

The Perte-du-Rhône Formation, a new Cretaceous (Aptian-Cenomanian) lithostratigraphic unit in the Jura mountains (France and Switzerland)

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Abstract During the late Early Cretaceous, the Jura domain was occupied by a photozoan carbonate platform, summarised in the Vallorbe Formation. From the earliest Aptian to the Late Cenomanian, open marine heterozoan and detrital marl, carbonate, and sandstone (up to 40 m thick) accumulated on top of the former Urgonian platform, followed during the Late Cretaceous by pelagic chalk and limestone. At the end of the Early Cretaceous, sediment accumulation was interrupted by several emersions and consecutive drowning phases identified in the field by angular discontinuities, iron crusts, and phosphatic conglomerates. Such sedimentary succession is particularly well visible in the present Bellegarde-sur-Valserine Basin of the Ain Department (eastern France). Therefore, in agreement with the Swiss Committee of Stratigraphy, we introduced new lithostratigraphic units to cover the time from the Aptian to the Cenomanian in the Jura mountains based on the type section near the historical outcrop of the Perte-du-Rhône in the Bellegarde Basin. The new Perte-du-

Rhône Formation is subdivided in a lower marly unit (Fulie Member), followed by a middle green sandstone unit with phosphatic conglomerates (Mussel Member), which is finally topped by a mica-rich sandstone unit (Poncin Member).

Keywords Jura mountains · Lithostratigraphy · Cretaceous · Aptian · Albian · Cenomanian

Abbreviations

UCBL	Université Claude-Bernard-Lyon-I
FSL	Faculté des Sciences de Lyon
MGL	Musée de Géologie de Lausanne
MHNG	Muséum d'Histoire naturelle de Genève
GEPI	Département de géologie et de paléontologie
MHNN	Muséum d'Histoire naturelle de Neuchâtel
MNB	Naturhistorisches Museum Basel

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1 Introduction

During the late Early Cretaceous, the Jura domain was occupied by a photozoan carbonate platform, the so-called Urgonian platform (Vallorbe Formation, Strasser et al. 2016, this issue; Masse 1976; Arnaud-Vanneau 1980; Arnaud 1981). In this palaeogeographic setting, today corresponding to the Jura mountains, the carbonate platform was represented by the innermost lagoon bordering a supposed land towards northwest (Tabular Jura of eastern France and western Switzerland). The important climatic changes that amplified from the latest Barremian onwards lead to the drowning of the platform from the earliest Aptian onwards. The carbonate “factory” rapidly but progressively changed

to open marine heterozoan sediments. In contrast to the more distal parts of the platform, represented by the neighbouring Alps, the Upper Schratenkalk (Urgonian) Member (Mb) did not deposit into the Jura mountains. Consequently, detrital sediments, dominated by marl, glauconite sandstone, and crinoidal limestone, sedimented on the roof of the former Urgonian platform. These detrital sediments deposited in the area actually occupied by the Central Jura from the earliest Aptian to the latest Albian, and though the Cenomanian in the area corresponding to the present Meridional Jura. In this time interval, the sedimentation was interrupted by ten drowning or flooding events (Linder et al. 2006; Föllmi and Gainon 2008; Masse and Fenerci-Masse 2011; Pictet et al. 2015), which delimit the different subunits or beds.

The studied area is situated in the thrust-and-fold and tabular Jura belts of western Switzerland and eastern France (Trümpy 1980; Sommaruga 1997), and more precisely in the Bellegarde-sur-Valserine Basin (eastern France, Fig. 1). The Bellegarde Basin is a triangle-shaped, low-elevation (400–600 m) area which is crossed by the Rhône and Valserine rivers. The Rhône runs from east to west in the eastern part of the basin, and then turns south at the city of Bellegarde-sur-Valserine towards Seyssel and Culoz villages, shortly after receiving the waters of the north to south flowing Valserine tributary. Bellegarde-sur-Valserine is a small industrial town at the confluence of both rivers, on the border between the departments of Ain and Haute-Savoie. It was one of the first French cities to benefit from public electricity in the late 19th century. In this context, the city acquired an hydraulic dam downstream to Genissiat, which was commissioned in 1948. Before that, the Rhône river flowed in a deep gorge in front of the city (Fig. 2a) and in times of low water, it was possible to see the Rhône river disappearing in the bottom of its bed (Fig. 2b). This hydrological peculiarity gave its name to this site, the Perte-du-Rhône, which dug through the Cretaceous sediments slightly inclined toward the east (Fig. 2c). The Perte-du-Rhône canyon, firstly cross-cuts the Cenozoic series comprising both the marine (OMM; Burdigalian) molasses and the freshwater (USM; Chatian-Aquitania) and, the “mid-Cretaceous” glauconite-rich sandstone and marl, and the Lower Cretaceous Urgonian carbonates at the bottom (Fig. 2d).

2 Previous studies and historical importance of the Perte-du-Rhône area

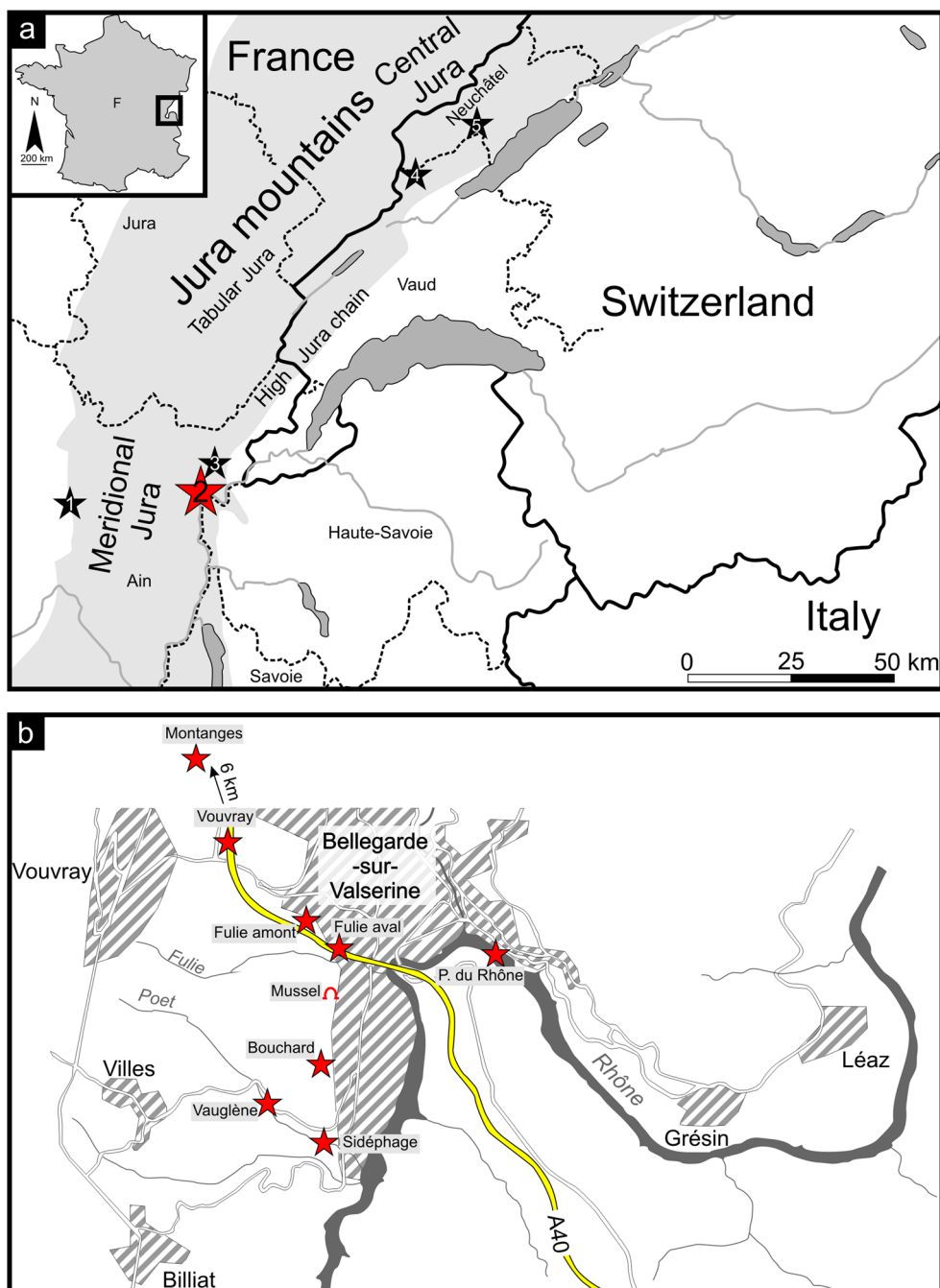
The rock exposure along the banks of the Rhône yielded many fossils cited for the first time by de Saussure (1779) who observed the “*cornes d’Ammon*”. Brongniart (1821, 1822) listed the fossils and dated the section of the “*chloritic Chalk*” (Fig. 3, now upper Albian—Lower Cenomanian). Escher (1841), made a brief description of

the Perte-du-Rhône section. He did not indicate any thickness information and only dated the yellowish limestone levels of the Neocomian. During the same year, in the first volume of the French Paleontology, d’Orbigny (1841) described new species of ammonites, some of which originate from the Perte-du-Rhône (*Ammonites brottianus*, *A. itierianus*). d’Orbigny (1842), referring on the lithology of different outcrops, introduced the Albian stage (Fig. 3) in these terms: “*Gault. L’étage ainsi nommé de ses argiles varie on ne peut davantage sous le rapport minéralogique. Il est en effet formé d’argiles, à ses parties moyennes, à Wissant (Pas-de-Calais), aux Côtes-Noires (Haute-Marne), à Gaty, à Maurepaire, à Dienville (Aube), et à Folkestone (Angleterre), mais à Wissant même, à Ervy (Aube), à Saint-Florentin (Yonne), à la Perte du Rhône (Ain), à Machéroménil (Ardennes), à Varennes (Meuse), il est aussi composé de grès verts, de grès blanchâtres; à Escragnolle (Var), il est représenté par une véritable glauconie crayeuse; à la Montagne-des-Fis (Savoie), par des roches noirâtres compactes. On voit donc que les noms de Gault, de glauconie sableuse, de grès vert inférieur, ne peuvent non plus être proprement appliqués dans tous les cas, ce qui me détermine à proposer, pour cet étage, le nom de terrain ALBIEN, l’Aube (Alba) le traversant à Dienville et sur beaucoup d’autres points.*”

The Perte-du-Rhône earned its status of type section for Albian age layers. From 1847 two important regional monographs were published in Switzerland including the description of many new species of ammonites. The first monograph focused on the Albian stage (Pictet and Roux 1847–1854), the second monograph on the Aptian stage (Pictet and Renevier 1854–1858). Renevier continued this work (Renevier 1854, 1855, 1875) and provided the first precise log of the Perte-du-Rhône section. Jacob (1907), in his memoir on Cretaceous Alpine outcrops, redescribed and named new species with certain type specimens (e.g. “*Acanthoceras*” = *Prolyelliceras geveyi*) coming from the Perte-du-Rhône. Finally, Jayet (1923, 1924, 1925, 1927) studied in a remarkable way the biostratigraphy and sedimentology of the Perte-du-Rhône section. During his comparative work on areas of the Albian of France and England, Breistroffer (1947) also discussed the fauna found in the Perte-du-Rhône.

Unfortunately, this famous and highly fossiliferous outcrop was drowned in 1948 by the water of the storage lake of the Génissiat hydraulic dam. The construction of the motorway viaduct between 1980 and 1982 offered large outcrops of the Aptian to Cenomanian layers, which were logged by M. Delamette and partially published in Kennedy and Delamette (1994). More recent searches were initiated in the last years by two of us (A.P. and B.M.) around Bellegarde-sur-Valserine (Ain, France) to locate all the outcrops and to supplement and improve the

Fig. 1 **a** Geographical map of the Jura mountains (eastern France and western Switzerland) with the location of the studied sections. **b** Focus on the Bellegarde-sur-Valserine Basin and position of the main outcrops visible in the area



unpublished stratigraphic log made by M.D. An equivalent section to the historical Perte-du-Rhône section has been relogged a few kilometre far in the Fulie gulch. Additionally, an important fauna of several thousand of specimens has been collected bed-by-bed. Furthermore, the draining of the hydraulic dam of Génissiat during the summer 2012 allowed us the observation and the logging of the historical Perte-du-Rhône section (Fig. 2e).

The recent research was carried out in two projects.

First, in the Ph.D. thesis of Pictet (2016) one separate chapter deals with the Aptian to Cenomanian sediments from the Jura mountains. It became necessary to clarify the local stratigraphy, in accordance with the rules of the International Stratigraphic Commission (ISC) stating that each lithostratigraphic unit is a body of rock that should be defined by a geographic component, its lithological properties, and its stratigraphic relation (Hedberg 1976). Second, as any nomenclature was missing, we suggested, in

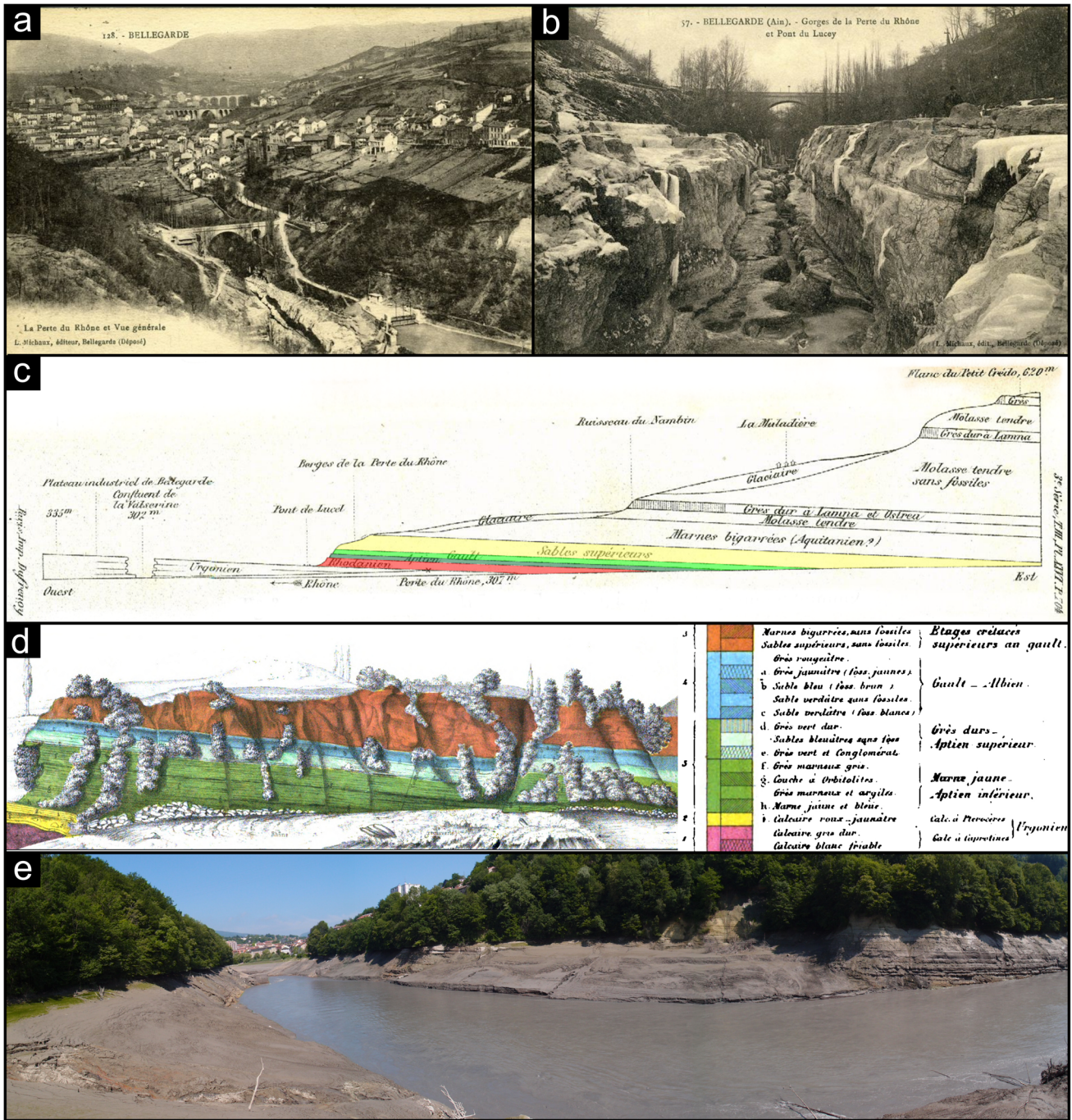


Fig. 2 a General northern view of the Perte-du-Rhône at the beginning of the 20th century, with the canyon overcome by the Lucey bridge, and the city of Bellegarde-sur-Valserine in the back. b Upstream north-western view of the Lucey bridge and the canyon. c Geological transect across the Rhône Valley modified from Renevier 1875. d Interpreted section of the Perte-du-Rhône, on the

right banc of the river, drawn by C. Vogt in Renevier 1854. e Actual situation, looking north from the left banc, of the Perte-du-Rhône during exceptional drainings of the Génissiat hydraulic dam like here in June 2012. The uppermost part of the Mussel Mb and the Poncin Mb are visible on the right side of the photography

the frame of the HARMOS project, an initiative launched in 2011 by the Swiss Geological Survey in order to harmonise the lithostratigraphic nomenclature in Switzerland, to define of a new lithostratigraphic unit, the Perte-du-

Rhône Formation. This new formation corresponds to the lowermost to middle late Aptian marly unit originally described as “Rhodanian” by Renevier (1855), to the middle late Aptian to latest Albian glauconitic “Grès verts

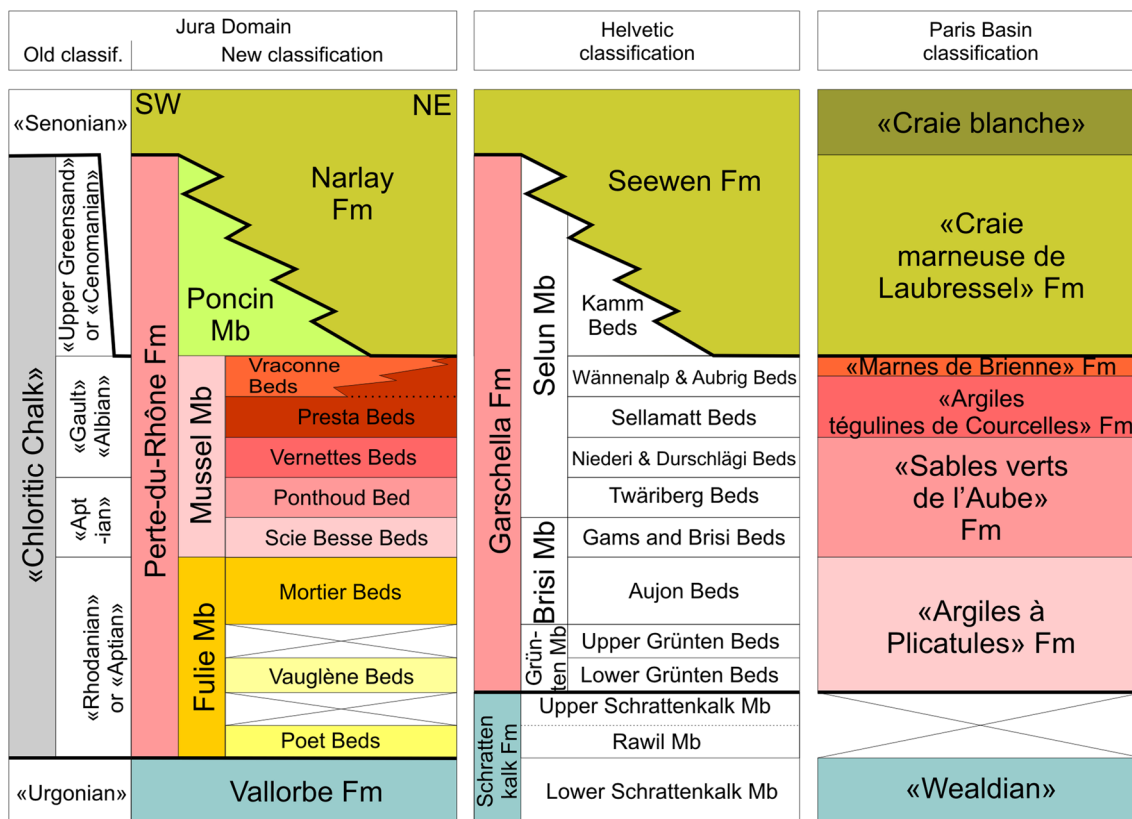


Fig. 3 Comparative figure of the lithostratigraphic units composing the Jura and adjacent Helvetic and Paris domains during the Barremian - Turonian time interval

jurassiens” from Donzeau et al. (1997), and to the Cenomanian “Sables supérieurs” from Renevier (1954). The type section is located on the edge of the Bellegarde-sur-Valserine city, which serves as type locality in agreement with the lithostratigraphic rules of the ICS.

3 Materials and methods

The revision of the lithostratigraphy of the earliest Aptian to Late? Cenomanian time interval in Bellegarde-sur-Valserine area has been based on traditional fieldwork (observations, sampling), microfacies analyses and interpretations, and ammonite biostratigraphy. For this study, nine sections in the Bellegarde Basin (Fig. 1a point 2, and 1b), one section in the Vraconne (Fig. 1a point 4), and one section in La Presta (Fig. 1a point 5) were carefully described, logged and sampled. Rock samples were collected on the main sections (Fulie section) at a variable sampling density (a few centimetres to 1 m) depending on the lithological changes. Microfacies analyses, sequence stratigraphy, sedimentology, and ammonite biostratigraphy were applied to each section. Particular attention has been paid to the

documentation of depositional geometries and discontinuity surfaces. The microfacies has been determined on 65 thin sections to describe the environmental changes in order to infer the eustatic variations.

The collected macrofauna, which is composed of cephalopods (ammonites, nautiloids, belemnites), gastropods, bivalves, serpulids, brachiopods, sponges, corals, and vertebrates (fishes, turtles), was used to infer environmental conditions, i.e. depth, temperature, luminosity, nutrients, and currents.

Aptian ammonite stratigraphy has been based on the zonal scheme of the Tethyan region proposed by the IUGS Lower Cretaceous “Kilian Group” during the 4th and the 5th International Meeting (Reboulet et al. 2011, 2014). However, because of palaeogeographical modifications, the Albian ammonite stratigraphy has been based on the zonal scheme of the European Province (Amédéo and Matrimon 2014) which shows more affinities to our fauna. For biostratigraphic purposes, fossils collected bed-by-bed in the field were examined. Additional fossils stored in the museums of Geneva (collections Delamette, Dubouloz, Eynard, Gaillard, Germain, Gsell, Jayet, Pictet, Rochat, général), Lausanne (collections Campiche, de Loriol, Renevier), Neuchâtel (collections Bourquin, Junod, general

stratigraphy, and University of Neuchâtel), Basel (collections Choffat, Frey, Renz), Lyon (collection Delamette), and Vienna were also documented. Fossil findings related to this study are mentioned in the text and the figures. In addition, several fossils collected on the same sections in previous studies have also been considered (Pictet and Roux 1847–1854; Pictet and Renevier 1854–1858; Donzeau et al. 1997; Delamette 1983; Kennedy and Delamette 1994).

4 Perte-du-Rhône Formation (PDR Fm)

Type locality: The type locality is situated along the Fulie creek, under the highway viaduct from the A40 which crosses the city of Bellegarde-sur-Valserine (Ain, France; Fig. 1b labels Fulie aval and Fulie amont; Fig. 4); Coordinates 717,591 m E/5,109,518 m N to 716,959 m E/5,109,847 m N (system WGS84, projection UTM, zone 31T).

The Fulie creek is accessible from the Verdun Avenue taking the dirt road forking below the highway viaduct. The section is visible along the creek and on the two sides of the small valley.

Parastratotype: La Presta (Val de Travers, Neuchâtel, Switzerland; Fig. 5); Coordinates 321,161 m E/5,199,960 m N to 321,068 m E/5,199,673 m N (system WGS84, projection UTM, zone 32T). This section represents the marl-dominated facies as being quite similar to the Paris Basin, which dominates in the Central Jura.

Thickness: The PDR Fm measures between 0 to more than 40 m depending of its position on the platform. The maximum sedimentary record is encountered along the High Jura Chain and especially along the main strike-slip faults which correspond to incised valleys.

Definition, subdivisions, lower boundary and geometries: The PDR Fm comprises heterozoan limestones and terrigenous sediments as clay, marl, and sandstone which are characterized by their rich phosphate and glauconite content. The lower part of the formation is mainly dominated by marl-limestone alternations and marls (Fulie Mb, Fig. 4), with heterozoan limestone at the base, followed by terrigenous dominated sediments to the top. The middle part of the formation (Mussel Mb, Fig. 4) includes terrigenous sediments dominated by glauconite sandstone which passes to the middle of the Mussel Mb to a crinoidal-dominated heterozoan limestone. To its top, the member suddenly passes to a planktic foraminifera-rich glauconite sandstone and marl, containing numerous phosphatic conglomerates (Fig. 4). The upper part of the formation is constituted by a micaceous green or orange sandstone (Poncin Mb, Fig. 4), locally extremely rich in planktic foraminifera.

Fig. 4 The Fulie section (Bellegarde-sur-Valserine, Ain, France) with age, litho- and biostratigraphy on the *left side*, and the sequence stratigraphic interpretations and description of the log on the *right side*

The PDR Fm usually overlies a discontinuity surface (D4 on Fig. 7a, b, d) on top of the Vallorbe Fm, which is karstified and sometimes bears a ferruginous crust. Nevertheless, the PDR Fm exhibits an onlap pattern following a SE–NW axis, toward the Tabular Jura where it overlaps first the Pierre Jaune de Neuchâtel (late Early Hauterivian), and finally the Jurassic rocks. The PDR Fm shows two main facies areas: the Meridional Jura dominated by marly-limestone and mostly sandstone deposits. A probable input of the clastic material from the Central Massif can be inferred. At the opposite side, the Central Jura, further from the detrital source and more subsiding, dominated by thick marly deposits (e.g. Fig. 6).

Biostratigraphic data and age: Biostratigraphic ages are based on ammonites, which are quite rare in the Fulie Mb, abundant in the Mussel Mb, and locally rich in the Poncin Mb. They provided a good age control detailed in the next chapter. In a general way, the PDR Fm gathers sediments from the earliest Aptian (*Deshayesites oglanlensis* Zone) to the latest Albian (*Praeschloenbachia briacensis* Zone) in the Central Jura while in the Meridional Jura, the formation extends until the Late? Cenomanian (Busnardo et al. 1966).

Geographic distribution and lateral equivalents: The PDR Fm is situated in the Meridional Jura (France: Isère, Savoie, Haute-Savoie, Ain) and in the Central Jura (France: Jura, Doubs; Switzerland: Vaud, Neuchâtel).

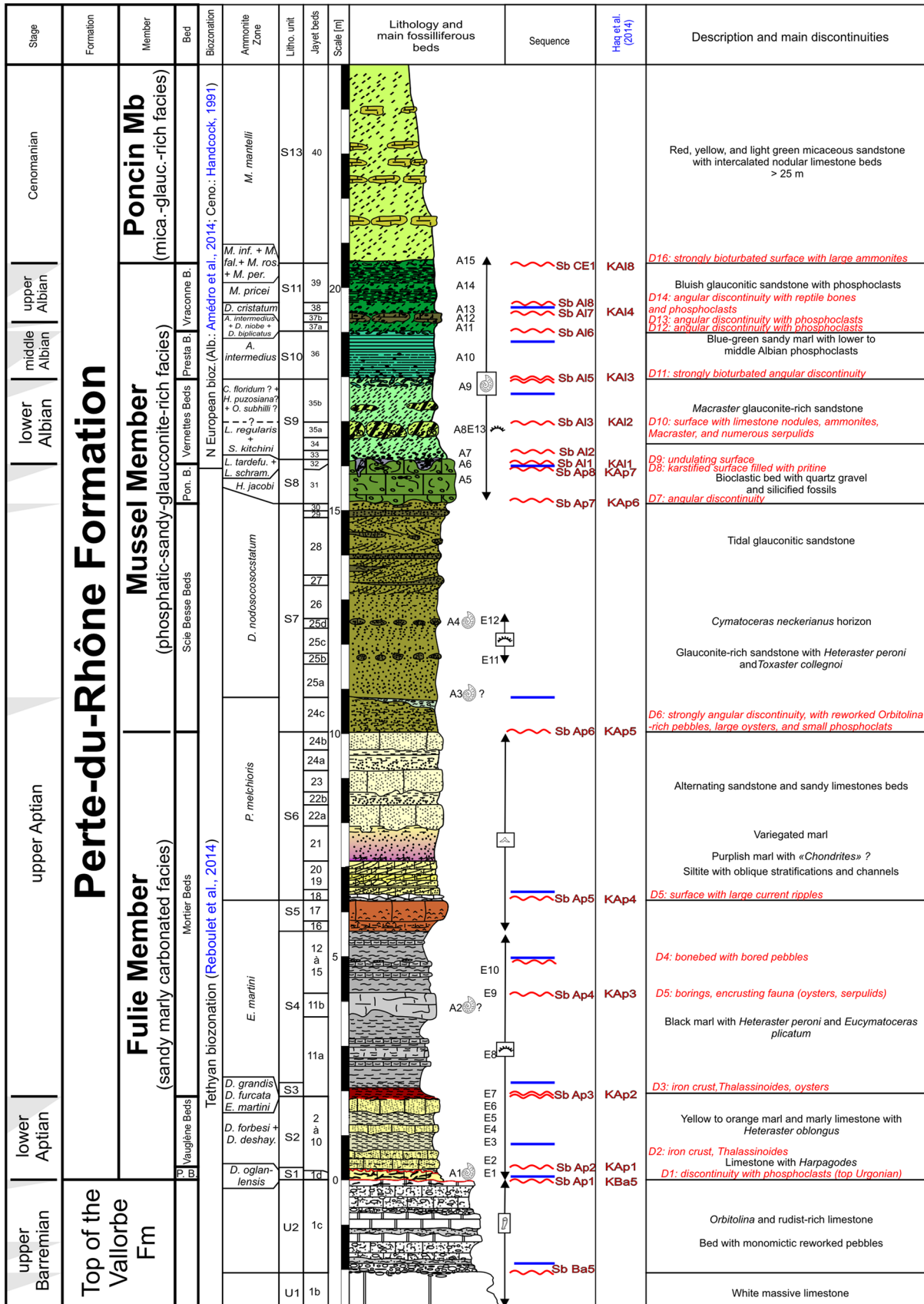
The PDR Fm is a lateral equivalent of the “Lower” and “Upper Orbitolina Beds” (Kaufmann 1867; Burckhardt 1896), the “Lumachelle” (Lory 1851) and the Albian (Jacob 1907) from the South Subalpine Chains; the Garschella Fm (Föllmi and Ouweland 1987) from the Helvetic domain; and the “Argiles à Plicatules” (Cornuel 1841), the “Sables verts de l’Aube” (Rat et al. 1979), the “Argiles tégulines de Courcelles” (Amédéo and Matrimon 2007), the “Marnes de Brienne” (Potier 1884), and the “Craie marneuse de Laubressel” (Péron 1887) *p.p.* from the Paris Basin.

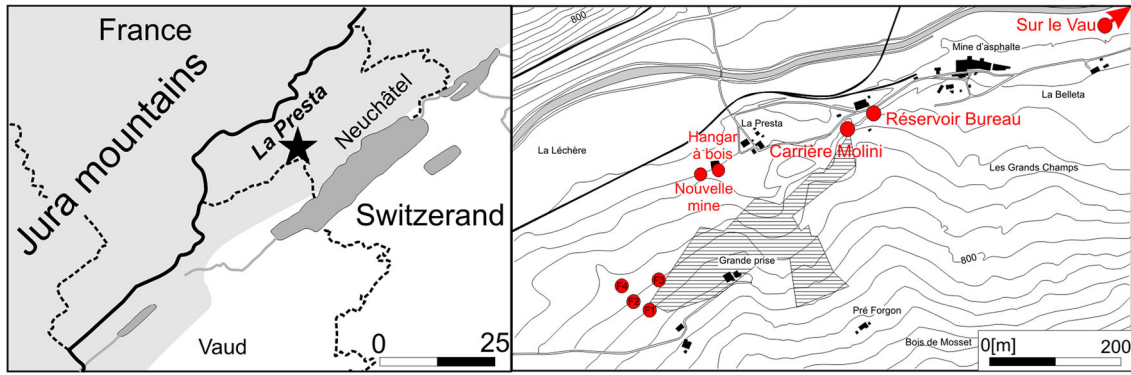
5 Lithostratigraphic subunits of the Formation

5.1 Fulie Member

5.1.1 Type locality

It is situated along the Fulie creek, as for PDR Formation (Fig. 1b). For the accessibility and the coordinates, see above as for the PDR Fm. Good outcrops of the member are also visible along the creek between Sidéphage and Vauglène (Fig. 1b).





Carrière Molini

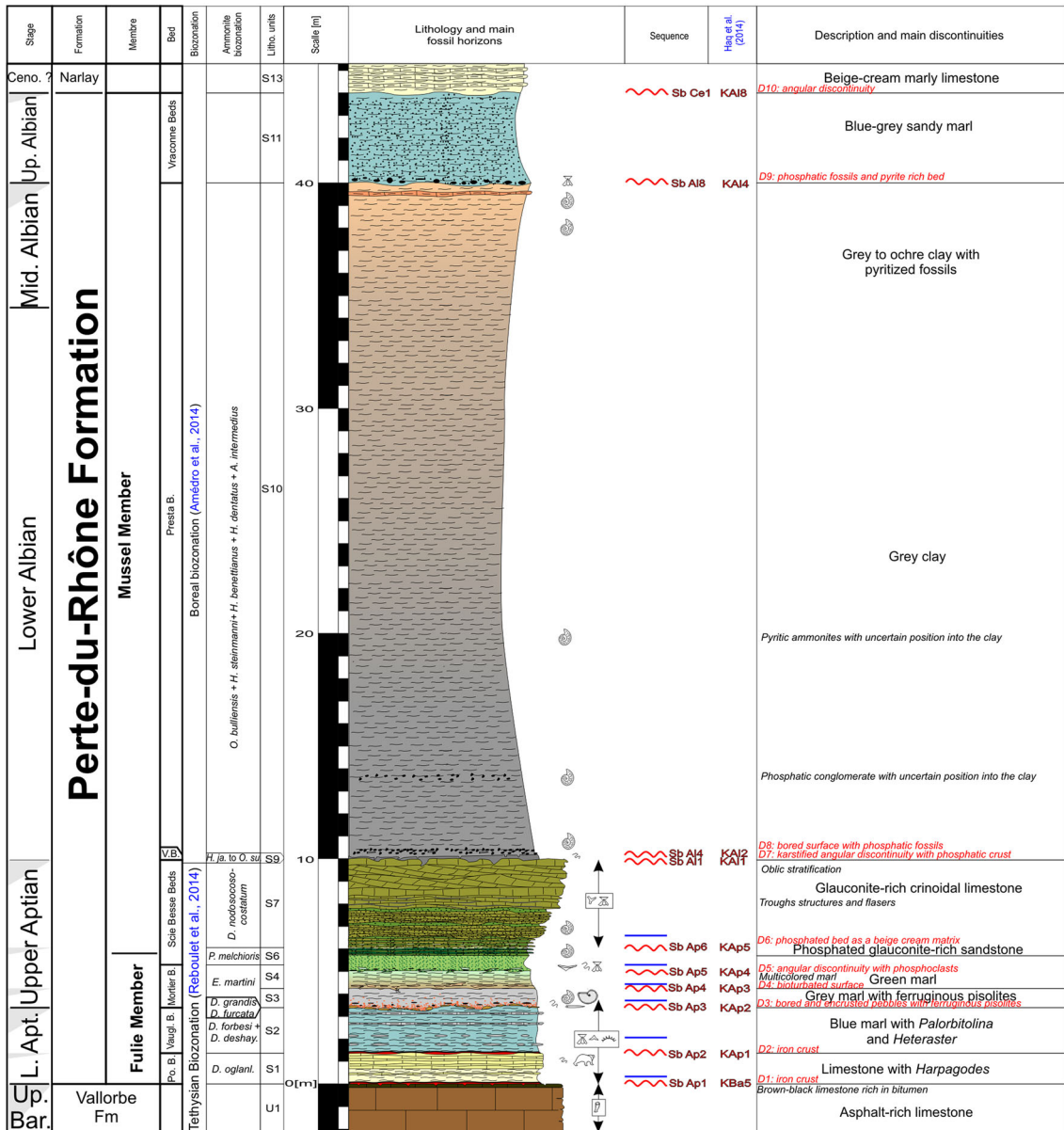


Fig. 5 The La Presta section (Val de Travers, Neuchâtel, Switzerland) with age, litho- and biostratigraphy on the left side, and the sequence stratigraphic interpretations and description of the log on the right side

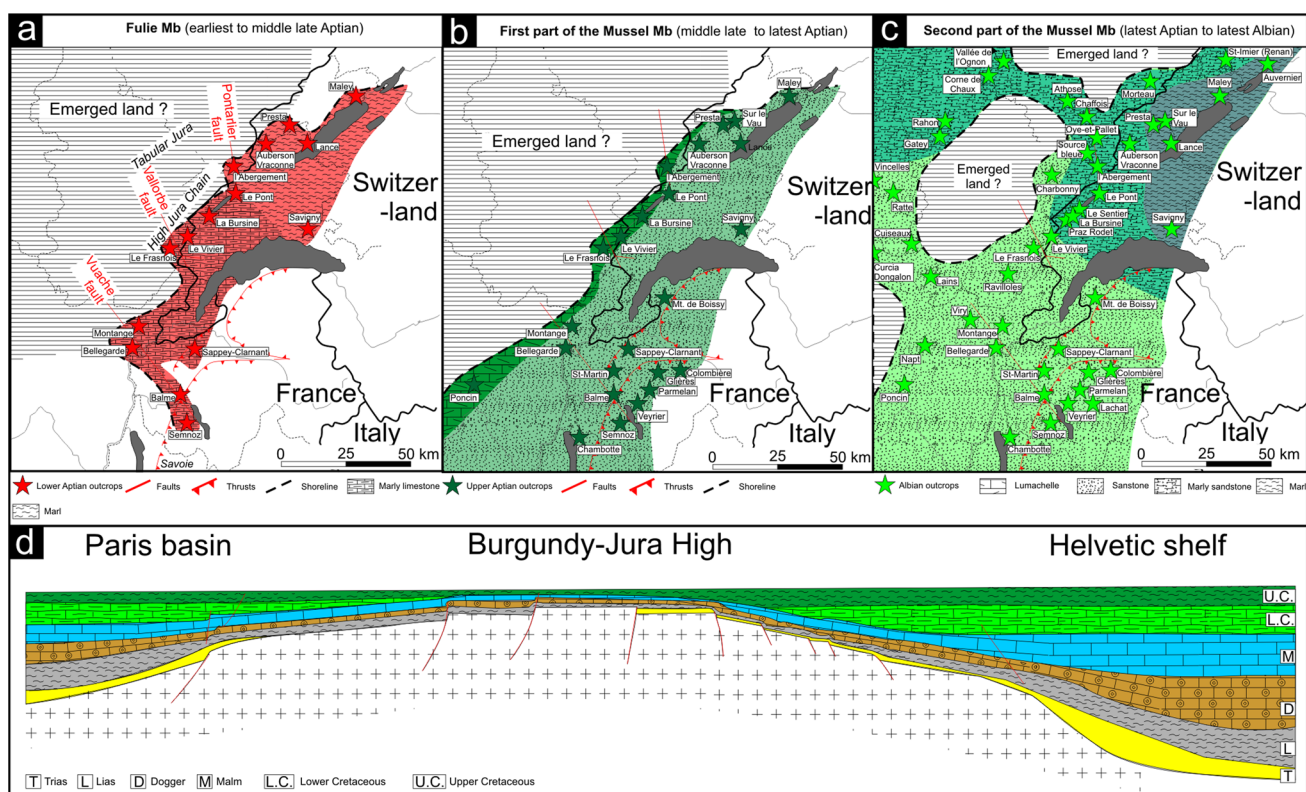


Fig. 6 Distribution map of the members composing the PDR Fm on the Jura-Burgundy High. **a** Repartition of the facies during the deposition of the Fulie Mb (early and early late Aptian) with the known outcrops indicated by *red stars*. **b** Deposition of the Aptian

part of the Mussel Mb with the known outcrops indicated by *dark green stars*. **c** Deposition of the Albian part of the Mussel Mb with the known outcrops indicated by *light green stars*. **d** Transect across the Jura-Burgundy High from the Paris basin to the NW Tethyan margin

5.1.2 Thickness

The Fulie Mb measures from 0 to more than 10 m depending of its position on the former carbonate platforms. The maximum sedimentary record is encountered along the main strike-slip faults of Vuache, Vallorbe, and Pontarlier (Fig. 6).

5.1.3 Definition, lateral variations and lower boundary

This member is defined by a marl and marly-limestone dominated unit which corresponds to the “Rhodanian” of Renevier 1855. The facies is mainly dominated by a marl-limestone alternation in the Meridional Jura and by marl in the Central Jura. The member rests upon the karstified top of the Urgonian limestone which sometimes bears a feruginous crust (discontinuity surface D4: Fig. 7a, b).

Geographic distribution and lateral equivalents: The Fulie Mb extends towards the northwestern until the boundary between the Jura thrust-and-fold belt and the Tabular Jura (Fig. 6).

The Fulie Mb passes laterally to the Lower and Upper Orbitolina Beds from the Subalpine chains, to the Rawil

Mb (Schenk 1992; Föllmi et al. 2007), the Grüntens Mb (Linder et al. 2006), and the lower half of the Brisi Mb (Föllmi and Ouwehand 1987; the Seelisberg, Risleten, Aujon, and Lutere Beds, Pictet 2016) in the Helvetic domain, and to the “Argiles à Plicatules” in the Paris Basin.

5.1.4 Subdivisions

From the base to the top of the Fulie Mb, three subunits have been identified (Fig. 7). The first one, the Poet Beds (unit S1, Figs. 4, 7d–e; *Harpagodes* Beds, Lower *Orbitolina* Beds), are a 0–2 m thick yellow to grey heterozoan marly-limestone, which microfacies is composed by a bioclastic wackstone-packstone (Fig. 7e). The Poet Beds deliver a rich macrofauna (e.g. Pictet and Campiche 1858; Pictet and Campiche 1858–1871) including rare ammonites (*Deshayesites* gr. *saxbyi* CASEY 1964, Fig. 7f), numerous gastropods (*Harpagodes pelagi* [BRONGNIART 1821], Fig. 7f), abundant echinoids (*Nucleolites roberti* [GRAS 1848]; *Pygaulus desmoulensis* AGASSIZ 1847, Fig. 7f; *Heteraster oblongus* [BRONGNIART 1821]), serpulids, corals, and bivalves (*Pholadomya*, *Trigonia*).

The second one, the Vauglène Beds (unit S2, Figs. 4, 7g–h; Upper *Orbitolina* Beds), are a 0–3 m thick alternation of yellow and orange marl and marly-limestone, which is composed of a sandy wackstone-packstone (Fig. 7h). In the Central Jura, these beds are more marly with less carbonate intercalations. The Vauglène Beds deliver a rich macrofauna (Pictet and Campiche 1858; Pictet and Campiche 1858–1871) of serpulids, gastropods, bivalves (*Pholadomya*, *Trigonia*), and ammonites (Fig. 7i).

The third one, the Mortier Beds (unit S3, Figs. 4, 7j–m), are 0–7 m thick marl-dominated alternation. The lower half is represented by 0–4 m thick black marl and grey limestone (Fig. 7j), which is made of sandy bioclastic wackstone-packstone (Fig. 7l). This first part is represented in the Central Jura by 1 m of grey and purple marl. In the Meridional Jura, the upper half comprises a 0–4 m thick multicoloured sandy marl in alternation with sandy limestone lenses (Fig. 7k); the latter showing a quartz-rich packstone microfacies (Fig. 7m). In the Central Jura, this upper part is represented by 1 m thick green marl. The base of the Mortier Beds is marked by a phosphatic conglomerate. In the Presta section, this level delivered a rich macrofauna of ammonites (Fig. 7n), belemnites, nautiloids, gastropods, serpulids, and bivalves (Pictet and Campiche 1858; Pictet and Campiche 1858–1871).

5.1.5 Biostratigraphic data and age

The ammonite fauna of the Fulie Mb reveals at least 13 taxa (see Renz and Jung 1978, p. 5; Martin-Closas et al. 2009; Clavel et al. 2012). The most characteristic biomarkers are represented on Fig. 7. They show a strong Tethyan affinity with the dominance of the *Deshayesitids* (Fig. 7f, i), *Douvilleiceratids* (Fig. 7i, n), and *Parahoplites* (Figs. 7n, 8c–f). For this reason and since there is likely no connection between the Paris Basin and the Tethys during the Aptian, we chose the Tethyan biostratigraphic scale (Reboulet et al. 2014).

The Fulie Mb starts in the earliest Aptian *Deshayesites ogranlensis* Zone, with *Deshayesites* gr. *saxbyi* CASEY 1964 (Fig. 7f3; Martin-Closas et al. 2009, p. 55) mainly occurring in this zone, and probably ends in the middle Late Aptian *Parahoplites melchioris* Zone with *Parahoplites* (Fig. 7n2; Renz and Jung 1978, p. 5).

5.2 Mussel Member

5.2.1 Type locality

The type locality is situated in the Mussel phosphates mine (Bellegarde-sur-Valserine, Ain, France; Fig. 1b labels Mussel); Coordinates 717,440 m E/5,109,099 m N (system WGS84, projection UTM, zone 31T). The Mussel mine is

Fig. 7 Facies and microfacies pictures from the Fulie Mb: **a** contact between the Vallorbe Fm and the Fulie Mb at the Montanges section (Ain, France). **b** Contact between the Vallorbe Fm and the Fulie Mb at the Bellegarde train station (Ain, France). **c** Microfacies from the last limestone bed from the Vallorbe Fm. **d** Facies from the Poet Beds in the “Nouvelle mine” at la Presta (Val de Travers, Neuchâtel, Switzerland). **e** Microfacies from the Poet Beds. **f** Macrofauna from the Poet Beds with *Heteraster oblongus* (BRONGNIART 1821) (f1, coll. A. Pictet, MHNG GEPI 84601), *Harpagodes pelagi* (BRONGNIART 1821) (f2, coll. A. Pictet, MHNG GEPI 84602), and *Deshayesites* gr. *saxbyi* CASEY 1964 (f3, coll. Delamette, UCBL FSL 105033). **g** Facies and contact between the Vauglène and Mortier Beds at Vauglène farm near Bellegarde. **h** Microfacies from the Vauglène Beds. **i** Ammonite fauna (i1, *Deshayesites grandis* SPATH 1930, coll. Frey, MNB J33405; i2, *Dufrenoyia furcata* SOWERBY 1936, coll. A. Pictet; MGL 2075a; i3, *Chelonicerias cornuelianum* [D’ORBIGNY 1841], coll. Frey, MNB J28181; i4, *Dufrenoyia dufrenoyi* [D’ORBIGNY 1841], coll. générale, MHNG GEPI 80720;) from the phosphatic conglomerate from la Presta, situated at the boundary between the Vauglène and Mortier Beds. **j**, **l** Facies and microfacies from the grey marl from the Mortier Beds. **k**, **m** Facies and microfacies of the motley marl and sandstone from the Mortier Beds. **n** Ammonite fauna (n1, *Epicheloniceras martini* [D’ORBIGNY 1841], coll. générale, MGL 97803; n2, *Parahoplites*, coll. générale, MHNN 26901;) from the Mortier Beds

accessible from the Rue du Château 12, which is a small grassy parcel. The mine is accessible by the manhole covers in the middle of the field. Other outcrops are also visible along creeks to Bouchard and to Fulie amount (Fig. 1b).

Parastratotype: La Vraconne section (Vaud, Switzerland; Fig. 9) has been chosen as a parastratotype locality for the Vraconne Beds which are more complete and thicker (Renz and Jung 1978); Coordinates 308,223 m E/5,190,269 m N (system WGS84, projection UTM, zone 32T).

5.2.2 Thickness

The Mussel Mb measures between 0 and more than 36 m depending of its position on the former carbonate platforms. The maximum sedimentary record is encountered along the main strike-slip faults of Vuache, Vallorbe, and Pontarlier (Fig. 6c). The thickest section is recorded in the Presta section with very thick Presta Beds (Fig. 5).

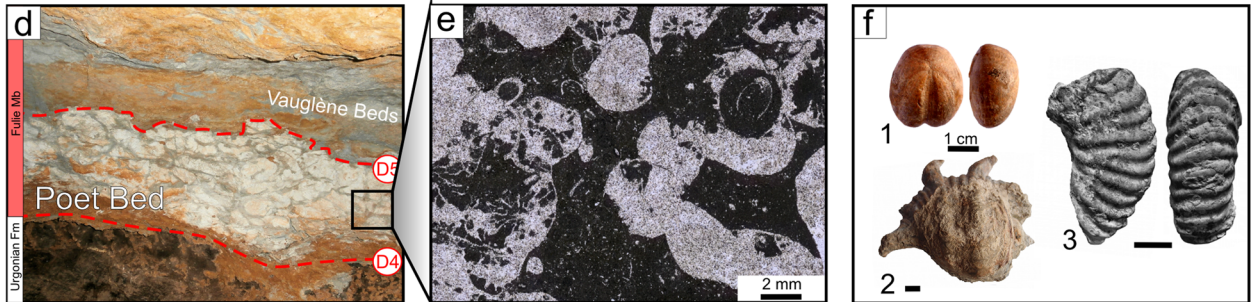
5.2.3 Definition, lateral variations and lower boundary

This member is defined by a glauconite-rich sandstone dominated facies, which passes temporarily in its middle part to a crinoidal limestone, more developed on its shallow borders (Fig. 6b). After this short carbonated event (“Lumachelle”), the glauconite-rich sandstone again becomes dominant. The Mussel Mb generally rests upon the Fulie Mb in the High Jura Chain, on the Vallorbe Fm in the boundary with the Tabular Jura, and on the Pierre Jaune de Nauchâtel in the Tabular Jura.

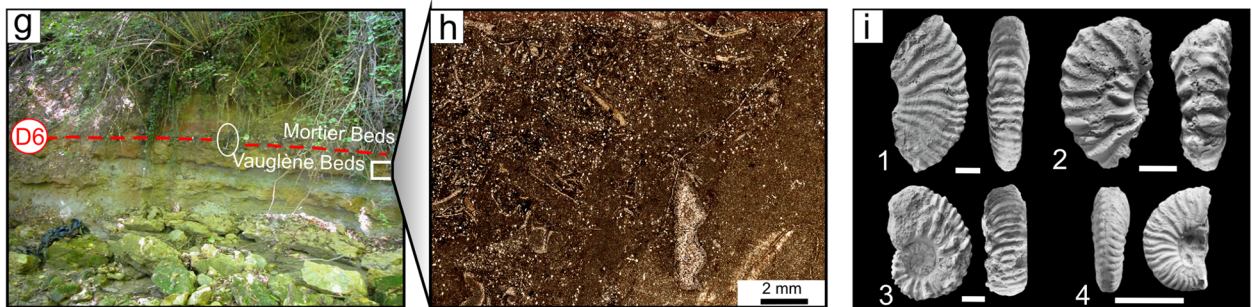
Lower Boundary with the Vallorbe Formation:



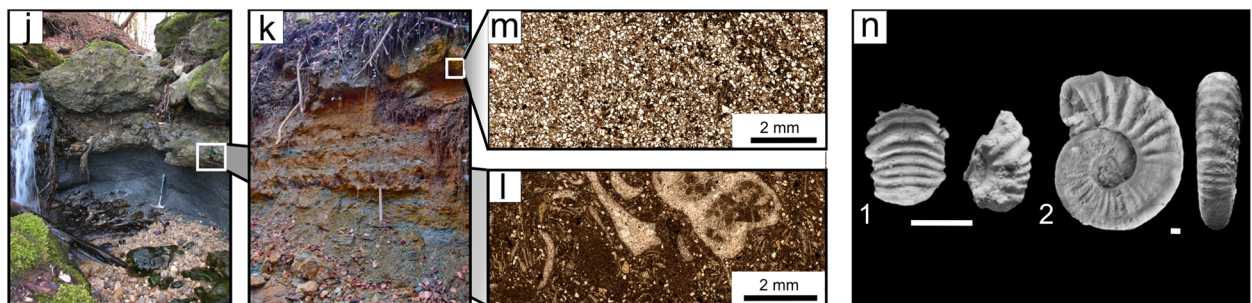
The Poet Bed:



The Vauglène Beds:



The Mortier Beds:



Geographic distribution: The Upper Aptian sediments forming the lower half of the Mussel Mb (Scie Besse Beds) roughly show the same distribution as the Fulie Mb (Fig. 6b) with a greater progradation in the Meridional Jura during the beginning of the latest Aptian-Albian transgression. The Albian sediments representing the upper half of the member (Vernettes, Presta and Vraconne Beds), largely overrun the Meridional and Central Jura, opening two sea-ways by the Bresse and Pontarlier straits (Fig. 6c).

The Mussel Mb passes laterally to: the “Lumachelle” and the “Albian” (Lory 1851; Jacob 1907; Breistroffer 1936) from the Subalpine chains; to the upper half of the Brisi Mb (Luitere 3 and 4 and Brisi Beds) and the Selun Mb *pro parte* (Frutzbach, Blonnière, Twäriberg, Nideri, Durschlägi, Sellamatt, Wannenalp, Aubrig, and Kamm beds) in the Helvetic domain; and to the “Sables Verts de l’Aube”, the “Argiles tégulines de Courcelles”, and the “Marnes de Brienne” Fms in the Paris Basin.

5.2.4 Subdivisions

From the base to the top of the Mussel Mb, five subunits have been identified (Fig. 8).

The first one, the Scie Besse Beds (Fig. 8a), is a 0–5 m thick green sandstone, which microfacies is characterized by a glauconite and quartz-rich bioclastic packstone (Fig. 8b). The glauconite-rich sandstone passes upwards to a tidal crinoidal limestone showing oblique stratification and flaser structures.

The second one, the Ponthoud Bed (S8, Figs. 4, 8d–e), is a 1 m thick green coquina-rich limestone, which is composed by a quartz and phosphate-rich packstone (Fig. 8e). The Ponthoud Bed delivered an heterotrophic fauna with numerous sponges, bryozoans, echinids, bivalves, gastropods, brachiopods, and rare ammonites (Fig. 8f; ~6 taxa; Pictet and Renevier 1854–1858; Pictet and Campiche 1858–1871) showing a strong affinity with the fauna of Clansayes (Kilian and Leenhardt 1890; Jacob 1905; Moulade 1965).

The third one, the Vernettes Beds (unit S9, Figs. 4, 8g–h), is a 0–10 m thick light green, white or orange, lightly marly sandstone. The microfacies is a glauconite and quartz-rich packstone (Fig. 8h). The Vernettes Beds includes a basal white phosphatic conglomerate, which delivered a rich benthic (echinids, bivalves, gastropods, brachiopods) and an abundant nectonic macrofauna (belemnites, and about 11 ammonites taxa, Fig. 8i, Pictet and Roux 1847–1854, Pictet and Campiche 1858–1871, Renz and Jung 1978). The ammonite fauna from these beds records the Aptian-Albian boundary and presents some unusual taxa. This fauna will be the subject of a future detailed palaeontological study.

The fourth one, the Presta Beds (S10, Figs. 4, 8j–k), is represented in the Meridional Jura by a 0–1 m thick green

Fig. 8 Facies and microfacies pictures from the Mussel Mb: **a**–**b** Facies and microfacies from the Scie Besse Beds of La Presta. **c** *Parahoplites* cf. *melchioris* ANTHULA 1899, coll. Pictet, MHNG GEPI 17445, zonal index from the Scie Besse Beds. **d**–**e** Facies and microfacies from the Ponthoud Bed from the Fulie (Bellegarde, Ain, France). **f** *Nolaniceras nolani* [SEUNES 1887], coll. Renevier, MGL 22447, former zonal index from the Scie Besse Beds. **g**–**h** Facies and microfacies from the Vernettes Beds from the Fulie section. **i** Ammonite fauna (i1, *Proleymeriella* aff. *schrammeni* [JACOB 1908], coll. Delamette, MHNG GEPI 54731; i2, *Leymeriella tardefurcata* [D’ORBIGNY 1841], coll. A. Pictet, MHNG GEPI 84603; i3, *L. regularis* [D’ORBIGNY 1841], coll. A. Pictet, MHNG GEPI 84604; i4, *Sonneratia dutempleana* [D’ORBIGNY 1850], coll. Renevier, MGL 12943) from the Vernettes Beds. **j** Boundary between the Presta and Vraconne Beds in the Mussel mine (Bellegarde, Ain, France). **k** Facies of the Presta Beds in the section of La Presta. **l** Ammonite fauna (l1, *Otohoplites subhilli* [SPATH 1942], coll. A. Pictet, MHNG GEPI 84605; l2, *Hoplites (Isohoplites) steinmanni* [JACOB 1907], coll. A. Pictet, MHNG GEPI 56723; l3, *Lyelliceras lyelli* [D’ORBIGNY 1841], coll. A. Pictet, MHNG GEPI 56723; l4, *Anahoplites intermedius* SPATH 1925, coll. A. Pictet, MHNG GEPI 84610) from the Vernettes Beds. **m**–**n** Facies and microfacies from the Vraconne Beds to the Mussel mine. **o** Ammonite fauna (o1, *Dimorphoplites biplicatus* [MANTELL 1822], coll. A. Pictet, MHNG GEPI 84606; o2, *Dipoloceras cristatum* [BRONGNIART 1822], coll. A. Pictet, MHNG GEPI 84607; o3, *Mortoniceras inflatum* [SOWERBY 1818], coll. A. Pictet, MHNG GEPI 84609; o4, *Mortoniceras fallax* [BREISTROFFER 1940], coll. Pictet, MHNG GEPI 19000) from the Vraconne Beds

marly mudstone. In the Central Jura, it is a 0–30 m thick grey clay. The Presta Beds contains a rich phosphatic or pyritized macrofauna mainly dominated by the necton (~26 ammonites taxa, Fig. 8l, Pictet and Roux 1847–1854, Pictet and Campiche 1858–1871, Renz and Jung 1978; sharks).

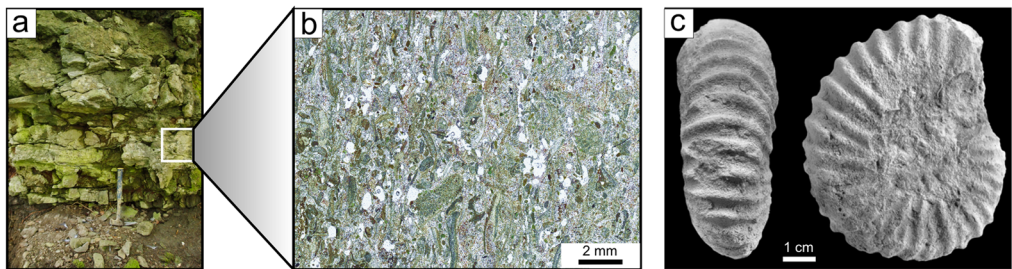
The last subunit, the Vraconne Beds (S11, Figs. 4, 8m–n), is in the Meridional Jura a 0–1.5 m thick dark green to yellow glauconite-rich packstone (Fig. 8n). In the Central Jura, it is a 4–11 m thick green sandstone or blue sandy marl. The Vraconne Beds comprise several phosphatic conglomerates very rich in benthic (echinids, bivalves, gastropods, brachiopods) and nectonic fauna (~180 ammonites taxa, Fig. 8o, Pictet and Roux 1847–1854, Pictet and Campiche 1858–1871, Renz 1968, Renz and Jung 1978; belemnites, turtles, sharks).

5.2.5 Biostratigraphic data and age

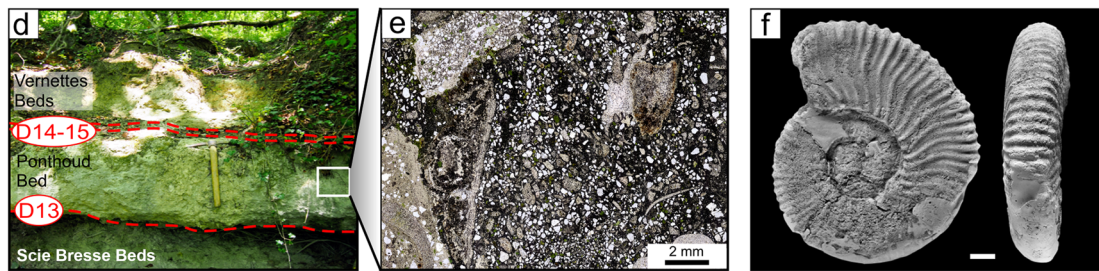
The ammonite fauna continuously dominated by Tethyan families as the Parahoplitids (Fig. 8c, f), therefore the Tethyan biotratigraphic scale (Reboulet et al. 2014) was maintained for the lower half of the Mussel Mb.

Due to the connection between the Paris Basin and the Tethys from the earliest Albian on, important fauna exchanges occurred with a strong incursion of North European communities (Owen 1973; Amédro 1992; Amédro et al. 2014) with the dominance of the Leymeriellidae (Fig. 8i), and the Hoplitidae (Fig. 8i, l, o)

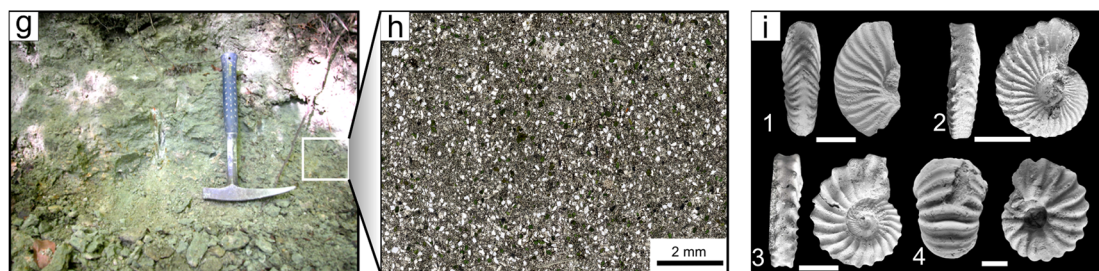
The Scie Besse Beds:



The Ponthoud Bed:



The Vernettes Beds:



The Presta Beds:



The Vraconne Beds:

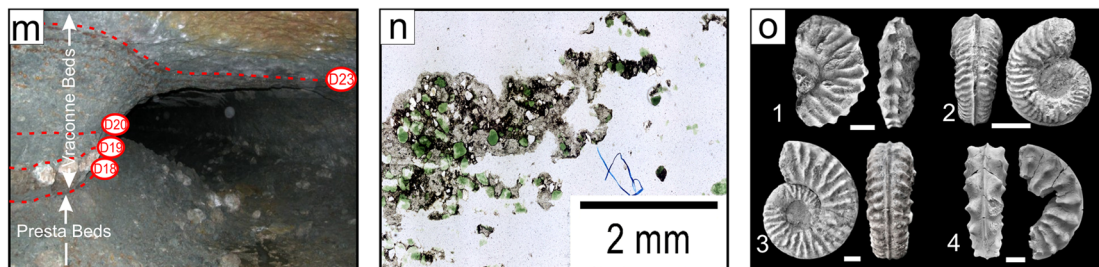
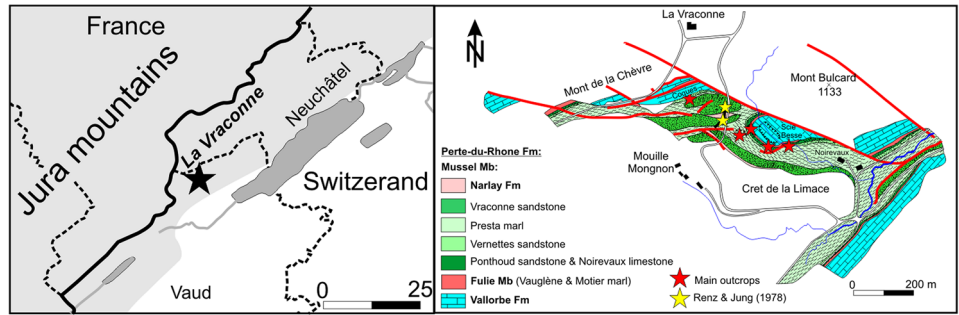
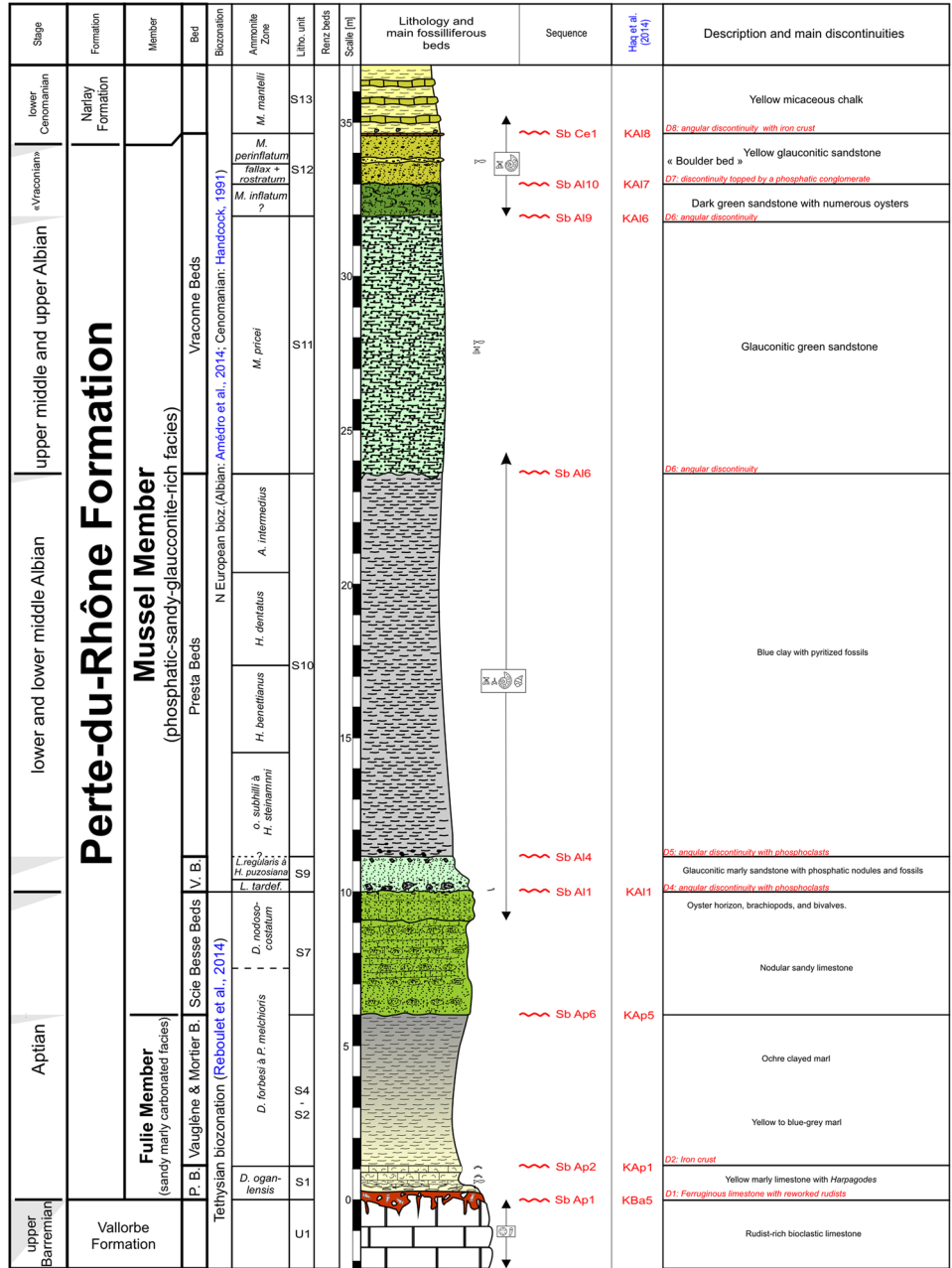


Fig. 9 The La Vraconne section (Vaud, Switzerland) with age, litho- and biostratigraphy on the left side, and the sequence stratigraphic interpretations and description of the log on the right side



La Vraconne



associated to cosmopolitan faunas as Lyelliceratidae and Brancoceratidae (Fig. 8l, o). For this reason, we choose the boreal biostratigraphic scale (Amédéo and Matrimon 2014) for the upper half of the Mussel Mb, also partially adopted by the IUGS Lower Cretaceous Ammonite Working Group (Kilian Group; Reboulet et al. 2011).

The Mussel Mb starts in the middle Late Aptian, *Parahoplites melchioris* Zone (Fig. 8c; Renz and Jung 1978), and ends in the latest Albian, *Mortoniceras perinflatum* or *Praeschloenbachia briacensis* Zone. All the zonal indexes were identified with the exception of *Deshayesites forbesi* CASEY 1961, *Diadochoceras nodosocostatum* (d'ORBIGNY 1841), *Cleonoceras floridum* CASEY 1960, *Hemisonneratia puzosiana* (d'ORBIGNY 1841), *Dimorphoplites niobe* (SPATH 1925) and *Praeschloenbachia briacensis* (SCHOLZ 1973). The *Diadochoceras nodosocostatum* and *Dimorphoplites niobe* Zones were however recognized on the basis of other characteristic taxa such as *Nolanoceras nolani* (SEUNES 1887), and *Euhoplites loricatus* (SPATH 1925).

5.3 Poncin Member

5.3.1 Type locality

The type section is situated near Poncin (Ain, eastern France), to the NW of the Mortaray hamlet, along the departmental road D85 from Mortaray to Challes. An abandoned sand quarry opens on the side of the road (Busnardo et al. 1966; Fig. 10); Coordinates 688,796 m E/5,108,174 m N (system WGS84, projection UTM, zone 31T).

Parastratotype: Perte-du-Rhône: coordinates 719,259 m E/5,109,959 m N (system WGS84, projection UTM, zone 31T) and Fulie amount (Fig. 1b) where a thicker succession can be studied (Renevier 1854, 1855, 1875; Jayet 1925, 1927). But contrarily to the Poncin section, the upper boundary is missing.

5.3.2 Thickness

The Poncin Mb measures between 0 to more than 25 m depending of its position on the former carbonate platforms. The maximum sedimentary record is encountered along the Vuache strike-slip fault (Fig. 6c), in the Perte-du-Rhône section (Fig. 1b).

5.3.3 Definition, lateral variations, palaeontological content and lower boundary

The Poncin Mb is defined in its type section by an orange mica-rich bioclastic sandstone with large quartz grains, alternating with white micritic nodular limestone beds. In

the Bellegarde Basin, the member is dominated by a light green to yellow marly glauconite and mica-rich sandstone, first containing some more indurated beds and above some cherts. This member passes laterally in direction to the Central Jura to the pelagic foraminifera-rich Narlay Fm (Strasser et al. 2016, this issue).

The Poncin Mb is quite fossiliferous (sponges, bivalves, oysters) in the Poncin area and contains a marker bed at its top, which is very fossiliferous, delivering ammonites (Busnardo et al. 1966; Fig. 11c). On the contrary, the Poncin Mb is almost completely devoid of macrofossils in the Bellegarde Basin, and delivered only one ammonite at its base (*Schloenbachia varians*; Fig. 11d).

The member starts on top of the Mussel Mb by the intermediary of a firmground (SbCE1 on Fig. 11b), or above a strongly erosive surface (SbCE1 on Fig. 11a). No subdivisions are defined at the moment.

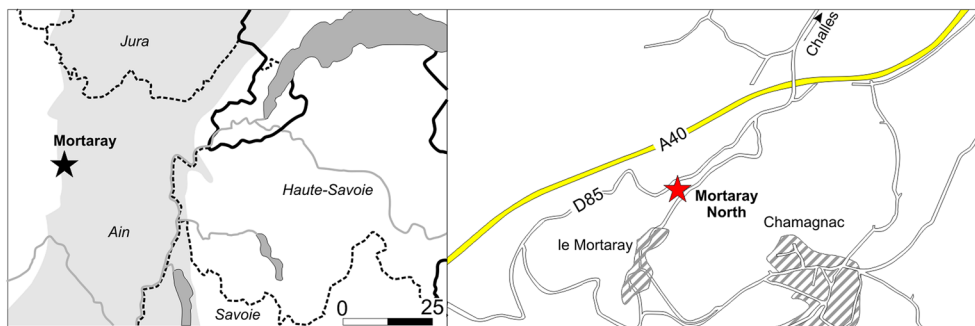
With regard to the geographic distribution and lateral equivalents, the Poncin Mb is only present in the Meridional Jura. It is an equivalent of the Narlay Fm in the Central Jura, of the Seewen Fm *p. p.* in the Helvetic domain; and of the “Craie marneuse de Laubressel” Fm *p.p.* in the Paris Basin.

5.3.4 Biostratigraphic data and age

The macrofauna, especially of the Poncin area is characterized by North European communities with the dominance of the Acanthoceratidae. For this reason, we choose the boreal biostratigraphic scale (Hancock 1991). The Poncin Mb starts in the earliest Cenomanian *Mantelliceras mantelli* Zone, and possibly extends to the Late Cenomanian (Busnardo et al. 1966).

6 Discussion

The Bellegarde Basin, in the French Ain Department provides one of the most complete and differentiated record of the succession of drowning phases which affected the Urgonian carbonate platform and the subsequent sediments composing the PDR Fm. The formation is characterized by phosphate and glauconite-rich sediments which span up to 30 Ma, represented by a maximum thickness of only 40 m. This condensed record documents a phase of profound environmental perturbation that started in the earliest Aptian, and amplified through the PDR Fm. This major disturbance triggered the drowning of the Urgonian platform, followed by the deposit of condensed heterozoan and terrigenous sediments. These sediments are interrupted by ten drowning or flooding events (Linder et al. 2006; Föllmi and Gainon 2008; Masse and Fenerci-Masse 2011; Pictet et al. 2015) of which five of them are considered as major events.



Mortaray North

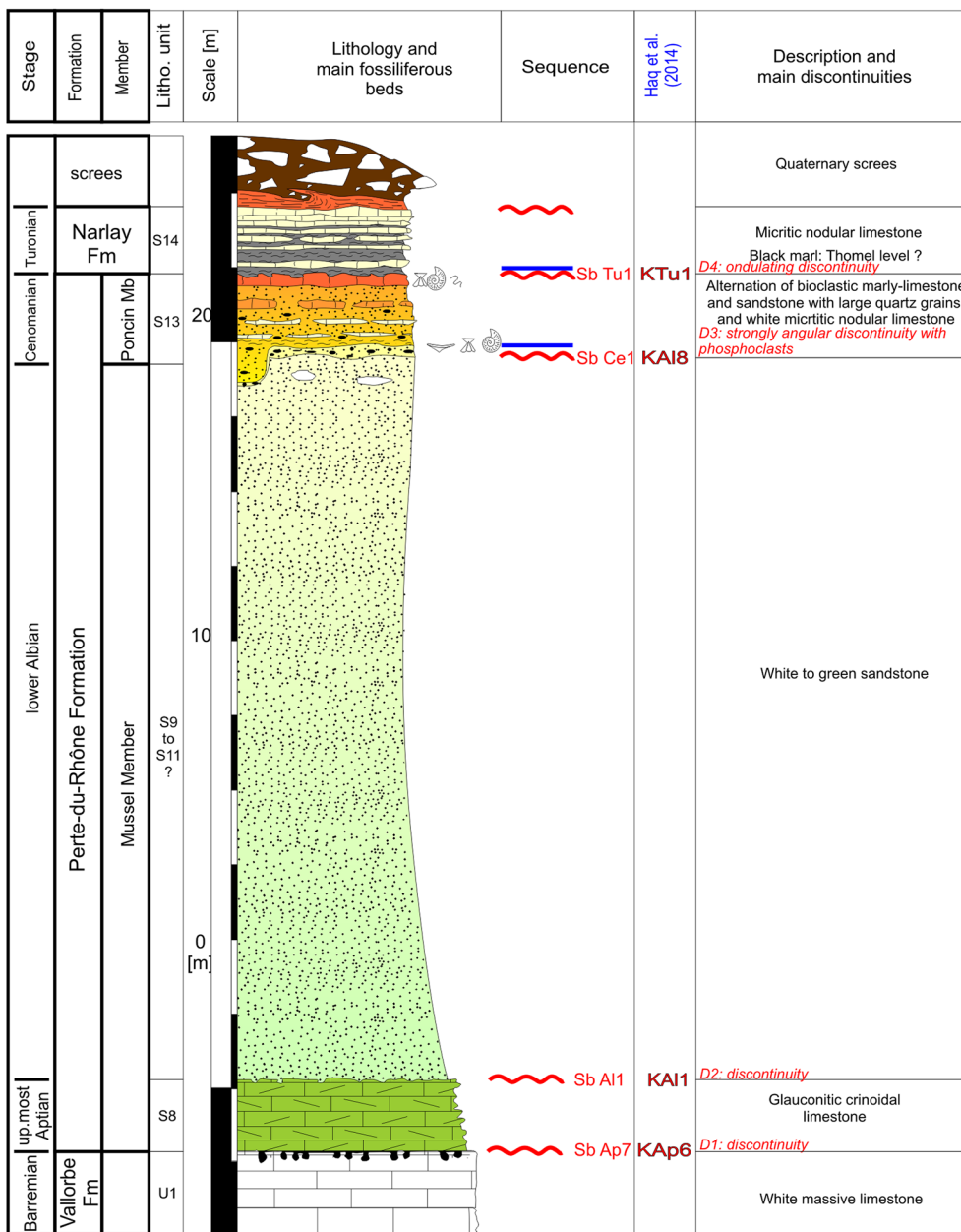


Fig. 10 The Mortaray section North (Ain, France) with age, litho- and biostratigraphy on the *left side*, and the sequence stratigraphic interpretations and description of the log on the *right side*

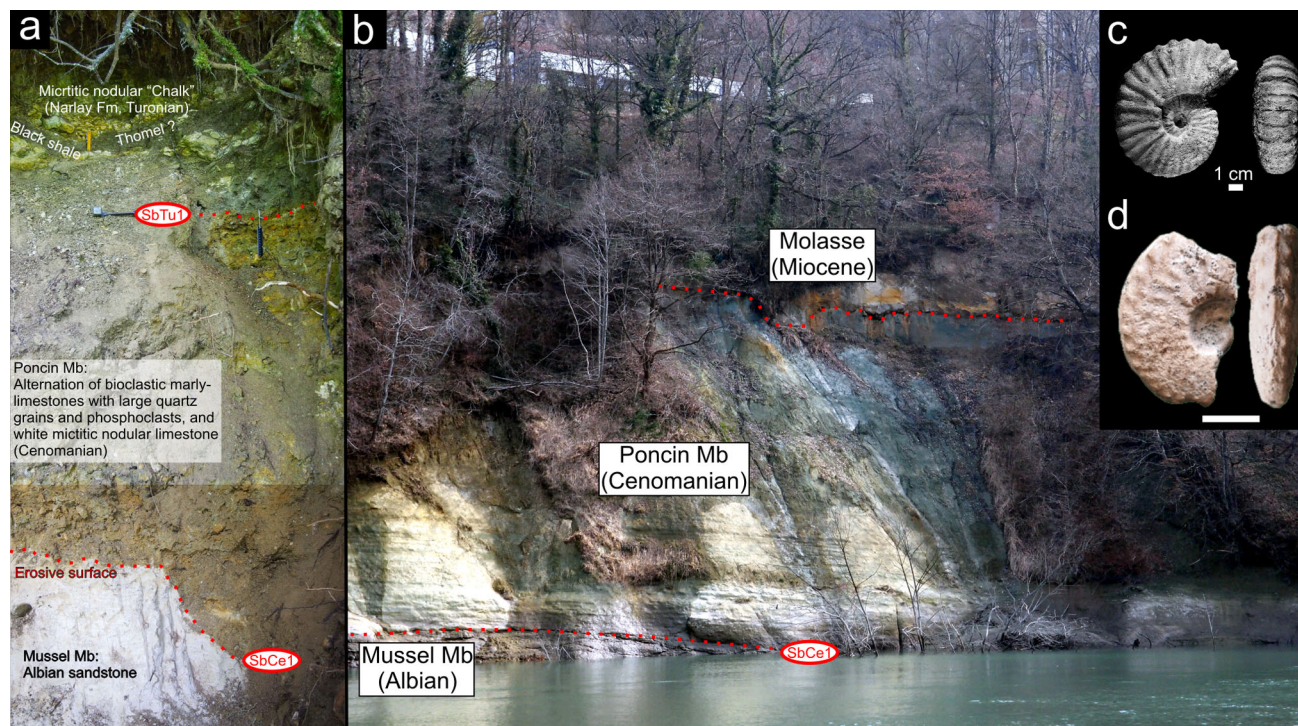


Fig. 11 **a** Iron-rich sandy facies of the Poncin Mb (Cenomanian) in between the Mussel Member (Albian) below and the Narlay Fm (Turonian) above, in the Poncin section (Ain, France). **b** North-eastern view from the left river bank of the glauconite-rich facies of the Poncin Mb (Cenomanian) in between the Mussel Member (Albian) below and the Molasse (Miocene) above, in the Perte-du-

Rhône section (Bellegarde, Ain, France). **c** *Mantelliceras dixonii* SPATH 1926 from the Early Cenomanian Poncin Mb at Poncin (Busnardo et al. 1966). **d** *Schloenbachia varians* (SOWERBY 1817), coll. A. Pictet, MHNG GEPI 84627; of the Early Cenomanian from the Mussel mine

The first event is a drowning phase associated with important karstification, which terminated the photozoan carbonate production on top of the Urgonian platform in the Jura mountains. It is assumed that this first crisis is linked or closely follows the Taxy Episode which occurred in the basin (Masse and Machhour 1998; Föllmi 2012). This drowning, dated at the *Deshayesites oglanlensis* Zone (earliest Aptian), is followed by a phase of carbonate production in a mesotrophic mode (Poet Beds). A second event, associated to a major flooding, initiated the erosion, condensation, and phosphogenesis processes from the middle *Deshayesites forbesi* Zone (late Early Aptian; Föllmi 2008; Masse and Fenerci-Masse 2011). This event is correlated with the global Oceanic Anoxic Event (OAE) 1a (Coccioni et al. 1987; Arthur et al. 1990; Bréhéret 1988, 1997; Weissert 1981; Kemper and Zimmerle 1982; Menegatti et al. 1998; Mutterlose et al. 2009; Heldt et al. 2008). The flooding led to a sedimentation phase dominated by terrigenous sediments as clay, marl, sandstone, and glauconitic sandstone, often with autigenic minerals as glauconite and discrete phosphatic conglomerates (Vauglène, Mortier, and Scie Besse Beds). A second and final phase of carbonate production in a heterozoan mode is documented from the *Diadochoceras nodosocostatum* and

Hypacanthoplites jacobi Zones (Scie Besse and Ponthoud Beds). This carbonate production is suddenly and definitively stopped by a third event, a drowning phase, which is associated with a strong increase of the erosion, condensation, phosphogenesis processes. This drowning is dated from the *Hypacanthoplites jacobi*—*Leymeriella schrammenni* zones (near or around the Aptian-Albian boundary), which is contemporary to the installation of the OAE 1b into the basin (Bréhéret 1994, 1997; Erbacher et al. 1999; Herrle et al. 2004). This major drowning is also associated with two marine connections between the Tethys and the Paris Basin that opened in the earliest Albian allowing important excursions of boreal ammonites into the Tethys. Following this transgression, a phase of condensed pelagic sediments started from this time with the deposition of glauconite-rich sandstone and marl interspersed with numerous condensed phosphatic conglomerates (Vernettes, Presta and Vraconne Beds). In the Central Jura, the PDR Fm ends by a fourth event or flooding, which led to the deposition of the Narlay Fm. This event is contemporaneous to the OAE 1d marking the Albian-Cenomanian boundary (Bréhéret and Delamette 1989; Bréhéret 1997; Scott et al. 2013). In the Meridional Jura, the PDR Fm went on with a mica and glauconite-rich sandstone, which ended

with a large emersion and consecutive drowning event. This discontinuity is associated to OAE 2 (Jarvis et al. 1988; Arthur et al. 1990; Lamolda et al. 1994), and to the deposition of the pelagic Turonian chalk and marl. As a consequence, the upper boundary to the Narlay Fm is diachronous with a Late? Cenomanian age in the Meridional Jura, whereas in the Central Jura it ends at the Albian-Cenomanian boundary.

7 Conclusions

According to the HARMOS project, which tries to harmonise the lithostratigraphic nomenclature in Switzerland, the sediments framed above by the Vallorbe Fm and below by the Narlay Fm are grouped into a new unit, the PDR Fm. The formation gathers heterozoan and terrigenous sediments which are characterized by their rich phosphate and glauconite content.

The PDR Fm comprises three members, from the base to the top: the marly interval of the Fulie Mb, the glauconite-rich sandstones and marls with intercalated condensed phosphatic conglomerates of the Mussel Mb, and the glauconite-rich to iron-rich sandstone of the Poncin Mb.

In the thrust-and-fold Jura belt, the PDR Fm measures up to and more than 40 m thickness. This is especially observed along incised palaeo-valleys, which formed along the main transtensive faults. On the contrary, the formation exhibits an onlap pattern toward and through the Tabular Jura, corresponding to a progressive transgression on the Jura-Burgundy threshold (Fig. 6d). As a consequence, the PDR Fm stratigraphically covers the Vallorbe Fm in the Jura fold-and-thrust belt, then the Pierre Jaune de Neuchâtel in the tabular Jura, and finally the Jurassic rocks of the Burgundy High (Guillaume 1966; Jacquin et al. 1998). The Fulie Mb and the lower part of the Mussel Mb (Aptian) do not extend further than the thrust-and-fold belts, while the upper part of the Mussel Mb and the Poncin Mb (Albian and Cenomanian) largely cross the Jura mountains by two strips, one along the Bresse corridor and another along the Pontarlier—Besançon axis. They correspond to two marine connections between the Tethys and the Paris Basin that opened from the earliest Albian, consequently allowing important excursions of boreal ammonites to the Tethys. The upper boundary to the Narlay Fm is diachronous with a Late? Cenomanian age in the Meridional Jura, aging toward the Central Jura where this boundary takes places at the Albian-Cenomanian boundary.

Thus in the present study, the Perte-du-Rhône area recovers its stratotypic status for the Aptian to Cenomanian sediments of the Jura mountains, and for its glauconitic type facies of the Albian as defined in the 19th century by

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