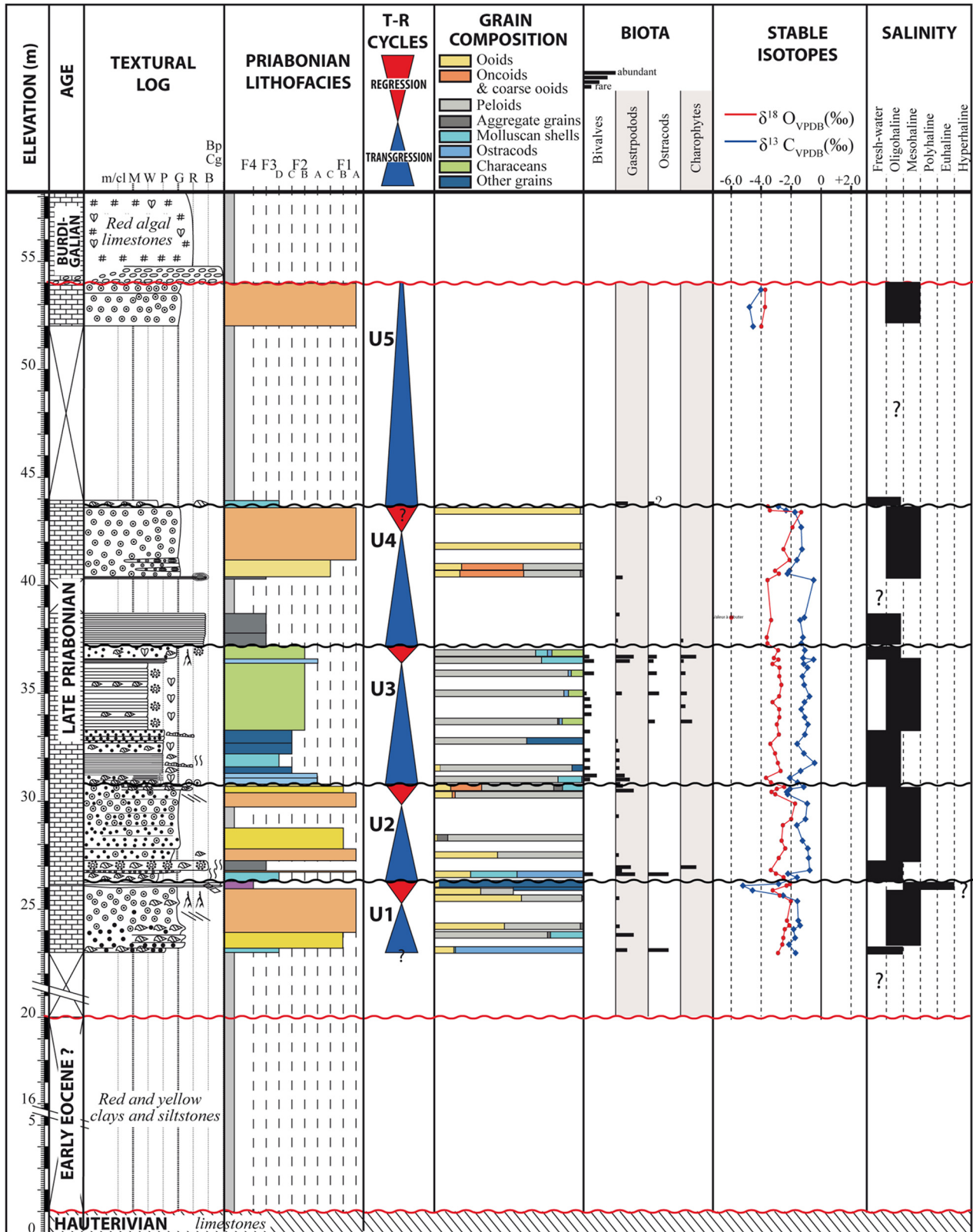


Fig. 9. Composite log of the butte Iouton succession compiling the depositional textures, the lithofacies stacking pattern, the interpreted transgressive-regressive (T-R) cycles, carbonate grain composition of limestones after point-counting on thin-sections, the relative abundance of selected preserved biota, $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ vertical changes and estimated salinity domains. See Figure 2 for detailed legend.

In cycle U3 (6.40 m thick) sediments are dominantly mud-supported (F2 facies) and organized into centimetre to decimetre-thick tabular strata (Fig. 7C). In the lowermost 2 metres, sedimentation is dominated by molluscan-rich ostracod wackestones (F2D facies) and molluscan-rich peloidal packstone (F2A facies) together with peloidal micrites with calcite rafts (F2C facies). The upper part of the cycle is dominated by the characean-rich peloidal wackestones and packstones (F2B) and molluscan-rich peloidal packstone (F1A). The top of the cycle displays incipient pedogenic modifications (root traces, circumgranular cracks).

The cycle U4 (6.40 m thick) shows at its base lacustrine stromatolites (F3 facies) that pass upwards into a decimetre thick oncoidal rich grainstones (F1C facies) that gives way to a massively bedded oolitic-peloidal grainstones (F1A facies). At the top, the cycle is capped by a sharp and smooth surface. The uppermost U5 cycle (10.40 m thick) begins with a molluscan-rich ostracodal wackestones containing *Viviparus soricensis* gastropods. After an observational gap of few metres, this cycle ends with a thick oolitic and peloidal grainstone interval that is truncated by an erosional surface. This unconformity separates the Priabonian limestones from the unconformably overlying transgressive marine Burdigalian limestones characterized by the coralline red algae *Lithothamnium sp* and marine bivalves *Pecten praescabriusculus* that rest on the basal conglomerates reworking Priabonian lacustrine limestones (Fig. 3C).

4.5 Carbon and oxygen stable isotopes

Prior to the analysis of the geochemical data of whole-rock bulk carbon and oxygen stable isotopes and to extract the primary geochemical signal, it is necessary to take into account the diagenetic overprints undergone by the investigated samples. In Table 2, samples have been classified as a function of the diagenetic features evidenced from macroscopic, thin-section and SEM observations. Most of the analysed samples are devoid of sparry calcite cements. In addition, in grainstone intervals (F1 facies), ooids are pervasively micritized, display significant microporosity and microrhombic calcite overgrowths (Fig. 5C–D), while aragonitic shells are converted into calcitic micrite (Fig. 6E–F). Moderate amounts of calcite microspar cements are present in a few samples of F2A facies while brecciated limestones (F4 facies) have undergone pervasive pedogenesis and pervasive sparry calcite cementation or calcite pseudomorphosis after gypsum (Fig. 8E–G).

In the whole carbonate succession, samples which are devoid of sparry calcite cement and pedogenetic features exhibit negative values of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values ranging from -3.99‰ to -1.33‰ PDB and from -4.79‰ to -0.43‰ PDB, respectively (Fig. 10A–B). Brecciated limestones (F4 facies), which are characterized by pedogenic features and sparry calcite cementation, are strongly ^{13}C -depleted. Grainstone samples (F1 facies) exhibit an inverted-J pattern on $\delta^{18}\text{O}$ - $\delta^{13}\text{C}$ plots (Fig. 10A).

Measurements from cycle U1 display a very narrow range of $\delta^{13}\text{C}$ since values which oscillate between -2.54‰ and -1.40‰ PDB while $\delta^{18}\text{O}$ values exhibit a moderately increasing trend, with values ranging from -2.87‰ to

-2.02‰ PDB (Fig. 10B). At the top of U1, $\delta^{13}\text{C}$ is strongly negative with values down to -5.21‰ PDB. A poorly-expressed covariant trend exists between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ within this cycle, especially in the oolitic-peloidal grainstones which corresponds to a part of the inverted-J trend. In cycle U2, $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ signals have much wider ranges of values (-3.35‰ to -1.86‰ PDB and -2.29‰ to -0.76‰ PDB respectively) and grainstone samples (F1 facies) exhibit a covariant trend similar to that of U1 cycle (Fig. 10C). In the lower part of cycle U2, stromatolites exhibit the most ^{13}C -enriched and ^{18}O -depleted signatures of the available database. In cycle U3, $\delta^{18}\text{O}$ values display little variations and range between -3.66‰ and -2.64‰ PDB whereas $\delta^{13}\text{C}$ fluctuates considerably with values ranging from -2.09‰ to -0.43‰ PDB (Fig. 10D). Within cycles U4 and U5, samples exhibit wide ranges of $\delta^{18}\text{O}$ with values ranging from -3.99‰ to -1.33‰ PDB and $\delta^{13}\text{C}$ ranging from -4.79‰ to -0.53‰ PDB. Stromatolites (F3) forming the lower part of the cycle display depleted ^{18}O and enriched ^{13}C isotope signatures.

5 Discussion

5.1 Depositional model for an oolitic saline lake margin

The analysis of carbonate microfacies, preserved biota, bedding patterns and sedimentary structures of individual lithofacies as well as the vertical succession of lithofacies enable the reconstruction of depositional models (Fig. 11) for further interpreting the vertical evolution of paleoenvironments and stages of transgression and regression of the paleolake.

5.1.1 Oolitic cycles (U1, U2, U4 and U5)

The lower intervals of the oolitic-peloidal cycles U1, U2, U4 and U5 are made of molluscan-rich ostracod wackestones (F2D) and laminated bindstones (F3). As suggested by microfacies analysis and preserved biota, such a facies association is indicative of a deposition in a very shallow, sub-emergent, low-energy, freshwater to oligo-mesohaline lake margin. The occurrence of scattered but well preserved ooids within the molluscan-ostracodal wackestones suggests that oolitic sediments formed coevally with the F2D–F3 low-energy lake margin association. In cycles U1, U2, U4 and U5, microbial laminites or molluscan-ostracodal wackestones are sharply overlain by oolitic-peloidal (F1A) or peloidal grainstones (F1B). The high degree of sorting in oolitic-peloidal grainstone, the lack of mud matrix and the occurrence of planar cross laminations suggest an increase in water energy compared with the underlying F2D and F3 facies. The planar cross-bedded oolitic grainstones (F1A) were likely deposited at the outer part of a lacustrine margin, in the vicinity of the main oolitic factory as supported by the dominant proportion of ooids. Indeed, the significant proportion of peloids as well as the variable degree of micritization of ooids suggest that the oolitic fraction of F1A is not produced *in situ* but likely derives from neighbouring, high-energy, oolitic shoals. Structureless oolitic-peloidal and peloidal grainstones (F1A–F1B) likely represent a slightly calmer area, possibly in back-shoal position. The structureless nature of such carbonate sand

Table 2. Carbon and oxygen isotope ratios, diagenetic features and depositional facies of measured samples.

Height (m)	$\delta^{13}\text{C}$ (‰ V-PDB)	$\delta^{18}\text{O}$ (‰ V-PDB)	Diagenetic features (macroscopic and/or thin-section observations)	Depositional facies
53,8	-4,01	-3,68	Grain micritization/microporosity	F1A
53	-4,79	-3,76	Grain micritization/microporosity	F1A
52,1	-4,55	-3,99	Grain micritization/microporosity	F1A
43,8	-2,83	-3,56	Grain micritization/microporosity	F2D
43,6	-2,34	-3,42	Grain micritization/microporosity	F1A
43,5	-1,74	-1,33	Grain micritization/microporosity	F1A
42,8	-1,32	-1,91	Grain micritization/microporosity	F1A
41,8	-1,27	-2,51	Grain micritization/microporosity	F1A
41,3	-1,61	-2,11	Grain micritization/microporosity	F1A
40,8	-2,11	-3,07	Grain micritization/microporosity	F1C
40,65	-2,24	-2,81	Grain micritization/microporosity	F1C
40,35	-0,53	-3,58	–	F3
38,5	-1,40	-3,35	–	F3
37,7	-1,21	-3,61	–	F3
37,4	-1,32	-3,58	–	F3
37,1	-1,08	-2,86	–	F2B
36,75	-1,20	-3,14	–	F2B
36,7	-0,50	-2,85	Primary	F2B
36,5	-1,16	-3,24	Rare calcite microspar cements	F2A
36,3	-0,90	-2,78	–	F2B
35,9	-1,24	-2,79	Rare calcite microspar cements	F2B
35,5	-1,14	-2,64	–	F2B
35	-0,78	-2,80	Rare calcite microspar cements	F2B
34,7	-1,12	-3,23	–	F2B
34,4	-1,32	-2,80	–	F2B
34	-1,08	-2,79	–	F2B
33,7	-0,88	-2,95	–	F2B
33,2	-1,07	-2,81	–	F2C
32,8	-1,59	-3,38	–	F2C
32,3	-1,15	-3,07	–	F2C
31,9	-0,43	-2,88	–	F2D
31,5	-1,37	-2,70	–	F2C
31,2	-2,09	-3,66	Microspar cements	F2A
31	-1,57	-3,35	Microspar cements	F2A
30,75	-1,17	-2,45	Grain micritization/microporosity	F1C
30,7	-2,07	-2,95	Microspar cements	F1B
30,55	-2,29	-3,30	Grain micritization/microporosity	F1B
30,45	-2,22	-3,06	Grain micritization/microporosity	F1B
30	-0,92	-1,86	Grain micritization/microporosity	F1A
29,3	-1,04	-1,99	Grain micritization/microporosity	F1B
29	-1,62	-2,54	Grain micritization/microporosity	F1B
28,3	-1,24	-2,63	Grain micritization/microporosity	F1B
27,9	-0,86	-2,39	Grain micritization/microporosity	F1B
27,5	-0,83	-2,82	Grain micritization/microporosity	F1A
26,95	-0,76	-3,35	–	F3
26,75	-2,21	-3,02	Grain micritization/microporosity	F1A
26,6	-1,60	-2,50	–	F2D
26,3	-2,83	-2,08	Pedogenic features/sparry calcite cements	F4
26,2	-5,21	-2,28	Pedogenic features/sparry calcite cements	F4
26	-4,57	-3,23	Pedogenic features/sparry calcite cements	F4
25,75	-2,54	-2,74	Grain micritization/microporosity	F1A
25,5	-1,58	-2,02	Grain micritization/microporosity	F1A
24,6	-1,52	-2,28	Grain micritization/microporosity	F1A
24,35	-1,40	-2,13	Grain micritization/microporosity	F1A
24,2	-1,84	-2,42	Grain micritization/microporosity	F1A
23,8	-1,73	-2,52	Grain micritization/microporosity	F1B
23,5	-2,15	-2,59	Grain micritization/microporosity	F1B
23,1	-1,70	-2,87	–	F2D

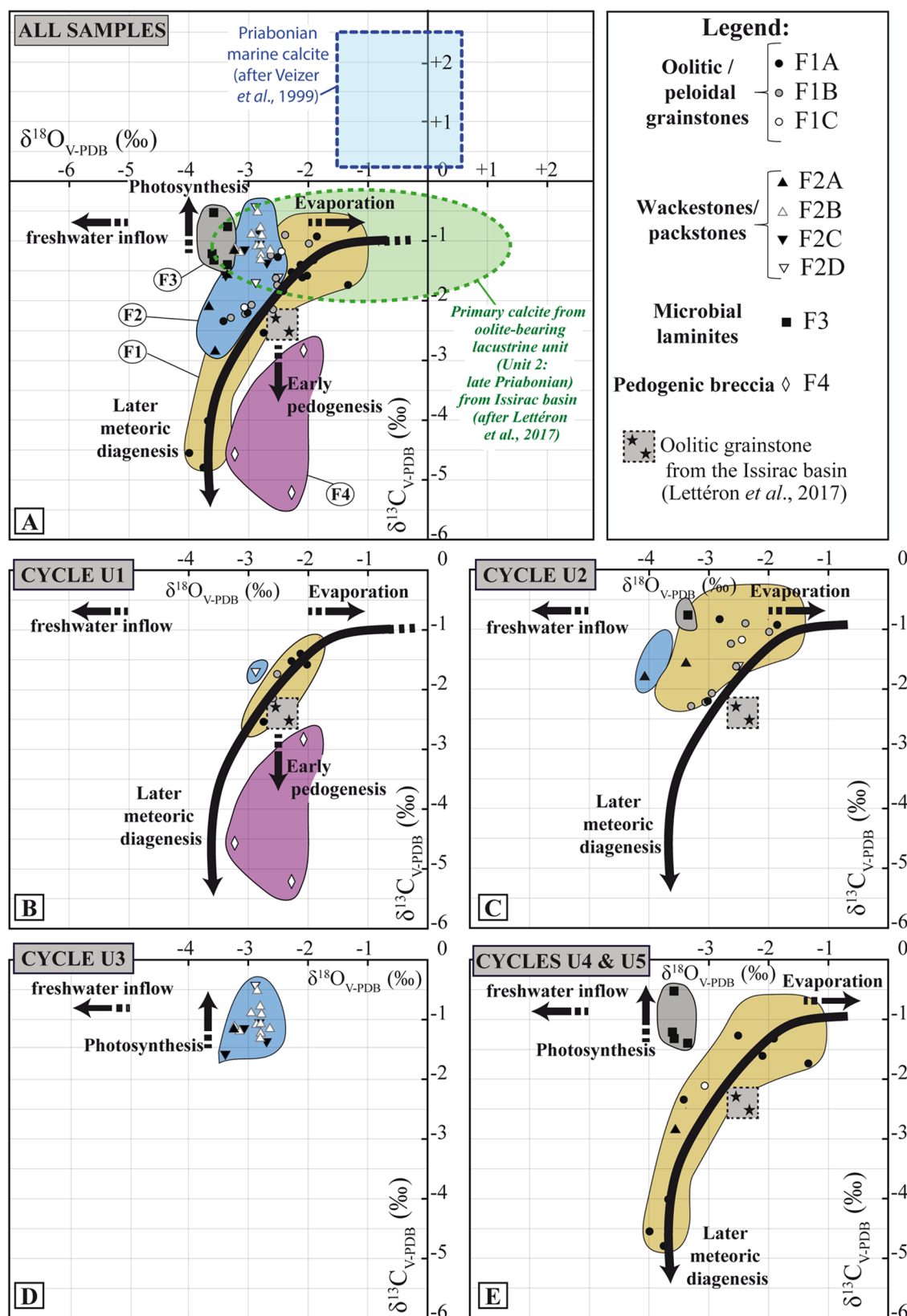


Fig. 10. Carbon and oxygen stable isotopes results. A) $\delta^{18}\text{O} - \delta^{13}\text{C}$ cross-plot for all samples ($n = 58$): the labels refer to the lithofacies (see text for further detail). The Priabonian marine box (Veizer *et al.*, 1999), isotope signatures of lacustrine carbonates from the Issirac basin (Lettéron *et al.*, 2017) as well as interpretations of factors controlling $\delta^{18}\text{O} - \delta^{13}\text{C}$ trends are reported. B-C-D) $\delta^{18}\text{O} - \delta^{13}\text{C}$ cross-plot for cycles U1 (B), U2 (C), U3 (D) and U4-U5 (E) with samples labelled as a function of lithofacies. Isotope values are expressed in per mil (‰) and are relative to V-PDB.

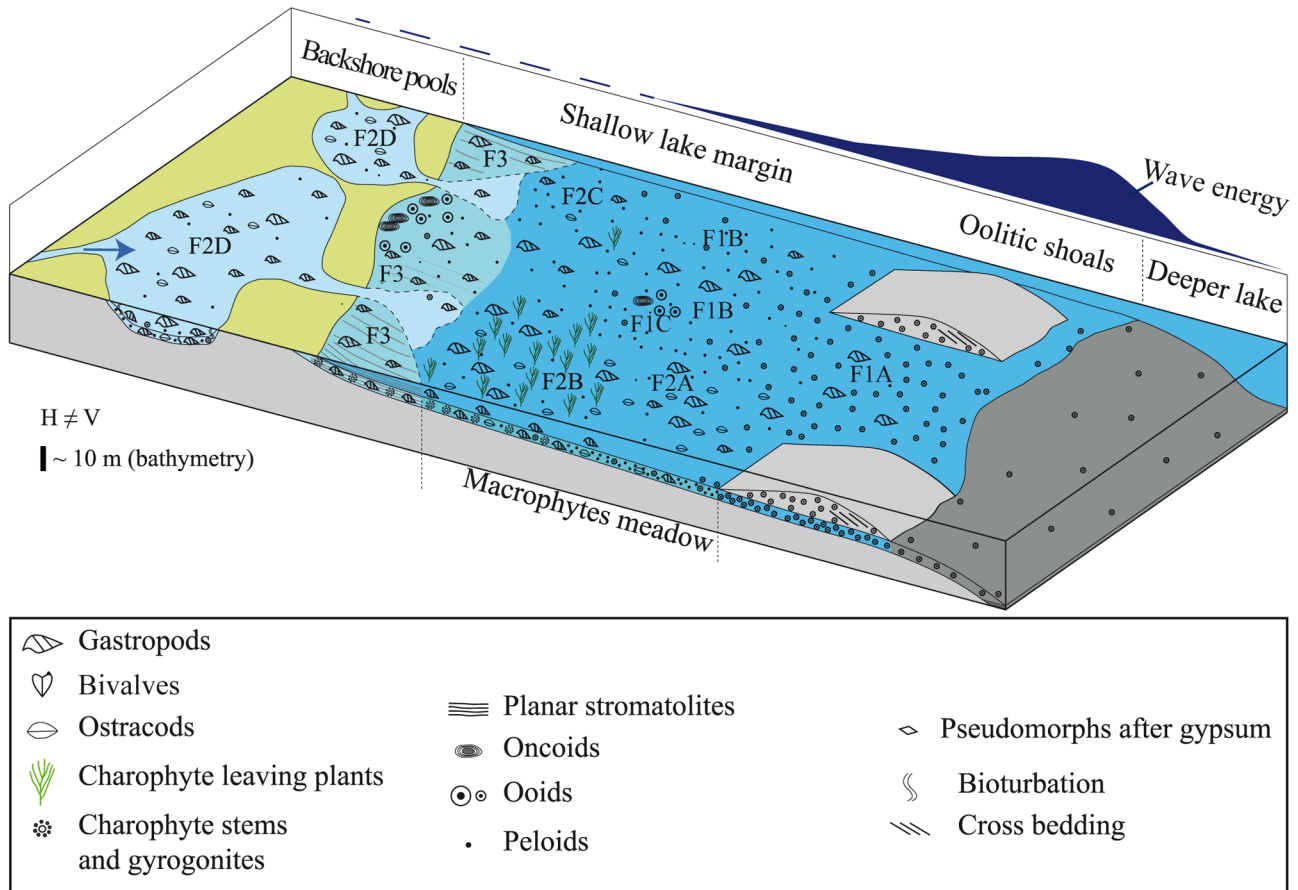


Fig. 11. Depositional model for the late Priabonian saline lake margin from Butte Iouton.

blankets has been interpreted, in shallow marine environments, as resulting from significant bioturbation of a stable substrate in a low to moderate energy back-shoal environments (Pomar *et al.*, 2015). Additionally, peloidal grainstones exhibit significant proportions of peloidal aggregates which are interpreted to form, in modern marine environments, in area with some water circulation allowing the winnowing of fines, followed by periods of stabilization (Wanless, 1981). Finally, the vertical facies transition recorded in cycles U1, U2, U4 and U5 suggests a lake transgression and a lacustrine carbonate ramp model (Fig. 11) displaying the following facies transition from proximal to distal areas: 1) a shallow marginal saline lake domain with deposition of planar microbial laminites (F3), and molluscan-ostracodal wackestone (F2D), 2) a more distal and open lacustrine environments with low to moderate energy characterized by the deposition of peloidal grainstones (F1B) and 3) a domain of higher energy with accumulation of ooids mixed with peloids (F1A). The area of ooid production as well as more distal (profundal) components of this lacustrine depositional model have not been captured by the studied outcrops.

Carbonate ramp models with oolite sand body development in open, shallow lacustrine setting have been documented in modern and ancient lacustrine environments. In the modern Great Salt Lake, similarly to the Butte Iouton lake margin, muddy sediments occupy the coastal area of the lake while oolite sand bodies develop in more open lake setting (Eardley, 1938, Bouton *et al.*, 2019). In the Eocene Green River

Formation (Utah), shoreline and protected nearshore carbonate sedimentation is characterized by mud-supported sediments with ostracods, mollusks and ooids, while shallow open lake margin is occupied by oolitic shoals (Williamson and Picard, 1974; Tänavsuu-Milkeviciene *et al.*, 2017). In the Upper Cretaceous to Paleocene Yacoraite Formation (Argentina), a high gradient carbonate ramp model is proposed with ostracod-rich low energy eulittoral deposits protected by oolitic shoals (Deschamps *et al.*, 2020). In the modern Lake Tanganyika, oolitic sand shoals dominate the open nearshore environment while inner and more protected area are characterized by charophyte-rich calcareous silts (Cohen and Thouin, 1987).

The Butte Iouton lake margin shows major differences with other published depositional models involving oolite formation. In the Pliocene Glens Ferry Oolite (Swirydzuk *et al.*, 1980), oolite sediments occupy both foreshore and shoreface environments and no mud-rich, low energy, carbonate deposits are documented from this lake margin. In the late Triassic Clevedon lake, shoreline deposits are dominated by oolitic beachrocks while trough cross-stratified oolitic grainstones characterize shoreface sedimentation (Milroy and Wright, 2002).

5.1.2 Mud-dominated cycle (U3)

Cycle U3 exhibits a distinct facies association since ooids are relatively uncommon and sediments have dominantly

muddy textures. The lower part of the cycle is characterized by an alternation of molluscan-rich peloidal packstones (F2A), peloidal wackestones to packstones with calcitic rafts (F2C) and molluscan-rich ostracod wackestones (F2D).

Similarly to cycles U1, U2, U4 and U5, the occurrence of F2D wackestones is indicative of very shallow, low energy environments, in the most proximal area of the lake margin. The upper part of the cycle is dominated by F2B characean wackestone which likely represents a slightly deeper (<10 m), low-energy marginal lake environment.

Finally, the facies succession in cycle U3 suggests a shallow, protected, low energy lake margin with extensive development of macrophytes (including charophytes and non-calcifying taxa). The scarce occurrence of ooids within F2D facies suggests the coeval formation of oolitic sediment in more open area of the lake margin. However, the lack of oolitic grainstones indicate that the supersaturation with regards to carbonate minerals required for ooid formation and high energy conditions have been never reached at the outcrop location during the deposition of U3 cycle.

5.2 Stable isotope signatures and paleohydrological implications

As evidenced by Hasiuk *et al.* (2016) and as supported by petrographic evidences (microporosity and microrhombic calcite overgrowths within micritized ooids: Fig. 5C–D), the inverted-J pattern on $\delta^{18}\text{O}$ - $\delta^{13}\text{C}$ plots (Fig. 10A) evidenced for grainstones from the whole section, likely results from neomorphic processes leading to microporosity development in meteoric environments. According to such an interpretation the $\delta^{18}\text{O}$ - and $\delta^{13}\text{C}$ -enriched end-member would represent the less-altered samples and therefore would approximate the primary signature of carbonate grains (ooids and peloids), the ooidal and peloidal grainstone being devoid of carbonate cement. Furthermore, the end-member of least meteoric alteration for grainstone samples (F1) ranges from -2.5‰ to 1.0‰ PDB in $\delta^{18}\text{O}$ and from -2.0‰ and -0.5‰ PDB in $\delta^{13}\text{C}$, which matches with primary signatures measured in late Priabonian ooid-bearing unit (Unit 2 in Lett  ron *et al.*, 2017) from the Issirac basin (Fig. 10A). Carbon and oxygen isotope signatures for wackestone-packstones (F2) and microbial laminites (F3) are significantly ^{18}O -depleted compared to the end-member of least meteoric alteration for grainstones (F1). The ^{18}O -depletion of stromatolites likely results from significant freshwater inputs while the ^{18}O -enriched values measured in F1 grainstones may reflect either more evaporative conditions, either mixture with neighbouring saline lake water as suggested by primary isotope signatures from the Issirac basin (Fig. 10A). The position of the Priabonian marine box (Fig. 10A, after Veizer *et al.*, 1999) makes also possible a mixture with marine-influenced waters. Additionally, the relative ^{13}C -enrichment could be partly related to a photosynthetic control on the carbon budget of the lake during the deposition of microbial (cyanobacterial) carbonates (Talbot and Kelts, 1990; Andrews *et al.*, 1993; Andrews *et al.*, 1997), as particularly evidenced in microbial laminites (F3) from cycles U2, U3, U4 and U5 (Fig. 10C–D–E) and by the vertical trend in the $\delta^{13}\text{C}$ - $\delta^{18}\text{O}$ plot from U3.

In cycle U1, a poorly-expressed covariant trend exists between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ (Fig. 10B), especially in the oolitic-peloidal grainstones which coincides with a segment of the overall inverted-J trend. Even though such an isotope trend likely largely result from neomorphic processes affecting micrite in meteoric environments (L  onide *et al.*, 2014; Hasiuk *et al.*, 2016) as suggested by petrographic observations, the interpretation of a partial preservation of a primary covariant trend cannot be entirely ruled out. Such primary covariant trends have been reported from a variety of modern lacustrine carbonates and are interpreted to result from hydrologic closure of the lake for long time periods and varying residence time of water and dissolve inorganic carbon (*e.g.* Talbot, 1990; Li and Ku, 1997).

The strongly negative excursion of $\delta^{13}\text{C}$ at top of cycle U1 (Fig. 9) reflects the formation of pedogenic carbonates during a phase of subaerial exposition (*e.g.* Allan and Matthews, 1982). Negative $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ excursion at top of cycles U2 and U4 suggest that the cycle is capped by a subaerial exposure surface (Fig. 9) in spite of the lack of petrographic evidence. Finally, the negative $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ excursion at top of U4 (Fig. 9) suggests that the cycle is capped by an intraformational subaerial exposure surface, while the very negative values at top of U5 are likely to be related to meteoric overprint during the long-duration subaerial exposure preceding the Burdigalian transgression.

5.3 Origin of transgressive-regressive cycles

The vertical succession of lithofacies and associated depositional environments, together with stable isotope signatures allows the identification of transgressive-regressive cycles (Fig. 9) and the reconstruction of lake margin evolution and changes in paleohydrologic setting. In cycles U1, U2, U4 and U5, the upward vertical facies change from mud-supported fabrics (F2 facies) or microbial laminites (F3 facies) from shallow and sheltered lake margin environments to oolitic and peloidal grainstones (F1A–B) deposited in moderate to high energy perennial waterbody records the lake transgression. The maximum flooding stage therefore occurs within the oolitic grainstone beds (F1A) which represents the most distal facies identified in the section. Pedogenetic features as well as carbon isotope signatures (Fig. 9) strongly suggest a subaerial exposition on top of these cycles which reflects the stage of maximum regression of the lake.

In the upper part of cycle U1, the abrupt upward vertical change in facies from oolitic-peloidal grainstone F1A to pedogenitized carbonate breccia (F4) together with the occurrence of pseudomorphs after gypsum are indicative of a forced lacustrine regression related to drying of the lake. In other oolitic cycles (U2, U4 and U5), the forced regressive stage is recorded by the subaerial exposure surfaces which sharply truncate the massive oolitic/peloidal grainstone intervals. It seems plausible to consider significant erosion during the forced regressive phase or during the early transgressive phase, as suggested by the lack of marginal/palustrine deposits preserved on top of these cycles. Moreover, it is not excluded that part of grainstone intervals has formed during a stage of normal regression. As an apparent paradox, the stable isotope signatures are indicative of greater

freshwater inputs with the wackestone (F2) and microbialitic (F3) beds (lower transgressive hemicycle) than in grainstone intervals (upper transgression to normal regression?) where they suggest either a more negative inflow-evaporation balance, or a mixture with a closed lake water body or even seawater. Similarly, the vertical changes in molluscan assemblages do not indicate a salinity decrease during transgression, but on the contrary the few freshwater taxa identified (*e.g.* *Viviparus*, *Lymnaea*, *Planorbis*) are mainly present in the wackestone and microbialitic facies from the lower transgressive hemicycles (Fig. 2). In contrast to other lake basins (*e.g.* Holocene, Dead Sea: Klinger *et al.*, 2003; Plio-Pleistocene, Lake Turkana: Nutz *et al.*, 2020), lake transgression does not result from an excess balance between freshwater inflow and evaporation. A lack of unequivocal control of paleohydrologic balance on transgressive/regressive cycle development has been regionally evidenced in coeval lake margin carbonate deposits from the Issirac and Saint-Chaptes basins (Letteron *et al.*, 2017, 2018, 2022), but also in other syn-tectonic lake basins (Chen and Hu, 2017).

Such a paradox can be explained by an increasing connexion of the Butte Iouton lake waters with regional salt waterbodies during transgression. This interpretation therefore implies that the lake basin to which the Butte Iouton carbonate margin represented an outflow of neighbouring salt water bodies. The volume of connected lake waters is controlled by a regional inflow-evaporation balance which is strongly dependent on climate conditions. In the case of Priabonian lakes from south-east France, lake closure and saline waters are associated with semi-arid conditions prevailing at regional scale (Letteron *et al.*, 2017; Letteron *et al.*, 2018). In contrast, the dominantly transgressive pattern of cycles evidenced in Butte Iouton margin likely results from both 1) local subsidence driven by normal faults in a regional extensional tectonic setting which is known regionally to have started as early as the middle Priabonian (Cavelier *et al.*, 1984; Sanchis and Séranne, 2000) and 2) saline water outflow from neighbouring regional waterbodies. Forced regression stages recorded at top of depositional cycles may result from: 1) periods of increased aridity associated with a fast and significant reduction in connected lake volume, or 2) the formation of an outlet which led to the fast emptying of the lake basin (Garcia-Castellanos, 2006).

In Cycle U3, the upward vertical transition from the F2C and F2D wackestone/packestone indicative of very sheltered and shallow area of the lake margin to characean wackestones (F2B) suggests a transgressive trend. Similarly to oolitic cycles, molluscan assemblages and isotope signatures are indicative of a connexion with a salt waterbody (evaporative or seawater-influenced lake), while the ^{13}C -enrichment is likely to be related to the effect of enhanced photosynthetic activity (*e.g.* Coletta *et al.*, 2001; Leng and Marshall, 2004), which is consistent with the extensive development of charophytes, cyanobacteria and possibly non-calcifying macrophytes. A subaerial exposition on top of cycle U4 is evidenced from the occurrence of pedogenic features (root-traces).

5.4 The Butte Iouton outcrop: a preserved relict of a regional-scale saline lake?

The vertical evolution of depositional environments and lake salinity recorded at Butte Iouton outcrop provide

significant insights into the paleogeography of Priabonian paleolakes at a larger regional scale. The lack of decreasing salinity trends within the carbonate cycles, as evidenced from the persistence of oligo-mesohaline mollusks, as well as the carbon and oxygen isotope signatures strongly suggest that the transgressive trends recorded by the vertical facies evolution at Butte Iouton is not related to an increase in lake water volume resulting from an increasing inflow-evaporation balance. The present data rather support the interpretation of a carbonate sedimentation in a subsident lake basin which is fed by the outflow of adjacent saline lakes. The relatively dry conditions evidenced regionally by Priabonian lacustrine sedimentation (Lettéron *et al.*, 2017; Lettéron *et al.*, 2018; Lettéron *et al.*, 2022) suggest that salinity may derive, at least partly, from a negative inflow-evaporation balance, but a salinization by recycling evaporites in the drainage area of the lake or within the lake itself is a possible interpretation. Indeed, as evidenced by Emre and Truc (1978), the erosion of the piercing Suzette diapir and subsequent sulfate recycling occurred coevally with the late Priabonian carbonate and evaporite sedimentation of the Mormoiron basin (~50 km north of Butte Iouton: Fig. 12). Additionally, connections with the Alpine Sea through topographic corridors may represent a possible origin for salinity in regional Priabonian lakes (Sissingh, 2001) even though a continental origin for evaporites from the Valence basin has been inferred from stable isotope and mineralogical analyses (Fontes *et al.*, 1996).

The Butte Iouton outcrop is located within a 20 km-wide corridor bounded by the Nîmes fault to the NW and structured by set of SW-NE-trending normal faults (Fig. 1A). To the southeast a thick (>4000 m) lacustrine sedimentation occurred in the Vistrenque Basin (Valette and Benedicto, 1995; Benedicto *et al.*, 1996). Although the age of the lowermost syn-rift interval (Série Grise Formation: ~2000 m-thick) is unknown, the similarity in depositional polarity (siliciclastic-dominated the south and carbonate-dominated the north) between the Série Grise Formation and the Célas formation from the Sommières, Saint-Chaptes and Alès basins may suggest a Priabonian age for the lower part of the syn-rift sedimentation in the Vistrenque basin, as suggested by Cavelier *et al.*, (1984). According to this hypothesis, the Butte Iouton outcrop would represent the northern shallow carbonate margin of a lake basin fed in siliciclastics from the southern collapsing Pyrenean reliefs. Additionally, the strike-slip movement of the Nîmes fault during a transitional tectonic phase comprised between the Pyrenean compression and the Gulf of Lion rifting (Séranne *et al.*, 2021) is consistent with the formation of a subsiding strike-slip basin, east of the Nîmes fault, capable to accumulate a thick sedimentary cover as early as the Priabonian times. The Série Grise Formation from the Vistrenque Basin is dominantly made of organic-rich shales interbedded with thin sandstone and conglomerate horizons (Cavelier *et al.*, 1984; Valette and Benedicto, 1995) suggesting profundal lake environments with terrigenous supplies.

On the footwall of the Nîmes fault, a small-sized and isolated lacustrine limestone outcrop was documented by Caziot (1896) at Puech d'Autel, within the city of Nîmes. These limestones contain a molluscan association including *Melanoides juliani*, *Brotia albigensis*, *Melanopsis acrolepta*, *Neritina*, *Galba longiscata* which is highly similar to that of the oligohaline, late Priabonian lacustrine limestones from the

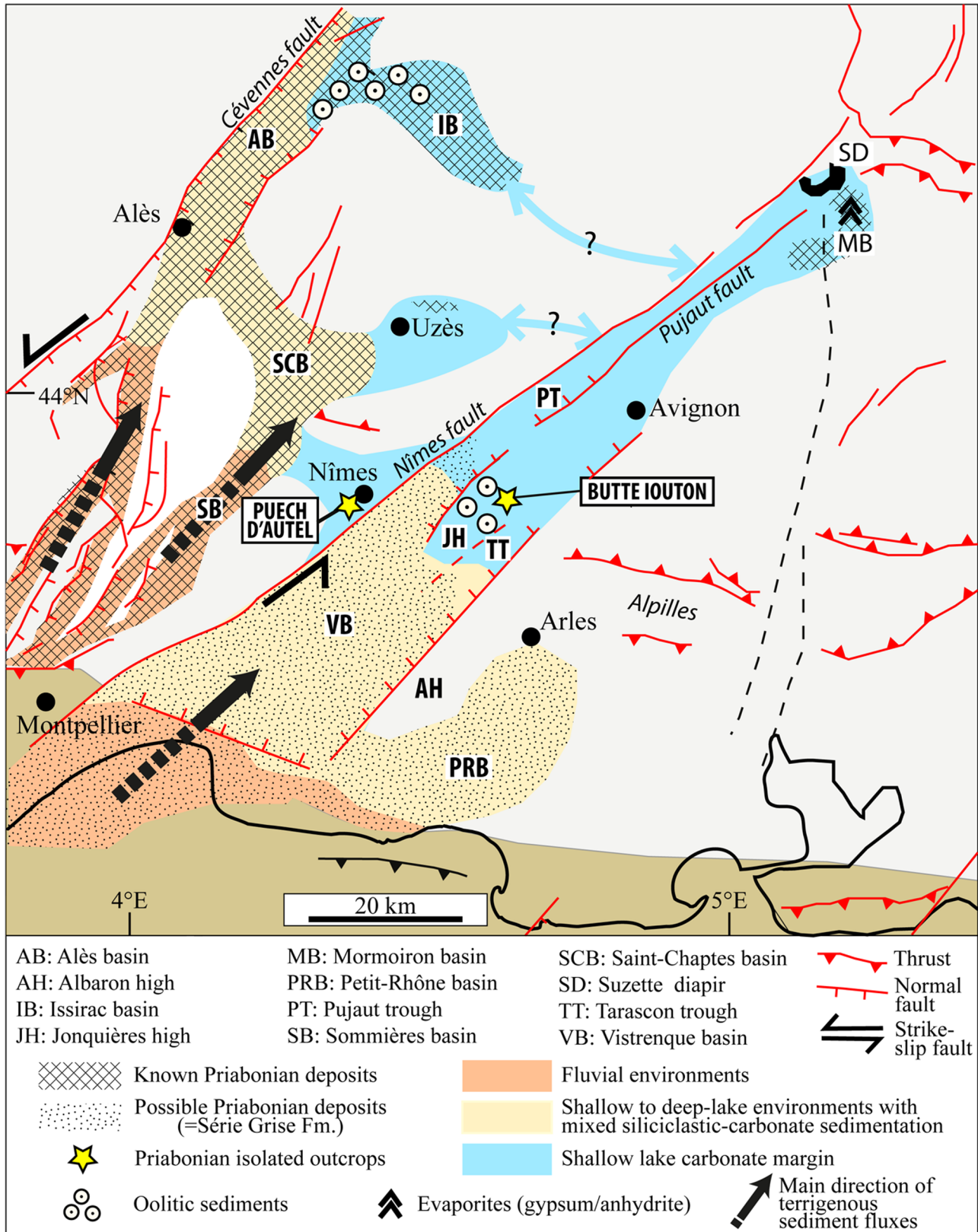


Fig. 12. Palaeogeographical reconstruction of saline lakes from Languedoc and southern Rhône valley during the late Priabonian. The siliciclastic fluxes are compiled from the previous studies: [Lettéron *et al.* \(2022\)](#) for the Célas sandstones from Sommières and ASCI systems, and [Cavelier *et al.* \(1984\)](#) for the plausible late Eocene to early Oligocene siliciclastic infill of the Vistrenque basin.

Issirac basin (Lettéron *et al.*, 2017) and the Butte Iouton. As a consequence, the Puech d'Autel limestones likely represent a relict outcrop of the northwestern shallow carbonate margin of the Vistrenque lake basin.

The proximity of the Priabonian outcrops from the Sommières and Saint-Chaptes basins (10 km) makes a connection with the ASCI saline lake strongly possible. Additionally, in the Issirac basin, Lettéron *et al.* (2017) argued for a correlation between maximum lacustrine transgressions and periods with the most deficient inflow-evaporation balance. These authors interpreted this apparent paradox as resulting from a connection of the Issirac lake waters with those of the Mormoiron and Vistrenque basins, during a period of relative aridity.

The presence of isolated outcrops of Priabonian lacustrine limestones with brackish fauna, 10 km northeast of the eastern termination of the Saint-Chaptes basin, near Uzès (BRGM, 1968) (Fig. 12), shows that the ASCI lake basin had a significantly wider extension towards the east and that a connection with the Vistrenque basin is a plausible hypothesis. As a consequence, various potential sills which could have connected the ASCI lake system with the Vistrenque-Mormoiron may be identified west of the Nîmes fault. More broadly, the dominant transgressive character of depositional sequences recorded locally in various Priabonian carbonate lake margins from southeast France (Issirac: Lettéron *et al.*, 2017; Saint-Chaptes: Lettéron *et al.*, 2018; Alès: Lettéron *et al.*, 2022; Butte Iouton: this study) associated with a persistence of oligo-mesohaline waters in a context of negative inflow-evaporation balance is indicative of interconnected, subsiding lacustrine area, the total volume of connected waters being much larger than that of individual lake basin (Fig. 12).

Finally, the oolitic carbonate ramp developing on the margins of the Vistrenque lake margin show significant analogies with various marine oolitic ramps regarding the overall facies model (e.g. Mississippian from Wales: Burchette *et al.*, 1990; Upper Jurassic from Spain: Pomar *et al.*, 2015; Jurassic from Morocco: Shekhar *et al.*, 2014): 1) oolite shoal developing on the outer ramp, 2) poorly structured oolitic grainstones forming in backshoal setting, 3) mud-supported and/or microbial carbonates developing in the low-energy, innermost area of the ramp and 4) the ramp distally passes into deep water environments.

6 Conclusion

The integrative approach (biostratigraphy, paleoecology, carbonate petrography, sedimentology and stable isotope geochemistry) applied to the study of lacustrine carbonates from Butte Iouton outcrops allowed reconstructing a depositional model for an oolitic saline lake margin and providing new insights into the Priabonian paleogeography of southeast France.

1 An oolitic lacustrine ramp model has been evidenced and displays the following facies transition from proximal to distal areas: (1) a shallow marginal saline lake domain with deposition of planar microbial laminites, and molluscan-ostracodal wackestone, (2) a more distal and open lacustrine environments with low to moderate energy characterized by the deposition of peloidal grainstones and

(3) a domain of higher energy with accumulation of ooids mixed with peloids. The area of ooid production (not captured by the studied outcrops) likely consisted in oolitic shoals within a high energy outer ramp setting.

- 2 Carbonate sedimentation dominantly occurred during stages of lake transgression. Subaerial exposure surfaces evidenced at top of depositional cycles are interpreted to result from forced regressions which occurred during periods of negative inflow-evaporation balance.
- 3 Molluscan associations suggest that oligo- to mesohaline waters dominantly prevailed during the studied time interval.
- 4 The apparent paradox between a dominant transgressive sedimentation and the persistence of saline conditions suggest that lake transgression is controlled by subsidence and outflows from neighbouring saline waterbodies, and not by an increase in regional lake water volume. The studied carbonate margin belongs to a set of interconnected saline lake waterbodies whose total volume is much greater than that created locally by subsidence.
- 5 The compilation of existing data regarding regional Priabonian deposits supports the interpretation of interconnected saline lake basins characterized by a siliciclastic-dominated southern margin whose sediment is sourced from the collapsing Pyrenean reliefs and by a carbonate-dominated northern margin with significant oolitic sedimentation in high-energy nearshore area.

References

- Allan JR, Matthews R. 1982. Isotope signatures associated with early meteoric diagenesis. *Sedimentology* 29(6): 797–817.
- Alonso-Zarza AM. 2003. Palaeoenvironmental significance of palustrine carbonates and calcretes in the geological record. *Earth-Science Reviews* 60: 261–298.
- Andrews JE, Riding R, Dennis PF. 1993. Stable isotopic composition of recent freshwater cyanobacterial carbonates from the British Isles: local and regional environmental controls. *Sedimentology* 40: 303–314.
- Andrews JE, Riding R, Dennis PF. 1997. The stable isotopic record of environmental and climatic signals in modern terrestrial microbial carbonates from Europe. *Palaeogeogr Palaeoclimatol Palaeoecol* 129: 171–189.
- d'Archiac A, de Verneuil E. 1845. Note sur une coupe du mont Pagnotte à Creil, prolongée en suivant le chemin de fer du Nord jusqu'à Tartigny (Oise). *Bulletin de la Société Géologique de France*, deuxième série 2: 334–345.
- Arenas C, Cabrera L, Ramos E. 2007. Sedimentology of tufa facies and continental microbialites from the Paleogene of Mallorca Island (Spain). *Sedimentary Geology* 197: 1–27.
- Arthaud F, Ogier M, Séguret M. 1981. Géologie et géophysique du Golfe du Lion et de sa bordure nord. *Bulletin du BRGM* 1(3): 175–193.
- Benedicto A, Labaume P, Séguret M, Séranne M. 1996. Low-angle crustal ramp and basin geometry in the Gulf of Lion passive margin: the Oligocene-Aquitainian Vistrenque graben, SE France. *Tectonics* 15(6): 1192–1212.
- BRGM. 1968. Notice de la carte géologique de la France au 1/50000: feuille Uzès n° 939, 12 p.

- Bodergat A-M., Briot D, Huguency M, Poidevin J-L, Picot L, Giraud F, *et al.* 1999. Incursions marines dans l'environnement lacustre du rift oligocène de Limagne (Massif Central, France) : apport des organismes halophiles et des isotopes du strontium, datation par les mammifères. *Bulletin de la Société géologique de France* 170: 499–511.
- Bouton A, Vennin E, Amiotte-Suchet P, Thomazo C, Sizun J-P., Virgone A, *et al.* 2019. Prediction of the calcium carbonate budget in a sedimentary basin: a “source-to-sink” approach applied to Great Salt Lake, Utah, USA. *Basin Research* 32: 1005–1034.
- Briot D, Poidevin JL. 1998. Stratigraphie 87Sr/86Sr de quelques laminites carbonates du Rupélien inférieur du fossé de Limagne : incursions marines dans le rift du Massif central français ? *Compte Rendus de l'Académie des Sciences, Paris* 236: 479–483.
- Burchette TP, Wright VP, Faulkner TJ. 1990. Oolitic sandbody depositional models and geometries, Mississippian of southwest Britain: implications for petroleum exploration in carbonate ramp settings. *Sedimentary Geology* 68: 87–115.
- Cavelier C, Alabouvette G, Amberger J-P, Cautru J-P., Charollais J, Chateaufneuf J-J, *et al.* 1984. Paléogène. In: Debrand-Passard ed. Synthèse géologique du Sud-Est de la France. *Mémoire du BRGM* 125: 389–468.
- Caziot M. 1896. Sur le Tertiaire inférieur des environs de Nîmes. *Bulletin de la Société géologique de France* 24: 1–32.
- Chen M, Hu X. 2017. Regression-transgression cycles of paleolakes in the Fen River Graben Basin during the mid to late Quaternary and their tectonic implication. *Frontiers in Earth Sciences* 11(4): 703–714.
- Cohen AS, Thouin C. 1987. Nearshore carbonate deposits in Lake Tanganyika. *Geology* 15: 414–418.
- Coletta P, Pentecost A, Spiro B. 2001. Stable isotopes in charophyte incrustations: relationships with climate and water chemistry. *Palaeogeography, Palaeoclimatology, Palaeoecology* 173: 9–19.
- Daley B. 1972. Macroinvertebrate assemblages from the Bembridge marls (Oligocene) of the Isle of Wight, England, and their environmental significance. *Palaeogeography, Palaeoclimatology, Palaeoecology* 11(1): 11–32.
- Dalrymple RW. 1992. Tidal depositional systems. In: Walker RG, James NP, eds. *Facies Models and Sea Level Changes*. Geological Association of Canada, pp. 195–218.
- Davaud E, Girardclos S. 2001. Recent freshwater ooids and oncoids from western Lake Geneva (Switzerland): indications of a common organically mediated origin. *Journal of Sedimentary Research* 71 (3): 423–429.
- De Roys M. 1846. Note sur la comparaison des bassins tertiaires du Midi avec celui de Paris. *Bulletin de la Société géologique de France (2^e série)* (3): 645–652.
- Deschamps R, Rohais S, Hamon Y, Gasparrini M. 2020. Dynamic of a lacustrine sedimentary system during late rifting at the Cretaceous-Palaeocene transition: example of the Yacoraite Formation, Salta Basin, Argentina. *The Depositional Record* 6: 490–523.
- Dèzes P, Schmid SM, Ziegler PA. 2004. Evolution of the European Cenozoic Rift System: interaction of the Alpine and Pyrenean orogens with their foreland lithosphere. *Tectonophysics* 389: 1–33.
- Dromart G, Dumas D. 1997. The salt basin of Valence (France). In: Busson G, Schreiber BC, eds. *Sedimentary Deposition in Rift and Foreland Basins in France and Spain*. New York: Columbia Univ. Press, pp. 195–239.
- Dumas E. 1876. Statistique Géologique, Minéralogique, Métallurgique et Paléontologiques du Département du Gard. Arthus Bertrand ed., 735 p.
- Dunham RJ. 1962. Classification of Carbonate Rocks According to Depositional Texture. In: Ham WE, ed. *Classification of Carbonate Rocks*. Tulsa: AAPG, pp. 108–121.
- Eardley AJ. 1938. Sediments of Great Salt Lake, Utah. *AAPG Bulletin* 22: 1305–1411.
- Embry AF, Klován JE. 1971. A Late Devonian Reef Tract on Northeastern Banks Island. *Canadian Petroleum Geology* 19: 730–781.
- Emre T, Truc G. 1978. Mise en évidence d'un contact discordant Oligocène-Trias dans le massif de Suzette. Implications tectoniques et conséquences sur l'origine des évaporites ludiennes du bassin de Mormoiron (Vaucluse). *Géologie Alpine* 54: 17–23.
- Esu D, Girotti O. 2010. The Late Oligocene Molluscan Fauna from Otranto (Apulia, Southern Italy): an example of alternating freshwater, lagoonal and emerged environments. *Palaeontology* 53(1): 137–174.
- Fontannes F. 1884. Description sommaire de la faune malacologique des formations saumâtres et d'eau douce du groupe d'Aix (Bartonien-Aquitainien) dans le bas Languedoc, la Provence et le Dauphiné. Georg H, Lyon, and Savy F, Paris, 60 p.
- Fontes J-C, Filly A, Gaudant J, Düringer P. 1991. Origine continentale des évaporites paléogènes de Haute Alsace : arguments paléo-écologiques, sédimentologiques et isotopiques. *Bulletin de la Société géologique de France* 162: 725–737.
- Fontes J-C, Gaudant J, Mélières F, Filly A, Schlund J-M. 1996. Origine continentale des évaporites paléogènes du fossé de Valence (Drôme) : données minéralogiques, isotopiques et paléo-écologiques. *Bulletin de la Société géologique de France* 167(4): 475–481.
- Fretter V, Graham A. 1978. The prosobranch molluscs of Britain and Denmark. Part 3-Neritacea, Viviparacea, Valvatacea, terrestrial and freshwater Littorinacea and Rissoacea. *Journal of Molluscan Studies* (Suppl. 5): 1–152.
- Freyet P, Plaziat J-C. 1982. Continental carbonate sedimentation and pedogenesis – Late Cretaceous and Early Tertiary of Southern France. In: Purser BH, ed. *Stuttgart: Contribution to Sedimentology*, Schweizerbart'sche Verlag 12: 217 p.
- Gallois A, Bosence D, Burgess PM. 2018. Brackish to hypersaline facies in lacustrine carbonates: Purbeck Limestone Group, Upper Jurassic-Lower Cretaceous. Dorset, UK: Wessex Basin. *Facies* 64: 12.
- Garcia A. 1994. Charophyta: their use in paleolimnology. *Journal of Paleolimnology* 10(1): 43–52.
- Garcia A, Chivas AR. 2006. Diversity and ecology of extant and Quaternary Australian charophytes (Charales). *Cryptogamie Algologie* 27(4): 323–340.
- Garcia-Castellanos D. 2006. Long-term evolution of tectonic lakes: climatic controls on the development of internally drained basins. *Geological Society of America Special Paper* 398: 283–294.
- Gorini C, Le Marrec A, Mauffret A. 1993. Contribution to the structural and sedimentary history of the Gulf of Lions (western Mediterranean), from the ECORS profiles, industrial seismic profiles and well data. *Bulletin de la Société géologique de France* 164(3): 353–363.
- Grambast L, Grambast-Fessard N. 1981. Étude sur les Charophytes tertiaires d'Europe occidentale III : le Genre Gyrogona. *Paléobiologie Continentale* 12(2): 1–35.
- Hargrave JE, Hicks MK, Scholz CA. 2014. Lacustrine carbonates from Lake Turkana, Kenya: a depositional model of carbonates in an extensional basin. *Journal of Sedimentary Research* 84: 224–237.
- Harris M, Faulkner P, Asmussen B. 2015. Macroscopic approaches to the identification of expedient bivalve tools: a case study investigating polymesoda (=Geloína) coaxans (Bivalvia: Corbiculidae) shell valves from Princess Charlotte Bay, Queensland, Australia. *Quaternary International* 427: 201–215.
- Hasiuk FJ, Kaczmarek SE, Fullmer SM. 2016. Diagenetic origins of the calcite microcrystals that host microporosity in limestone reservoirs. *Journal of Sedimentary Research* 86: 1163–1178.

- Kahle CF. 1974. Ooids from Great Salt Lake, Utah, as analogue for the genesis and diagenesis of ooids in marine limestones. *Journal of Sedimentary Geology* 44(1): 30–39.
- Klinger Y, Avouac J-P, Bourlès D, Tisnéat N. 2003. Alluvial deposition and lake-level fluctuations forced by Late Quaternary climate change: the Dead Sea case example. *Sedimentary Geology* 162(1–2): 119–139.
- Leng MJ, Marshall JD. 2004. Palaeoclimate interpretation of stable isotope data from lake sediment archives. *Quaternary Science Reviews* 23(7–8): 811–831.
- Léonide P, Fournier F, Reijmer JJG, Vonhof H, Borgomano J, Dijk J, *et al.* 2014. Diagenetic patterns and pore space distribution along a platform to outer-shelf transect (Urgonian limestone, Barremian-Aptian, SE France). *Sedimentary Geology* 306: 1–28.
- Lesueur J-L. 1991. Étude sédimentologique et stratigraphique du Bassin Paléogène d'Apt-Manosque-Forcalquier (Alpes de Haute Provence). Modalités de la transition Burdigalienne. Ph.D. thesis. Bordeaux III, France: University M. de Montaigne, 407 p.
- Lettéron A. 2018. Caractérisation sédimentologique, stratigraphique et paléoenvironnementale du système carbonaté lacustre à salinité variable du bassin d'Alès et des régions limitrophes (Priabonien, SE France) : implications paléoclimatiques et paléogéographiques. PhD thesis. Aix-Marseille University, 344 p.
- Lettéron A, Fournier F, Hamon Y, Villier L, Margerel J-P, Bouche A, *et al.* 2017. Multi-proxy paleoenvironmental reconstruction of saline lake carbonates: Paleoclimatic and paleogeographic implications (Priabonian-Rupelian, Issirac Basin, SE France). *Sedimentary Geology* 358: 97–120.
- Lettéron A, Hamon Y, Fournier F, Séranne M, Pellenard P, Joseph P. 2018. Reconstruction of a saline, lacustrine carbonate system (Priabonian, St-Chartes Basin, SE France): depositional models, paleogeographic and paleoclimatic implications. *Sedimentary Geology* 367: 20–47.
- Lettéron A, Hamoun Y, Fournier F, Demory F, Séranne M, Joseph P. 2022. Stratigraphic architecture of a saline lake system: from lake depocenter (Alès Basin) to margins (Saint-Chartes and Issirac basins), Eocene-Oligocene transition, south-east France. *Sedimentology* (in press). <https://doi.org/10.1111/sed.12920>, <hal-03406458>.
- Li H-C, Ku L. 1997. $\delta^{13}\text{C}$ - $\delta^{18}\text{O}$ covariance as a paleohydrological indicator for closed-basin lakes. *Palaeogeography, Palaeoclimatology, Palaeoecology* 133: 69–80.
- Mauffret A, Gorini C. 1996. Structural style and geodynamic evolution of Camargue and Western Provencal basin, southeastern France. *Tectonophysics* 15 (2): 356–375.
- Ménillet F. 1973. Carte géologique de la France au 1/50 000, feuille Nîmes. BRGM Edition.
- Milroy PG, Wright VP. 2002. Fabrics, facies control and diagenesis of lacustrine ooids and associated grains from the Upper Triassic, southwest England. *Geological Journal* 37: 35–53.
- Miranda NAF, Perissinotto R, Appleton CC. 2010. Salinity and temperature tolerance of the invasive freshwater gastropod *Tarebia granifera*. *South African Journal of Science* 106(3/4): Art. #156, 7 p. <https://doi.org/10.4102/sajs.v106i3/4.156>.
- Morton B, 1983. Mangrove bivalves. In: Russell-Hunter WD, ed. *The Mollusca* 6. Orlando: Academic Press, pp. 77–138.
- Noulet J-B. 1854. Mémoires sur les coquilles fossiles des terrains d'eau douce du Sud-Ouest de la France. Paris: Victor Masson, 125 p.
- Nutz A, Schuster M, Barboni D, Gassier G, Van Bocxlaer B, Robin C, *et al.* 2020. Plio-Pleistocene sedimentation in West Turkana (Turkana Depression, Kenya, East African Rift System): Paleolake fluctuations, paleolandscapes and controlling factors. *Earth Science Reviews* 111: 103415.
- Pellat E, Allard M. 1895. Dépôts lacustres de la Butte Iouton entre Comps et Beaucaire (Gard). *Bulletin de la Société géologique de France* 23: 434–436.
- Plaziat J-C, Younis WR. 2005. The modern environments of Molluscs in southern Mesopotamia, Iraq: a guide to paleogeographical reconstructions of Quaternary fluvial, palustrine and marine deposits. *Carnets de Géologie* 2005/01: 18 p.
- Pomar L, Aurell M, Badenas B, Morsilli M, Al-Awwad SF. 2015. Depositional model for a prograding oolitic wedge, Upper Jurassic, Iberian basin. *Marine and Petroleum Geology* 67: 556–582.
- Reichenbacher BA, Uhlig U, Kowalke T, Bassler B, Matzke-Karasz Schenk B. 2004. Biota, paleoenvironments and biostratigraphy of continental Oligocene deposits of the South German Molasse Basin (Penzberg syncline). *Palaeontology* 47(3): 639–677.
- Reid C, Groves J. 1921. The Charophyta of the Lower Headon Beds of Hordle (Hordwell) Cliffs (South Hampshire). *Quarterly Journal of the Geological Society of London* 77: 175–192.
- Riveline J. 1986. Les charophytes du Paléogène et du Miocène inférieur d'Europe occidentale. *Cahiers de Paléontologie*, volume 8. Paris: Muséum national d'Histoire naturelle, 304 p.
- Riveline J, Berger J-P, Feist M, Martin-Closas C, Schudack M, Soulié-Märsche I. 1996. European Mesozoic-Cenozoic charophyte biozonation. *Bulletin de la Société géologique de France* 167(3): 453–468.
- Roduit N. 2007. JMicroVision : un logiciel d'analyse d'images pétrographiques polyvalent. PhD thesis. University of Geneva, 128 p.
- Roman F. 1903. Contributions à l'étude des Bassins lacustres de l'Éocène et de l'Oligocène du Languedoc. *Bulletin de la Société géologique de France (4^e série)* 3: 546–616.
- Roman F. 1910. Faune saumâtre du sannoisien du Gard. *Bulletin de la Société géologique de France (4^e série)* 10: 927–955.
- Rouchy J-M. 1997. Paleogene continental rift system of Western Europe: locations of basins, paleogeographic and structural framework, and the distribution of evaporites. In: Busson G, Schreiber BC, eds. *Sedimentary Deposition in Rift and Foreland Basins in France and Spain*. New York: Columbia Univ. Press, pp. 45–94.
- Rouchy J-M, Blanc-Valleron M-M. 2009. Les évaporites matériaux singuliers, milieux extrêmes. Paris: Vuibert, 184 p.
- Sanchis E, Séranne M. 2000. Structural style and tectonic evolution of a polyphase extensional basin of the Gulf of Lion passive margin: the Tertiary Alès Basin, southern France. *Tectonophysics* 322: 243–264.
- Sandberg PA. 1975. New interpretations of Great Salt Lake ooids and of ancient non-skeletal carbonate mineralogy. *Sedimentology* 22: 497–537.
- Sandberg PA. 1980. The Pliocene Glenns Ferry oolite: lake-margin carbonate deposition in the southwestern Snake River plain—Discussion and replay. *Journal of Sedimentary Petrology* 50: 997–998.
- Séranne M, Benedicto A, Truffert C, Pascal G, Labaume P. 1995. Structural style and evolution of the Gulf of Lion Oligo-Miocene rifting: role of the Pyrenean orogeny. *Marine and Petroleum Geology* 12: 809–820.
- Séranne M, Couëffé R, Husson E, Baral C, Villard J. 2021. The transition from Pyrenean shortening to Gulf of Lion rifting in Languedoc (South France) – A tectonic-sedimentation analysis. *BSGF – Earth Sciences Bulletin* 192: 27.
- Serres M. de. 1827. Notes sur la série des terrains tertiaires du Midi de la France. *Annales des sciences naturelles* 11: 325–331.
- Shekhar R, Sahni I, Benson G, Agar S, Amour F, Tomas S, *et al.* 2014. Modelling and simulation of a Jurassic carbonate ramp outcrop, Amellago, High Atlas Mountains, Morocco. *Petroleum Geoscience* 20: 109–124.

- Sissingh W. 2001. Tectonostratigraphy of the West Alpine Foreland: correlation of Tertiary sedimentary sequences, changes in eustatic sea-level and stress regimes. *Tectonophysics* 333: 361–400.
- Schäfer A, Stapf KRG. 1978. Permian Saar-Nahe Basin and recent Lake Constance (Germany): two environments of lacustrine algal carbonates. In: Matter A, Tucker ME, eds. Modern and Ancient Lake Sediments. *IAS Special Publication* 2: 83–107.
- Swirydzuk K, Wilkinson BH. 1979. The Pliocene Glens Ferry oolite: lake-margin carbonate deposition in the southwestern Snake River plain. *Journal of Sedimentary Petrology* 49: 995–1004.
- Swirydzuk K, Wilkinson BH, Smith GR. 1980. The Pliocene Glens Ferry oolite—II: Sedimentology of oolitic lacustrine terrace deposits. *Journal of Sedimentary Petrology* 50: 1237–1248.
- Tabb DC, Moore DR. 1971. Discovery of the Carolina Clam, *Polymesoda caroliniana* (Bosc), a supposed Florida disjunct species, in Everglades National Park, Florida. *Gulf Research Reports* 3(2): 265–281.
- Talbot MR. 1990. A review of the palaeohydrological interpretation of carbon and oxygen isotopic ratios in primary lacustrine carbonates. *Chemical Geology* 80: 261–279.
- Talbot MR, Allen PA. 1996. Lakes. In: Reading HG, ed. *Sedimentary Environments: Processes, Facies and Stratigraphy*. Oxford: Blackwell Science, pp. 83–124.
- Tänavsuu-Milkeviciene K, Sarg JF, Bartov Y. 2017. Depositional Cycles and Sequences in an Organic-Rich Lake Basin: Eocene Green River Formation, Lake Uinta, Colorado and Utah, U.S.A. *Journal of Sedimentary Research* 87(3): 210–229.
- Triat JM, Truc G. 1974. Evaporites paléogènes du domaine rhodanien. *Revue de géographie physique et de géologie dynamique* 16: 235–262.
- Truc G. 1978. Lacustrine Sedimentation in an Evaporitic Environment: the Ludian (Palaeogene) of the Mormoiron Basin, Southeastern France. *Special Publications of the International Association of Sedimentologists* 2: 189–203.
- Tucker ME, Wright VP. 1990. Carbonate sedimentology. Oxford: Blackwell, 482 p.
- Valette M. 1991. Étude structural du gisement salifère Oligocène de Vauvert (Gard). Thèse de doctorat. Univ. Montpellier II, 229 p.
- Valette M, Benedicto A. 1995. Chevauchements gravitaires halotectoniques dans le bassin distensif de Camargue (marge du golfe du Lion, SE de la France). *Bulletin de la Société géologique de France* 166(2): 137–147.
- Veizer J, Ala D, Azmy K, Bruckschen P, Buhl D, Bruhn F, *et al.* 1999. $^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ evolution of Phanerozoic seawater. *Chemical Geology* 161(1–3): 59–88.
- Velasco J, Millán A, Hernández J, Hernández J, Gutiérrez C, Abellán P, *et al.* 2006. Response of biotic communities to salinity changes in a Mediterranean hypersaline stream. *Aquat Biosyst* 2: 12. <https://doi.org/10.1186/1746-1448-2-12>.
- Van Den Berg MS, Coops H, Simons J, De Keizer A. 1998. Competition between *Chara aspera* and *Potamogeton pectinatus* as a function of temperature and light. *Aquatic Botany* 60: 241–250.
- Wanless HR. 1981. Fining-upward sedimentary sequences generated in seagrass beds. *Journal of Sedimentary Petrology* 51: 445–454.
- Wattine A, Vennin E, De Wever P. 2003. Évolution d'un environnement carbonaté lacustre à stromatolithes, par l'approche paléo-écologique (Carrière de Montaigu-le-Blin, bassin de Limagne, Allier, France). *Bulletin de la Société géologique de France* 174(3): 243–260.
- Williamson CR, Picard M.D. 1974. Petrology of carbonate rocks of the Green River Formation (Eocene). *Journal of Sedimentary Petrology* 44(3): 738–759.
- Ziegler PA. 1992. European Cenozoic rift system. In: Ziegler PA, ed. *Geodynamics of Rifting, Volume I, Case History Studies on Rifts: Europe and Asia*. *Tectonophysics* 208: 91–111.

Cite this article as: Semmani N, Fournier F, Léonide P, Feist M, Boularand S, Borgomano J. 2022. Transgressive-regressive cycles in saline lake margin oolites: paleogeographic implications (Priabonian, Vistrenque basin, SE France), *BSGF - Earth Sciences Bulletin* 193: 8.