De Kaenel *et al. Swiss J Palaeontol* (2020) 139:6
https://doi.org/10.1186/s13358-020-00209-5

Swiss Journal of Palaeontology

RESEARCH ARTICLE

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New biostratigraphical data (calcareous nannofossils, ammonites) and Early to Late Barremian transition in the Urgonien Jaune facies and Marnes de la Russille complex of the Swiss Jura Mountains

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Abstract

In the central Jura Mountains (Western Switzerland), the Urgonien Jaune (UJ) facies with the Marnes de la Russille beds (MRu) have provided very rich nannofloras associated with very rare Tethyan ammonites. A late Early Barremian nannoflora of the Mid-Barremian Event (MBE, following a regional tectonic event of an earliest Barremian synsedimentary tectonic crisis) was found in MRu of the lower UJ and includes 42 genera with 90 species. Among them, *Biscutum jurensis* De Kaenel, n. sp., *Flabellites eclepensensis* De Kaenel, n. sp., *Palaeopontosphaera giraudii* De Kaenel, n. sp., *Rhagodiscus buisensis* De Kaenel, n. sp., and *Vagalapilla rutledgei* De Kaenel, n. sp., are recognized as five new species. This nannoflora is a mixture of Boreal and Tethyan taxa with 20 nannofossil markers (*Assipetra terebrodentarius*, *Broinsonia galloisii*, *Calcicalathina oblongata*, *Cyclagelosphaera rotaclypeata*, *Diloma placinum*, *Ethmorhabdus hauterivianus*, *Flabellites eclepensensis*, *Gorkaea pseudoanthophorus*, *Nannoconus abundans*, *Nannoconus pseudoseptentrionalis*, *Palaeopontosphaera giraudii*, *Palaeopontosphaera pinnata*, *Placozygus howei*, *Placozygus reticulatus*, *Reinhardtites scutula*, *Rhagodiscus buisensis*, *Rhagodiscus eboracensis*, *Tegulalithus septentrionalis*, *Tubodiscus jurapelagicus*, *Zeugrhabdotus moulladei*) indicating very precisely the nannofossil Zones LK19 (Boreal)–NC5D (Tethyan) as well as the Elegans (Boreal) and Moutonianum (Tethyan) ammonite Zones of the latest Early Barremian. The ammonites in the basal UJ facies of Early Barremian age are reworked *Lyticoceras claveli* (Nodosoplicatum Zone, Early Hauterivian) and reworked *Cruasiceras* cf. *cruasense* (Sayni Zone, early Late Hauterivian), and *Pseudometahoplites* sp. juv. (Compressissima to Vandenheckii Zones, Early to Late Barremian transition) from the basal MRu. The new palaeontological and sequential results of this study allow a revision of previous data from Godet et al. (2010) precisely assigning a Barremian age to the MRu of the central Jura Mountains (Tethyan Compressissima to lower Sartousiana and Boreal uppermost Fissicostatum to middle Denckmanii ammonite Zones, Boreal LK20B-LK19-LK18 and Tethyan NC5D nannofossil Zones), within the Early to Late Barremian UJ (Tethyan Hugii to lower Sartousiana and Boreal Rarocinctum to middle Denckmanii ammonite Zones, Boreal LK20C to LK18 and Tethyan NC5C-NC5D nannofossil Zones) and below the Late Barremian Urgonien Blanc facies (Tethyan Sartousiana ammonite Zone).

Keywords: Biostratigraphy, Ammonites, Nannofossils, Urgonian facies, Barremian, Jura Mountains, W-Switzerland

Editorial handling: Susanne Feist-Burkhardt & Daniel Marty

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Introduction

The shallow marine deposits of the Urgonian facies of this study (Figs. 1, 2, 3) are historically well known since the middle 19th century in the Swiss Jura Mountains. Marcou (1859, p. 127) evoked the Roches du Mauremont for the Urgonien Jaune facies and Marnes de la Russille complex of the Mormont Hill (cf. Eclépens quarry section). Jaccard (1969, p. 141) gave the first description of the Marne(s) de la Russille [with marl(s) indicated in the singular or plural] within Couches de Bôle (= calcaires intermédiaires de Bôle, De Tribolet 1856, p. 70), also named Urgonien inférieur (Desor and Gressly 1859) or Russillien (Schardt and Dubois 1902). More recently, Strasser et al. (2016) have placed the Urgonien Jaune sensu Remane et al. (1989) in their Gorges de l'Orbe Formation and the topmost Marnes de la Russille intercalation with Urgonien Blanc (UB) carbonates in their Vallorbe Formation.

However, these two formations remained poorly defined and poorly dated and are in need to be revised in detail. Furthermore, the new nomenclature of Strasser et al. (2016) is hardly applicable to the peculiar section of Eclépens. For these reasons, a more sedimentological, facies-based approach was chosen, using as terminology the Urgonien Jaune (UJ) facies for shallow marine and tidal yellowish bioclastic limestones, and the Marne(s) de la Russille (MRu) facies for the marly intercalations. We consider the Couches de Bôle (Merdasson section *in* Cotteau 1862–1867, p. 107–108) as Barremian strata between "Neocomian" and Aptian, as they were already well known to be particularly fossiliferous with, among many other marine invertebrates, common stromatopororoids and Alcyonarian corals (Fig. 1j, Octocorallia mainly characterized by a profusion of typical calcitic sclerites in the sediments), some colonial corals (Hexacorallia), rudists forming local reefs (*Pachytraga tubiconcha* Astre 1961, Remane et al. 1989, Blanc-Alétru 1995), echinoids [*Goniopygus peltatus* (L. Agassiz 1838), *Pseudocidaris clunifera* (L. Agassiz 1840), *Cidaris lardyi* Desor 1855, *Astrolampas productus* (L. Agassiz 1836), *Heteraster couloni* (L. Agassiz 1839)] and brachiopods [*Glosseudesia ebrodunensis* (de Loriol 1864), including *Rhynchonella lata* d'Orbigny 1847, *Sulcirynchia gillieroni* (Pictet 1872), *Sulcirynchia picteti* (Burri 1956), *Sulcirynchia renauxiana* (d'Orbigny 1847), *Lepidorynchia dichotoma* Burri 1956, *Loriolithyris* and *Sellithyris* spp.]. The Urgonien Blanc (UB) facies is used for the topmost, rudist-rich, whitish limestones characterized by rudists such as *Requienia ammonia* (Goldfuss 1838) and *Agriopleura* spp. and interpreted as lagoonal deposits.

Detailed studies and descriptions of the Urgonian platform series in the Swiss Jura Mountains are given by Remane et al. (1989) and Blanc-Alétru (1995), but their Hauterivian or Barremian age has remained uncertain and controversial until now. A Late Hauterivian age was assigned to the Gorges de l'Orbe Formation and a Late Hauterivian to Early Barremian age to the Vallorbe Formation with the topmost MRu layers, based on orbitolinid biostratigraphy and sequence stratigraphy (Clavel et al. 2007, 2013, 2014; Charollais et al. 2008, 2013; Conrad et al. 2012; Granier et al. 2014; Strasser et al. 2016). But, for other authors with a quite different interpretation of the orbitolinid biostratigraphy and sequence stratigraphy, both formations are mainly considered as Late Barremian according to sequence stratigraphy, biostratigraphy of orbitolinids, nannofossils and K–Ar isotopes (Arnaud-Vanneau and Arnaud 1990; Blanc-Alétru 1995; Arnaud et al. 1998; Adatte et al. 2005; Godet et al. 2010, 2011, 2012, 2013). Our new biostratigraphical data mainly based on nannofossils and ammonites allow to solve this age discrepancy. The aim of this study is to close more than 30 years of controversy about the age of the Urgonian facies in the Swiss Jura Mountains.

Geological settings

The Eclépens quarry section across the Mormont Hill (coord. 2531.250/1167.180, map 1:25′000 of Switzerland) is well known since the studies of Blanc-Alétru (1995) and Godet et al. (2010) with an unusually thick Urgonien Jaune–Marne de la Russille complex of 47 m (Figs. 2, 3). The section is dated with the standard Tethyan ammonite biozonation of Reboulet et al. (2018) and begins with dark grey Early Hauterivian marls corresponding to the top of the Marnes bleues d'Hauterive (Radiatus Zone) overlain by marly and calcareous beds (Mergelkalk Zone *in* Godet et al. 2010, p. 1091, fig. 2) attributed to the Loryi Zone in the Neuchâtel area (Remane et al. 1989; Mojon et al. 2013). These layers constitute a transitional facies preceding the oolithic yellowish Pierre jaune de Neuchâtel (PJN) well developed above, with in its middle part (between lower and upper PJN) the thin marly and glauconite-rich layer of the Marnes d'Uttins having provided in Eclépens and in the Swiss Jura Mountains some ammonites of the Nodosoplicatum Zone (Remane et al. 1989; Godet et al. 2010; Mojon et al. 2013) such as *Lyticoceras claveli* Busnardo and Thieuloy 1989, *Lyticoceras subhystricoides* (Kilian and Reboul 1915) and *Saynella clypeiformis* (d'Orbigny 1841). These Hauterivian deposits were recently formalized within the Grand-Essert Formation (Strasser et al. 2016), subdivided into Hauterive Member for the basal marly complex and Neuchâtel Member for the PJN complex (Strasser et al. 2018). The basal part of the UJ facies with very rare reworked Hauterivian ammonites (*L. claveli* and *Cruasiceras* cf. *cruasense* (Torcapel 1884) of the late Early Hauterivian Nododosoplicatum ammonite Zone and early Late Hauterivian Sayni ammonite Zone, respectively, cf. Reboulet et al. 2018; this study, Fig. 4.1–5)

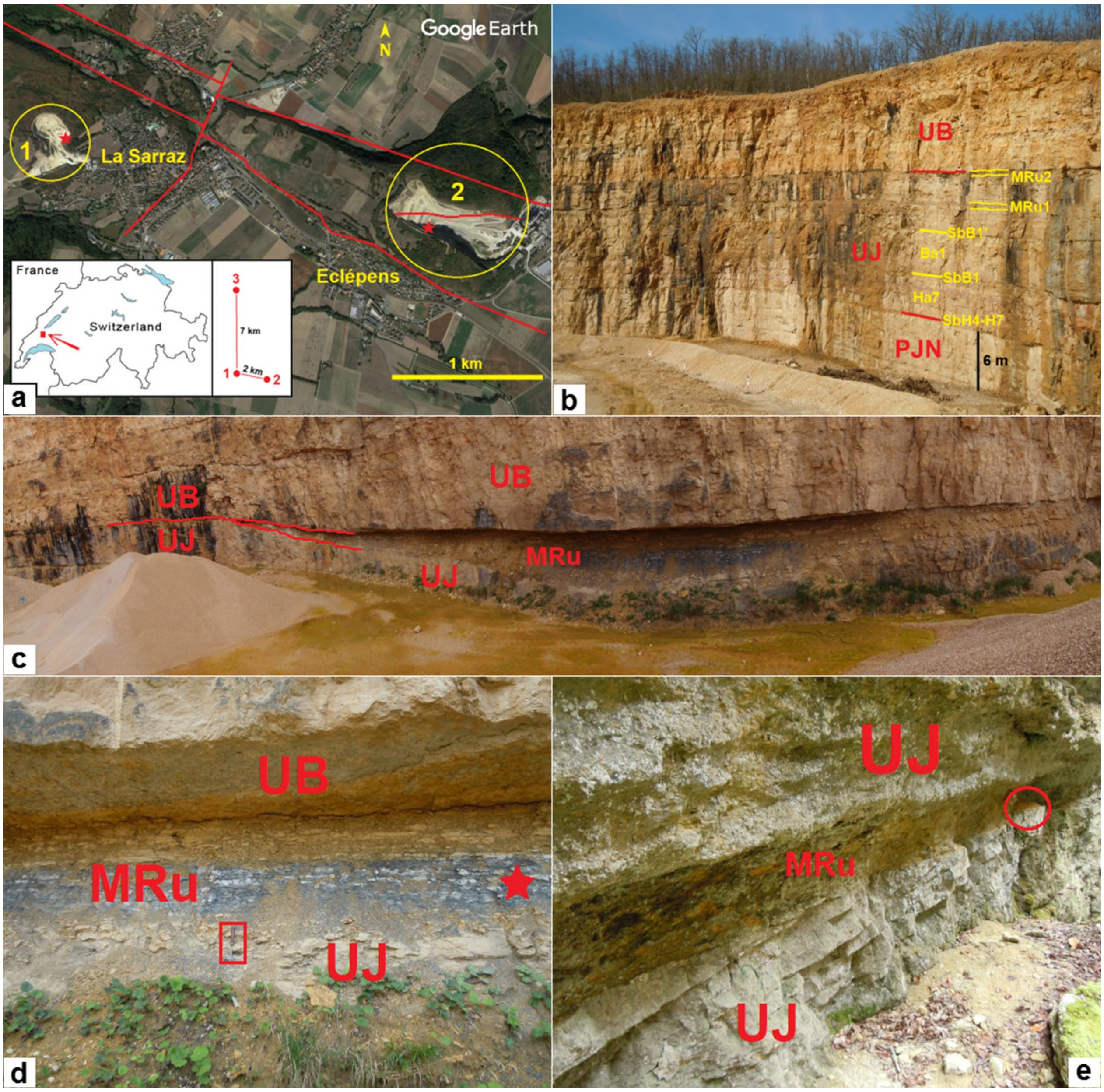


Fig. 1 **a** Location maps with aerial view (Google Earth, Copernicus Sentinel data 2018 / NPOC) in the Vaud Jura Mountains (W-Switzerland), red square indicated by red arrow = study area, yellow circle 1/red spot 1 = Les Buis quarry near La Sarraz, yellow circle 2/red spot 2 = Eclépens quarry of the Mormont Hill, red spot 3 = Montcherand section in the Gorges de l'Orbe, red stars = studied sections, network of red lines = the Mormont—La Sarraz fault system reported from the geological map of Switzerland 1:25′000. **b** La Sarraz–Les Buis quarry (8/3/2020), northern part of the quarry, UB = Urgonien Blanc, MRu1-2 = Marnes de la Russille (layers 1 and 2), UJ = Urgonien Jaune, PJN = Pierre jaune de Neuchâtel, Ha7-Ba1 = basal Early Barremian sequences with sequence boundaries SbH4-H7, SbB1 and SbB1′ (cf. Fig. 3). **c**, **d** La Sarraz–Les Buis quarry, southern part of the quarry, channelized and very fine-grained Marnes de la Russille (**c**: 7/6/2014; **d**: 17/8/2014, hammer in red frame = 31.5 cm long, red star = late Early Barremian LSBMRu1 sample with nannoflora of NC5D/LK19 biozones reported in this study). **e** Upper part of the Montcherand section along the Orbe river (23/11/2014), truncated and bevelled layer of basal shallow marine Marnes de la Russille above transgressive inclined foresets of large ripples, red circle diameter = 31.5 cm (small ammonite *Pseudometahoplites* sp. juv. was found in the mound of yellow marls on top inside). Captions: UB = Urgonien Blanc, MRu = Marnes de la Russille, UJ = Urgonien Jaune. **f**–**g** La Sarraz–Les Buis quarry (8/3/2020), northern part of the quarry and detail of Fig. 1b, h (right parts), TST = Transgressive system track with reddish ripples of the sequence Ha7, HST = Highstand system tracks marked by two thick whitish coarse beds forming the top of sequences Ha7 and Ba1, respectively, Ba1′-Ba2-Ba3 = late Early-to-early Late Barremian sequences with sequence boundaries SbB1′, SbB2 and SbB3 (cf. Fig. 3). **h**–**i** La Sarraz–Les Buis quarry (23/2/2020), northern part of the quarry (**h**) and detail of NW cliff (red square, **i**) with transverse cross sections of two small proximal MRu1-2 channels (yellow ellipses) forming the distal larger channel (Figs. 1c, d and 3) about 20 m below and 250 m laterally at the base of the opposite SE cliff. **j** Rare and well-preserved Alcyonarian corals from the uppermost massive UJ limestones (early Late Barremian) of the Eclépens quarry

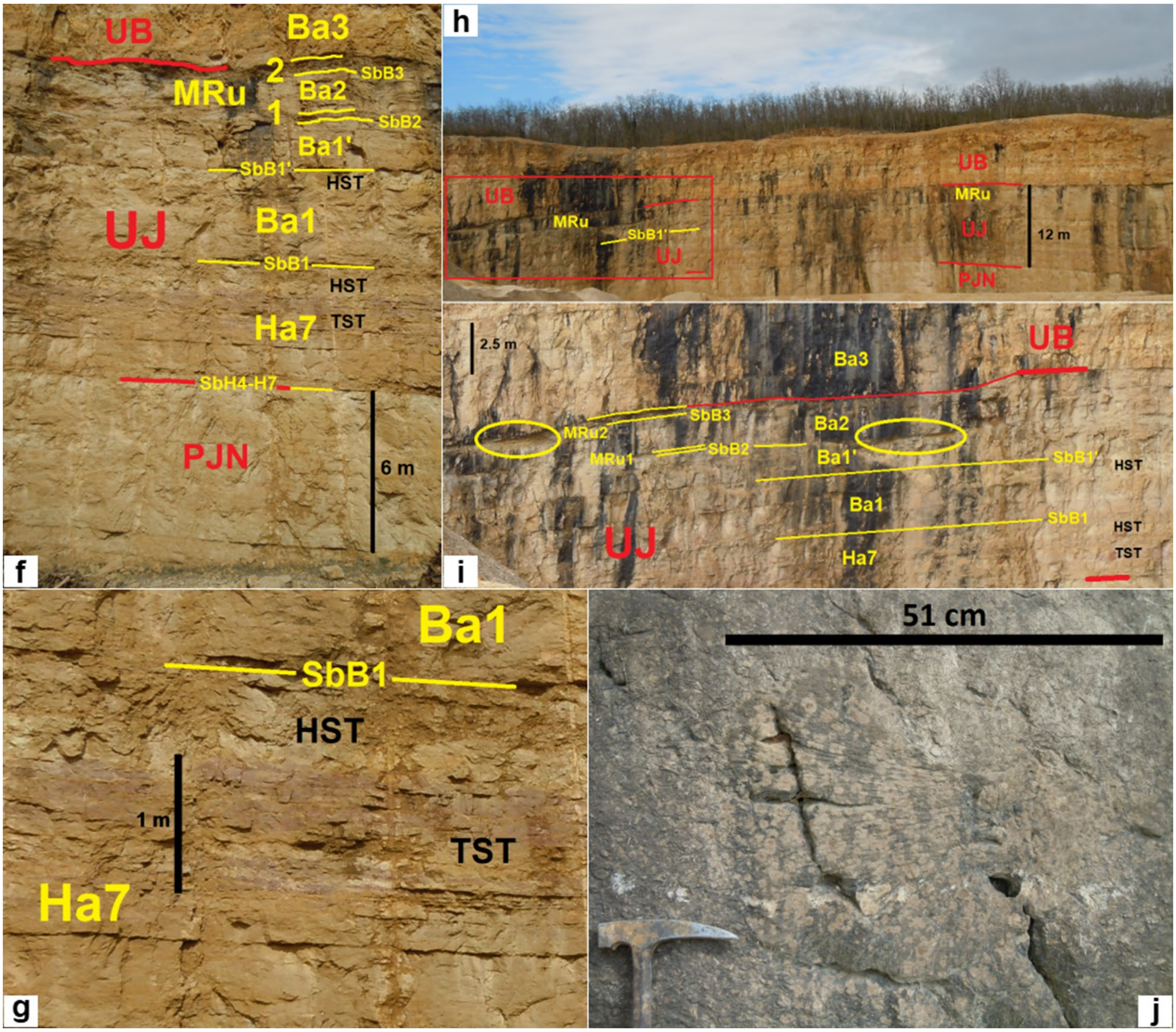


Fig. 1 continued

is constituted by a very thin yellow marly layer overlaid by two massive beds of yellowish bioclastic glauconite-bearing limestones. Small basal, erosive channels with glauconitic and phosphatized/silicified quartz-sand-rich infillings are also well visible locally (Godet et al. 2010, p. 1095–1097, fig. 7D, E, F). More abundant greyish and yellowish/reddish Marnes de la Russille (MRu) intercalations are usually recognized on top of the UJ–MRu complex in the Eclépens section, but the UJ limestones alternate also with several other dark grey marly layers (yellow by alteration) containing early Late Barremian nannofloras attributed to the Sartousiana ammonite Zone incl. the Feraudianus Subzone on its top (De Kaenel *in* Godet 2006 and Godet et al. 2010). Frequent stromatoporoids characterize a large part of the UJ limestones and the dark marls of the Eclépens section which commonly correspond to the classical feature and definition of the MRu with well-developed stromatoporoid bioconstructions in the Swiss Jura Mountains (Remane et al. 1989; Blanc-Alétru 1995). The benthic foraminifera from the UJ and UB facies of the Eclépens quarry section notably include *Neotrocholina friburgensis* Guillaume and Reichel 1957, *Choffatella decipiens* Schlumberger 1905 and orbitolinids (*Praedictyorbitolina*, *Paracoskinolina*, *Valserina* and *Paleodictyoconus* spp.) associated with some Dasycladalean algae (cf. Montcherand section below), all attributed to the Late Hauterivian–Early/Late Barremian by Blanc-Alétru (1995) or to the Late Hauterivian only by

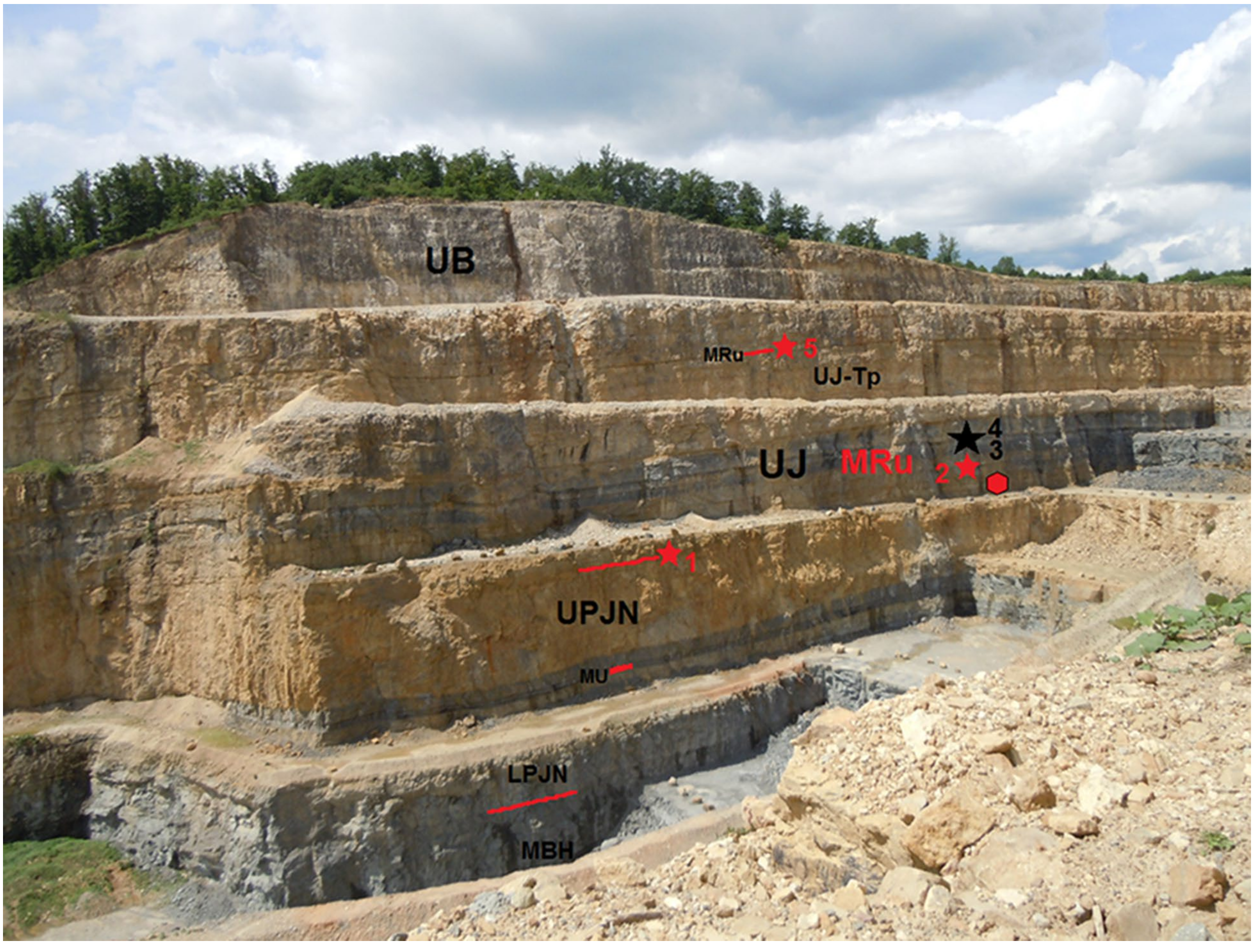


Fig. 2 Western part of the Eclépens quarry (17/6/2018). Captions: UB = Urgonien Blanc, MRu = Marnes de la Russille, UJ-Tp = Urgonien Jaune top part, UJ = Urgonien Jaune, UPJN = Upper Pierre jaune de Neuchâtel, MU = Marnes d'Uttins (late Early Hauterivian Nodosoplicatum Zone), LPJN = Lower Pierre jaune de Neuchâtel, MBH = Marnes bleues d'Hauterive (Early Hauterivian Radiatus Zone), black star = marly beds with early Late Barremian nannofloras reported from Godet et al. (2010), red hexagon = basal limestones with glauconite and early Late Hauterivian ammonite *Cruasiceras* cf. *cruasense*, red stars = marls with new Early Barremian (1–2) and early Late Barremian (3–5) nannofloras

Clavel et al. (2007, 2014). Godet et al. (2010) identified in the Urgonian facies of Eclépens two sequence boundaries (SbE2, SbE3) and two maximum flooding surfaces (mfsE2, mfsE3), whereas SbE3 and mfsE3 are correlated with the late Barremian sequence Ba3 defined by Arnaud (2005) in his reference sections of SE-France.

The section of the La Sarraz–Les Buis quarry (Fig. 1 b–d, f–i; coord. 2528.240/1168.170, map 1:25′000 of Switzerland) is thinner than in the Eclépens quarry, both sections being separated by the Mormont–La Sarraz fault system in the extension of the Pontarlier fault system (Fig. 1a; Sommaruga et al. 2012, p. 54; Schmitt et al. 2016). The La Sarraz–Les Buis quarry section starts with 8 m of yellowish massive PJN facies which end with a major discontinuity forming a well-developed hardground bioperforated and incrusted by very large, flat oysters. The overlying UJ–MRu complex has a thickness of only 12 m and is subdivided in three main parts separated by sedimentary discontinuities or sequence boundaries (Fig. 1b, h). The lower part of the UJ limestones with two massive beds overlay the PJN facies. These lower UJ beds are mainly yellowish, roughly bioclastic and oolithic limestones. Some thinner layers are whitish and around 1 m of reddish tabular cross-bedding can be observed in the middle part of the first basal massive UJ bed above the PJN carbonates (Fig. 1f, g). The glauconite-rich layers observed in the basal UJ of the Eclépens quarry are absent. The upper yellowish UJ limestones (5–7 m) include two marly bioclastic and quartz-rich levels MRu1 and MRu2. Locally, very fine-grained siliciclastic marls from the layers MRu1 and MRu2 constitute marly infillings in metric to decametric erosive

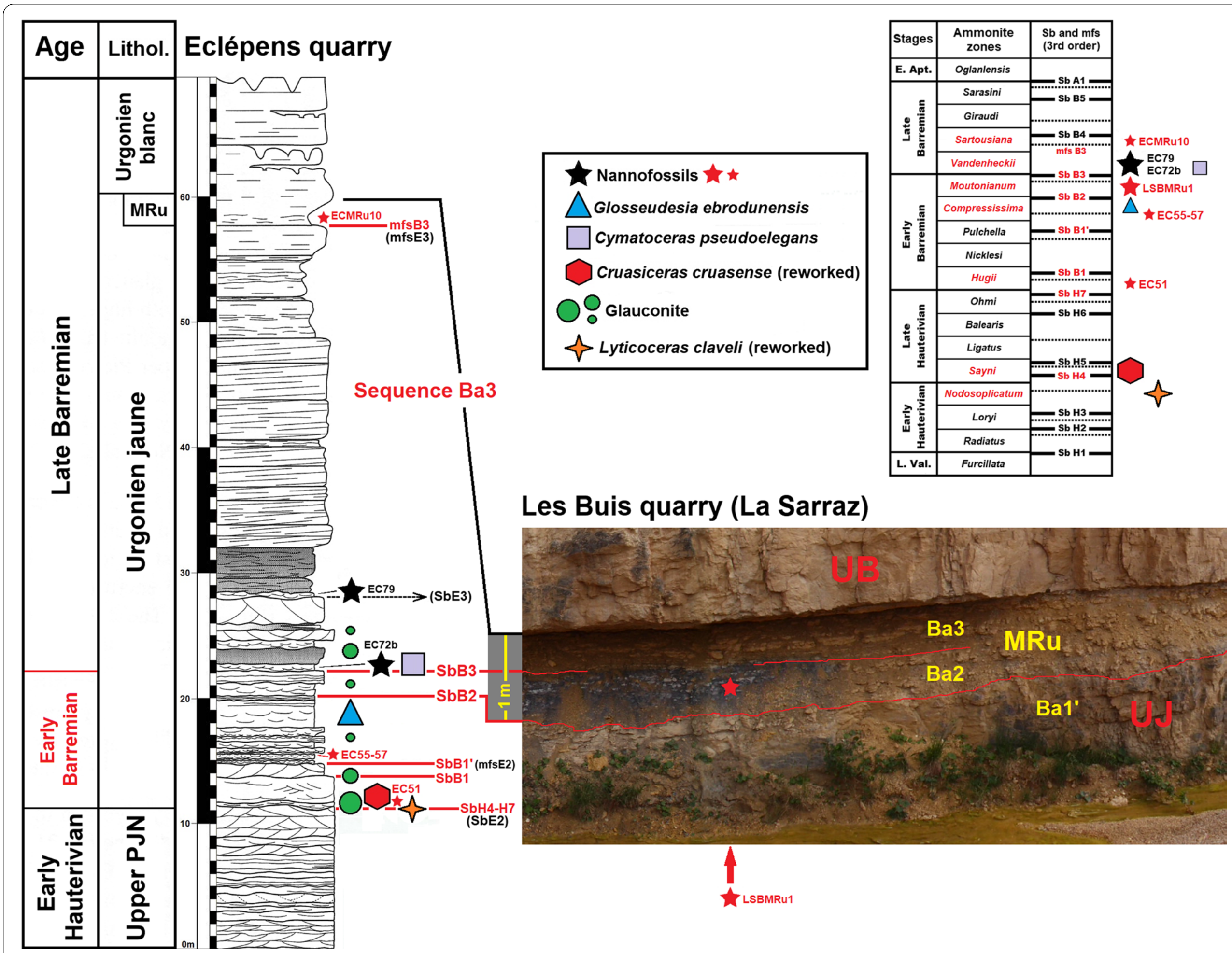


Fig. 3 Part of the Eclépens quarry section log (non-coloured reference log and data reported from Blanc-Alétru 1995; Godet et al. 2010 Adatte et al. 2005, 2015) with new biostratigraphical and sequential data of this study indicated by coloured elements (cf. Fig. 2), compared to the section of La Sarraz–Les Buis quarry (cf. Fig. 1c) with early Late Hauterivian–early Late Barremian 3rd order sequences Ha4 to Ba3 (delimited in red) and new late Early Barremian nannoflora of the Tethyan NC5D and Boreal LK19 biozones reported in this study (LSBMRu1 sample = red star). Captions: UB = Urgonien Blanc, MRu = Marnes de la Russille, UJ = Urgonien Jaune. The table (upside right) with latest Valanginian to Early Aptian Tethyan ammonite biozones and 3rd sequences is adapted/modified from Arnaud (2005) according to Reboulet et al. (2018)

channels analysed in this study (Fig. 1c-d, h-i and Fig. 3). Other overlapping channel structures with truncated oblique strata can be observed in the upper bioclastic UJ and basal UB limestones. The upper part of the section, represented by 15 m of massive whitish UB facies, provided orbitolinids (*Praedictyobitolina*, *Valserina* and *Paleodictyoconus* spp.) and Dasycladalean algae (*Salpingoporella genevensis* Conrad 1969 ex Conrad, Praturlon and Radoičić 1973), which would indicate a Late Hauterivian age according to Clavel et al. (2007, 2014).

The Montcherand section (Gorges de l'Orbe, 7 km north of La Sarraz) described by Blanc-Alétru (1995) is characterized by a thick marly MRu series (20 m) and UB carbonates (50 m) with Late Hauterivian–Early/Late Barremian microfossils like benthic foraminifera (*Choffatella decipiens* Schlumberger 1905, orbitolinids: *Praedictyorbitolina*, *Paracoskinolina* and *Valserina* spp.) and Dasycladalean algae [*Dissocladella hauteriviana* Masse 1999, *Actinoporella fragilis* (Conrad 1970) Granier 1994, *Angioporella neocomiensis* Conrad and Masse 1989]. The particular interest of this section is the channelized base of the MRu (Fig. 1e) characterized by a tiny Mid-Barremian ammonite *Pseudometahoplites* sp. juv. found in 2014 and presented in this study for the first time (cf. Results, Fig. 4.6–18).

Materials and methods

During this study lasting from 2014 to 2019, three very rare ammonites were collected, 2 fragments from the basal marly layer and surrounding glauconitic limestone of the Urgonien Jaune (UJ) in the Eclépens quarry, and a juvenile specimen collected with microfossils from the basal Marnes de la Russille (MRu, sample OM4) in the Montcherand section. Micropalaeontological material was isolated in the laboratory from marls (MRu) of the Eclépens quarry (3 samples EC72b, EC79, ECMRu10), La Sarraz–Les Buis quarry (10 samples LSBMRu 0 to 9) and Montcherand section (1 sample OM4). These samples each of about 1–5 kg dry weight were wet-sieved with mesh width ranging from 250 µm to 2 mm and picked using a binocular loupe. 16 samples with nannofossils from the sections of Eclépens (6 samples EC51, EC55, EC57, EC72b, EC79, ECMRu10) and La Sarraz–Les Buis (10 samples LSBMRu 0 to 9) were prepared on glass slides (Figs. 5, 6) according to the improved method described by De Kaenel and Villa (1996) and studied using a Leica DM2500P light microscope. Photographs and micrographs of the palaeontological material were obtained using natural light, CLSM "confocal laser scanning microscopy" and optical microscopy with artificial light (cross-polarized/XP light and phase-contrast light for nannofossils using an Olympus DP71 digital camera) or scanning electron microscopy (SEM). Light micrographs (LM) are included in Figs. 7, 8, 9, 10, 11. The reference material for the nannofossils is conserved in the collection of E. De Kaenel, reference samples of sediments for the nannofossils (Figs. 12, 13) as well as the ammonites are deposited in the collection of the Musée géologique de Lausanne (abbr. MGL, UNIL-Dorigny, Lausanne).

Results

The UJ facies of the studied sections have provided ammonites and nannofossils presented in detail hereafter and in Fig. 3, with other miscellaneous micro- and macro-fossils, and particular sedimentological features.

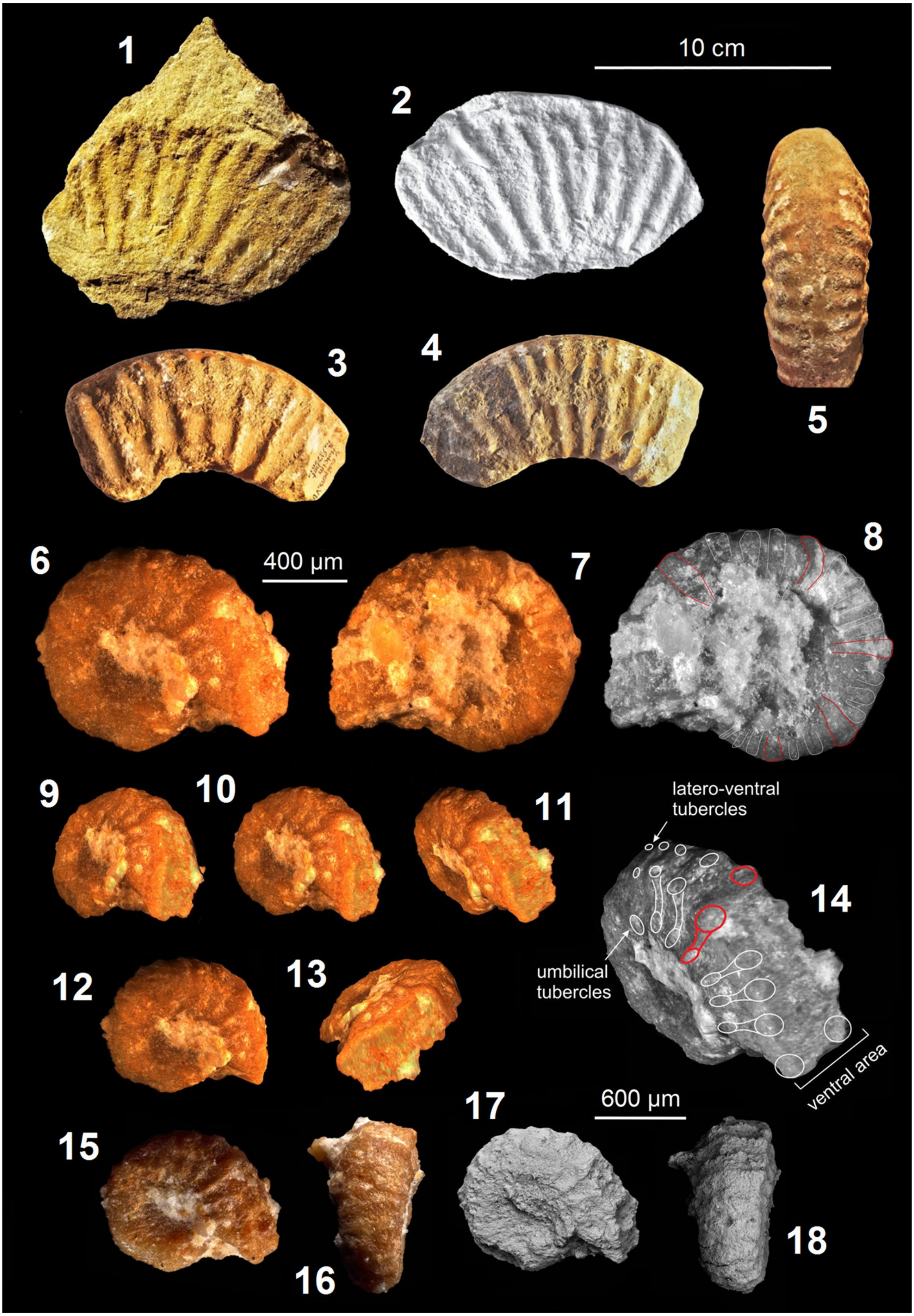
Ostracods, benthic foraminifera, other micro- & macro-fossils and minerals of varying significance

In the sections of La Sarraz–Les Buis quarry and Montcherand (Gorges de l'Orbe), typical Barremian ostracods (according to Babinot and Colin 2011) were collected in the MRu: *Rehacythereis* gr. *geometrica* Damotte and Grosdidier 1963, *Neocythere (Centrocythere) gottisi* Damotte and Grosdidier 1963, *Cytherelloidea ghabounensis* Bischoff 1964, *Trochinius consuetus* Kuznetsova 1961 (rare taxon from La Sarraz–Les Buis and Eclépens sections), *Paracypris levis* Kuznetsova 1961, and *Schuleridea*, *Bairdoppilata* (very large and smaller specimens), *Asciocythere*, *Cytherella* spp. In these two sections, benthic foraminifera such as *Neotrocholina friburgensis* Guillaume and Reichel 1957, *Choffatella decipiens* Schlumberger 1905, big *Reophax* sp. and Nodosariids are also present as well as very frequent sclerites of Alcyonarian corals. The very fine-grained siliciclastic and nannofossil-rich marls constituting the Marnes de la Russille (MRu) at La Sarraz–Les Buis quarry also have provided heavy minerals: grains of red garnet reworked/transported from distant northern crystalline massives and abundant pyrite with frequent large diagenetic framboids (about 200–250 µm) indicating organic-rich sediments (Wilkin et al. 1996; Gallego-Torres et al. 2015), well-preserved in the lower dark grey part of the channelized marly infilling.

From the Eclépens quarry section, EC72b-79 samples have yielded a rare and poorly preserved microfauna with ostracods [*Protocythere triplicata* (Roemer 1841), *Strigosocythere strigosa* Grosdidier 1964, *R.* gr. *geometrica*, *N. (C.) gottisi*, *C. ghabounensis*, *T. consuetus*, *P. levis*, and *Schuleridea*, *Bairdoppilata*, *Asciocythere*, *Cytherella* spp.] and benthic foraminifera (*C. decipiens*, *N. friburgensis*, big *Reophax* sp.). Grey marly layers and yellowish limestones below EC72b are further characterized by large brachiopods as *Glosseudesia ebrodunensis* (de Loriol 1864) of biostratigraphical interest (Gaspard 1989, Lobacheva 1990, Middlemiss 1981, 1983, Middlemiss in Remane et al. 1989), big rounded stromatoporoids and nautilids as *Cymatoceras pseudoelegans* (d'Orbigny 1840). ECMRu10 sample with siliciclastic rubefied marls (Fig. 14c, d) provided microfossils such as mainly very recrystallized marine benthic foraminifera (orbitolinids, *C. decipiens*, *N. friburgensis*, *Cuneolina hensoni* Dalbiez 1958, big *Reophax* sp.), rare ostracods (*Strigosocythere* cf. *chalilovi* Kuznetsova 1961, *N. (C.) gottisi*, large *Bairdoppilata* sp.) and sclerites of Alcyonarian corals. Rubefied marls indicate a subsequent emersion trend with terrestrial input/alteration before the deposits of the prograding lagoonal UB facies upon a horizontal bedding-surface and almost isochronous surface like in La Sarraz–Les Buis only 2 km to the Northwest.

Ammonites

The few ammonites collected during this study in the Urgonien Jaune (UJ) facies of the Swiss Jura Mountains (Fig. 4) are of Tethyan affinity according to the biostratigraphical references for the ammonite biozonation (Vermeulen and Thieuloy 1999; Vermeulen 2007; Reboulet et al. 2009, 2014, 2018). Two ammonites (Fig. 4.1–5) were collected in 2014–2015 by workmen of the Eclépens quarry at the base of the UJ, a little above the upper Pierre jaune de Neuchâtel (UPJN). A fragment


1
2
3
4
5
10 cm
6
7
8
400 µm
9
10
11
12
13
14
latero-ventral
tubercles
umbilical
tubercles
ventral area
15
16
17
18
600 µm

(See figure on previous page.)
Fig. 4 Ammonites from the Urgonien Jaune (UJ) of the Vaud Jura Mountains. **1**–**2**: *Cruasiceras* cf. *cruasense* (Torcapel 1884), reworked, original negative imprint (1) and positive plaster mould (2) of an adult whorl portion, Eclépens quarry, basal UJ, early Late Hauterivian (Sayni Zone), MGL 101510. **3**–**5**: *Lyticoceras claveli* (Busnardo and Thieuloy 1989), reworked fragment in opposite lateral views (3–4) and ventral view (5), Eclépens quarry, basal UJ, late Early Hauterivian (Nodosoplicatum Zone), MGL 97797. **6**–**18**: *Pseudometahoplites* sp. juv., internal mould of a nucleus, Montcherand section (Gorges de l'Orbe), basal Marnes de la Russille, Mid-Barremian Compressissima/Moutonianum to Vandenheckii Zones, MGL 101512, imagery by CLSM "confocal laser scanning microscopy" (6–14), optical microscopy (15–16) and SEM "scanning electron microscopy" (17–18) with lateral views (opposite sides: 6, 7–8, 15, 17), ventral views (11, 13–14, 16, 18) and variable views by 3D image rotation (9–13), ornamentation schemes (8, 14) with tubercles and ribs marked in red for primary ribs or in white for secondary ribs

of *Lyticoceras claveli* Busnardo and Thieuloy 1989 (*in* Remane et al. 1989) from the Early Hauterivian Nodosoplicatum Zone was firstly collected in a thin marly layer just below the bioclastic UJ limestones and is clearly reworked from the underlying UPJN according to the oolithic grainstone infilling of the shell. Later, a negative imprint of *Cruasiceras* cf. *cruasense* (Torcapel 1884) from the early Late Hauterivian Sayni Zone was found in the basal yellow massive and glauconite-rich UJ limestones. These two Hauterivian ammonite species have a very close morphology (Thieuloy et al. 1983). *Lyticoceras claveli* exhibits large-sized evolute shells, a subrectangular section a little higher than wide with a wide slightly rounded and relatively smooth venter, broad radial and rounded ribs firstly alternating with short intermediate ribs then regularly bifurcated from mid-flanks. *Cruasiceras cruasense* is characterized by generally larger-sized specimens with distinctly evolute shells, a subrectangular section clearly higher than wide and with a narrow well-rounded venter area crossed by ribs. The ornamentation is typical with slightly prorsiradiate and flexuous ribs bifurcated in the upper third of the flanks. In November 2014, a very small specimen (nucleus) assigned to *Pseudometahoplites* sp. juv. (Compressissima to Vandenheckii Zones, Early to Late Barremian transition, Vermeulen 2007) was collected in the first lowermost layer of the Marnes de la Russille in the Montcherand section within the Gorges de l'Orbe (Figs. 1e, 4.1–18). This tiny ammonite was found fortuitously by searching for ostracod microfossils in a marly sample from the layer OM4 of the section described by Blanc-Alétru (1995, fig. 67, p. 159), in an outcrop along the Orbe river (coordinates 2528.790/1175.510, map 1:25′000 of Switzerland). It is a juvenile specimen with a very small (< 1 mm) embryonic conch and the first stages of ornamentation typical of the Holcodiscidae (D. Bert, pers. comm. 2015). The genus *Pseudometahoplites* is characterized by specimens of small size. The shell is evolute with thick whorls characterized by a sub-trapezoidal section as high than wide, and with a flat venter. The ornamentation is strong with radial to prorsiradiate ribs bearing pinched umbilical bullae and massive rounded latero-ventral tubercles linked on the venter by a rib (Vermeulen 2007).

Calcareous nannofossils

The results below concentrate on sample LSBMRu1, which was the key sample to date the Marnes de la Russille. After dating this sample (Figs. 5, 6), additional samples were collected in the La Sarraz–Les Buis quarry and the detailed list of species observed in these samples is presented in Fig. 12. Moreover, previous samples EC72b and EC79 from Godet et al. (2010) were re-analysed with unpublished samples EC51, EC55 and EC57 from the base of the Urgonien Jaune (UJ) facies collected by E. De Kaenel with A. Godet and K. Föllmi at Eclépens in 2005. These new results are presented in Fig. 13.

Calcareous nannofossil abundance and preservation

The nannoflora of the sample La Sarraz–Les Buis quarry/Marnes de la Russille (abbr. LSBMRu1) is common (4 specimens per field of view, cf. In situ Assemblage, Fig. 12). The preservation of nannofossils is variable, generally moderate but some specimens are well preserved. Nannofossils show some minor etching and minor overgrowth.

Calcareous nannofossil assemblage and biostratigraphy

The assemblage of sample LSBMRu1 is characterized by a high diverse nannoflora with 42 genera and 90 species observed despite the fact that some subspecies are not considered in this study (e.g. *A. infracretacea larsonii* and *A. terebrodentarius youngii*). This high diversity of species may reflect the surface-water fertility. Previous studies, however, have not reported such a high diversity. Aguado et al. (2014a) reported 37 species from samples of the same age in the Tethyan Realm. Crux (1989) and Jeremiah (2001) reported about 45 species from samples of the same age in the Boreal Realm. The novelty of sample LSBMRu1 is the presence of both Boreal and Tethyan species resulting in this exceptionally high diversity. This sample represents a **unique** nannoflora assemblage of endemic Boreal and Tethyan species. In addition, this sample shows that during the Barremian, selected endemic taxa (both in the Boreal and Tethyan realms), along with select cosmopolite taxa, are more widely distributed than previously reported. The assemblage in

(See figure on next page.)

Fig. 5 Integrated Late Hauterivian–Barremian nannofossil biostratigraphy with Boreal–Tethyan ammonite and calcareous nannofossil zones calibrated to ages from Gradstein et al. (2012). Boreal LK Zones by Jeremiah (2001) and Tethyan NC Zones by Roth (1978, 1983) with subdivisions of Bralower (1987). Stratigraphic positions of the Eclépens (EC) and La Sarraz–Les Buis (LSBM) samples are indicated in the left column

sample LSBMRu1 comprises a mixture of cosmopolitan, endemic, Tethyan and Boreal taxa. The detailed systematic taxonomy chapter discusses the origin of the taxa.

The nannoflora is dominated by abundant *Watznaueria barnesiae*, *Watznaueria fossacincta* and *Watznaueria ovata* with a few *Glaukolithus choffatii*, *Lithraphidites carniolensis*, *Palaeopontosphaera elliptica*, *Retecapsa octofenestra*, *Rhagodiscus asper*, *Reinhardtites scutula* and *Tegulalithus septentrionalis*. The abundance of *Gorkaea pseudoanthophorus* is between few and rare. Other species are rare to very rare. LSBMRu1 is also characterized by very rare species of *Nannoconus abundans*, *Nannoconus pseudoseptentrionalis*, *Micrantholithus hoschulzii* and *Micrantholithus obtusus*. *Broinsonia galloisii*, *Calcicalathina oblongata*, *Ethmorhabdus hauterivianus*, *Flabellites eclepensensis*, *Cyclagelosphaera sulcata*, *Rhagodiscus buisensis* and *Tubodiscus jurapelagicus*, which is explained by the fact that these species have their lowest or highest occurrences at this time.

The following terms are used to indicate the individual species abundance: HO = highest occurrence, HRO = highest regular occurrence, HFO = highest few occurrence, HIO = highest increase occurrence, LIO = lowest increase occurrence, LFO = lowest few occurrence, LRO = lowest regular occurrence, LO = lowest occurrence. The stratigraphical distribution of the nannofossils in this sample is presented in Fig. 6.

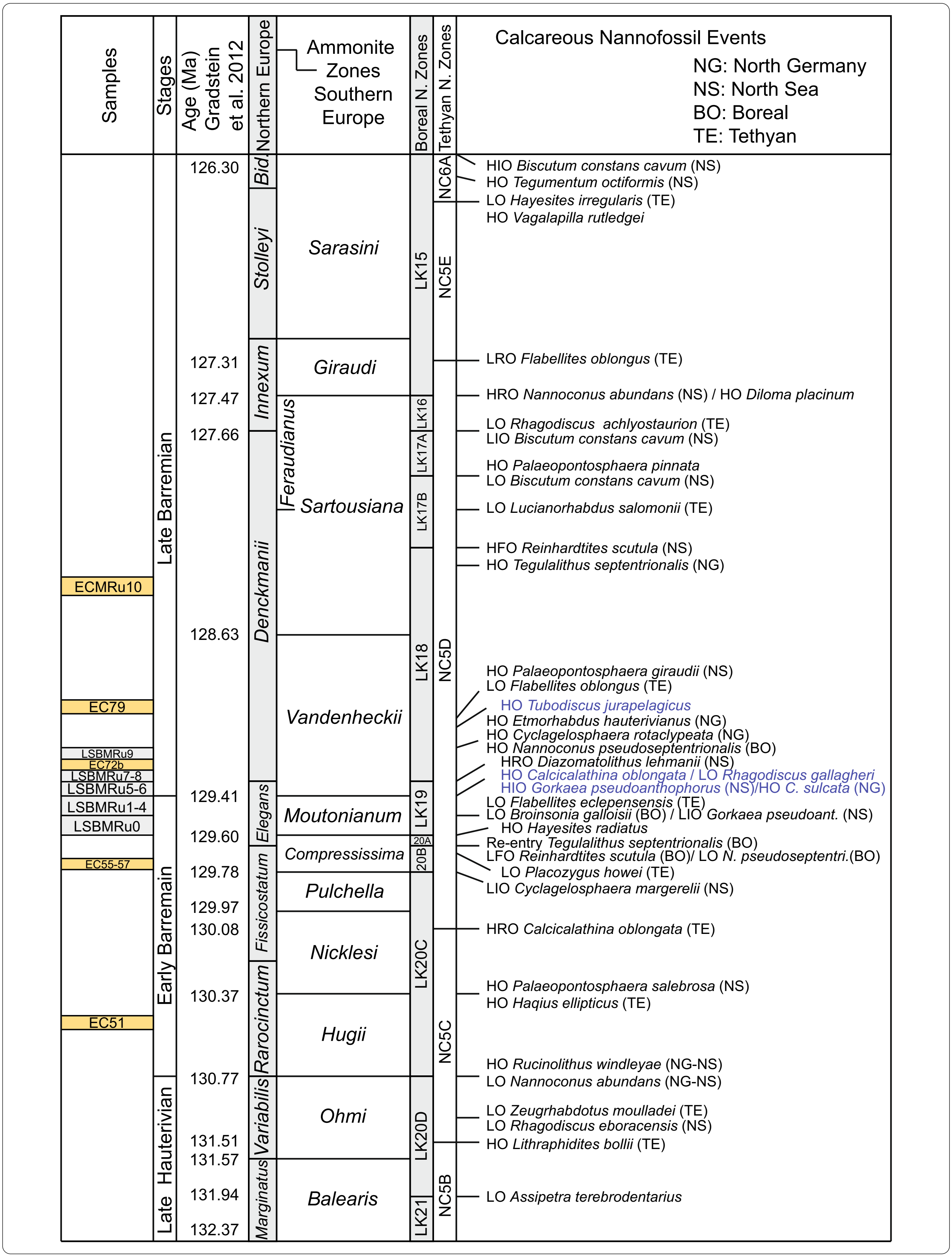
An integrated approach utilizing both Tethyan and Boreal schemes, calibrated to GTS2012, was taken to determine the age of this sample:

- Tethyan zonal scheme (NC zones) of Roth (1978, 1983) with subdivisions of Bralower (1987): LSBMRu1 belongs to the lower part of Zone NC5D. This subzone is defined at the base by the HRO of *Calcicalathina oblongata* and at the top by the LRO of *Flabellites oblongus*. One Tethyan event described by Aguado et al. (2014a) is of primary importance to date this sample: LO of *Flabellites eclepensensis* De Kaenel, n. sp. (his small *Flabellites oblongus*). Other important Tethyan events are the LO of *Placozygus howei* and HO of *Calcicalathina oblongata*.

- Boreal zonal scheme (LK zones) of Jeremiah (2001): this scheme uses single, multiple and quantitative events to define zonal and subzonal boundaries. LSBMRu1 belongs to Zone LK19 defined at the base by the HIO of *Cyclagelosphaera margerelii* and at the top by the HRO of *Diazomatolithus lehmanii*. *C. margerelii* is rare and *D. lehmanii* is present in LSBMRu1. Because of the number of Boreal nannofossil species, the LK scheme is more accurate to date LSBMRu1. Four Boreal events observed by Crux (1989) are of primary importance to date this sample: the re-entry (term used by Crux 1989) of *Tegulalithus septentrionalis*, the increase of *Reinhardtites scutula*, the presence of *Ethmorhabdus hauterivianus* and *Broinsonia galloisii*.

Biostratigraphic implications

The present study provides an excellent opportunity to correlate the Boreal and Tethyan nannofossil markers and to improve the biostratigraphy of the Early–Late Barremian. During this period, the nannofloras show some strong provincialism. Most of the events observed belong to the Boreal zonal scheme (LK) of Jeremiah (2001), but Tethyan (NC) markers are also present. The outcrop of the Marnes de la Russille with sample LSBMRu1 is intermediate between these two realms and other studies on nannofossils do not exist for this intermediate palaeolatitude corresponding to the location of the central Jura Mountains. The stratigraphic distribution of calcareous nannofossils from LSBMRu1 is shown in Fig. 6 with the standard marker species of the NC and LK zonal scheme. With all Tethyan and Boreal markers, the age of LSBMRu1 is very precisely determined by the ammonite zonation: upper Moutonianum Zone (Tethyan) or middle-upper Elegans Zone (Boreal). A very precise correlation of the Moutonianum and Elegans Zones (Fig. 5) is from Mutterlose et al. (2014), who correlated the base of Elegans Zone with the uppermost Compressissima Zone and its top with the lowermost Vandenheckii Zone. These biostratigraphic correlations indicate that the LO of *B. galloisii* (Boreal) and *F. eclepensensis* (Tethyan) are in the same horizon. *Calcicalathina oblongata* (Tethyan) recorded in the same horizon indicates an age not younger than the Moutonianum Zone. The HO of *C. oblongata* (Tethyan) in sample LSBMRu4 is correlated with the the top of the Moutanianum Zone (Figs. 5, 12). Aguado et al. (2014a) moved the NC5D/NC5E subzonal boundary to LO of *F. eclepensensis* in the uppermost Early Barremian Moutonianum Zone. We are not following this new position and this boundary is still better placed at LRO of *F. oblongus* in the Late Barremian Giraudi Zone. In the same way, the NC5C/NC5D subzonal boundary is not moved to HO of *C. oblongata*, but still placed in the upper Nicklesi Zone with a position corresponding to HRO of *C. oblongata*.


Samples
Stages
Age (Ma) Gradstein et al. 2012
Northern Europe
Ammonite Zones Southern Europe
Boreal N. Zones
Tethyan N. Zones
Calcareous Nannofossil Events
NG: North Germany
NS: North Sea
BO: Boreal
TE: Tethyan
Late Barremian
Early Barremain
Late Hauterivian
126.30
127.31
127.47
127.66
128.63
129.41
129.60
129.78
129.97
130.08
130.37
130.77
131.51
131.57
131.94
132.37
ECMRu10
EC79
LSBMRu9
EC72b
LSBMRu7-8
LSBMRu5-6
LSBMRu1-4
LSBMRu0
EC55-57
EC51
Bid.
Stolleyi
Innexum
Denckmanii
Elegans
Fissicostatum
Rarocinctum
Variabilis
Marginatus
Sarasini
Giraudi
Feraudianus
Sartousiana
Vandenheckii
Moutonianum
Compressissima
Pulchella
Nicklesi
Hugii
Ohmi
Balearis
LK15
LK16
LK17A
LK17B
LK18
LK19
20A
20B
LK20C
LK20D
LK21
NC6A
NC5E
NC5D
NC5C
NC5B
HIO Biscutum constans cavum (NS)
HO Tegumentum octiformis (NS)
LO Hayesites irregularis (TE)
HO Vagalapilla rutledgei
LRO Flabellites oblongus (TE)
HRO Nannoconus abundans (NS) / HO Diloma placinum
LO Rhagodiscus achlyostaurion (TE)
LIO Biscutum constans cavum (NS)
HO Palaeopontosphaera pinnata
LO Biscutum constans cavum (NS)
LO Lucianorhabdus salomonii (TE)
HFO Reinhardtites scutula (NS)
HO Tegulalithus septentrionalis (NG)
HO Palaeopontosphaera giraudii (NS)
LO Flabellites oblongus (TE)
HO Tubodiscus jurapelagicus
HO Etmorhabdus hauterivianus (NG)
HO Cyclagelosphaera rotaclypeata (NG)
HO Nannoconus pseudoseptentrionalis (BO)
HRO Diazomatolithus lehmanii (NS)
HO Calcicalathina oblongata / LO Rhagodiscus gallagheri
HIO Gorkaea pseudoanthophorus (NS)/HO C. sulcata (NG)
LO Flabellites eclepensensis (TE)
LO Broinsonia galloisii (BO) / LIO Gorkaea pseudoant. (NS)
HO Hayesites radiatus
Re-entry Tegulalithus septentrionalis (BO)
LFO Reinhardtites scutula (BO)/ LO N. pseudoseptentri.(BO)
LO Placozygus howei (TE)
LIO Cyclagelosphaera margerelii (NS)
HRO Calcicalathina oblongata (TE)
HO Palaeopontosphaera salebrosa (NS)
HO Haqius ellipticus (TE)
HO Rucinolithus windleyae (NG-NS)
LO Nannoconus abundans (NG-NS)
LO Zeugrhabdotus moulladei (TE)
LO Rhagodiscus eboracensis (NS)
HO Lithraphidites bollii (TE)
LO Assipetra terebrodentarius

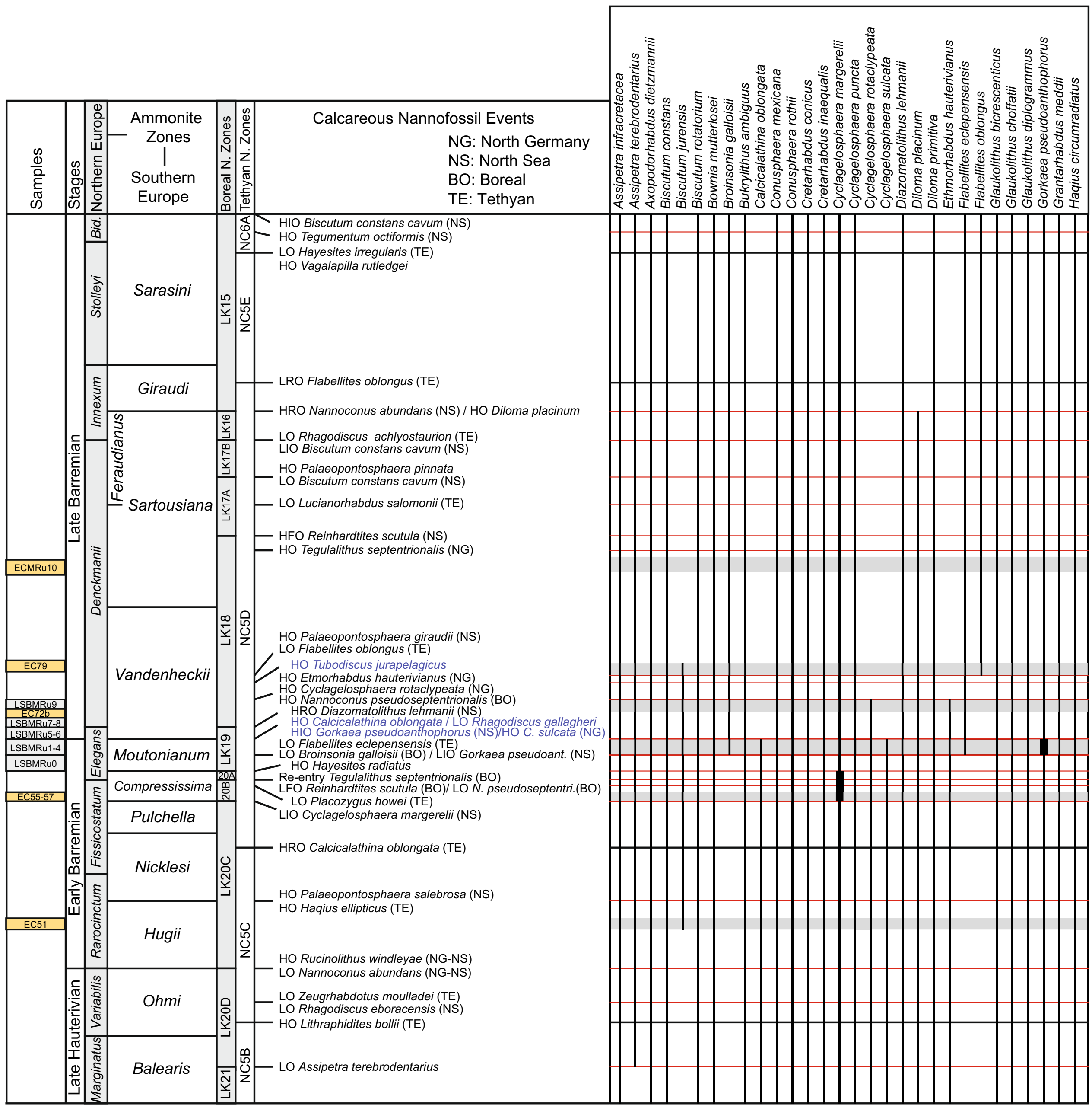


Fig. 6 Late Hauterivian–Barremian stratigraphic range for the 90 species of LSBMRu1 (La Sarraz–Les Buis quarry) and *Flabellites oblongus* of EC79-ECMRu10 (Eclépens quarry)

Additional results and data

Data of samples LSBMRu1 and EC72b-79 are completed with analyses of 9 other samples LSBMRu0/2–9 and ECMRu10 (Figs. 12, 13, 14a, b) collected in the Marnes de la Russille (MRu) of La Sarraz–Les Buis quarry and Eclépens quarry. LSBMRu1 in the middle part of the channelized dark grey marls (MRu) was by far the richest and most interesting sample for nannofossils. The nannoflora observed in LSBMRu can be placed mostly in the Moutonianum ammonite Zone of the late Early Barremian. Rare typical specimens of the Late Barremian marker *Flabellites oblongus* were observed in EC79 and ECMRu10 only, but not in the highest LSBMRu7-9 samples of yellowish more calcareous marls with decreasing nannofossil diversity. *Rhagodiscus gallagheri* Rutledge and Bown 1996 was found in EC72b/

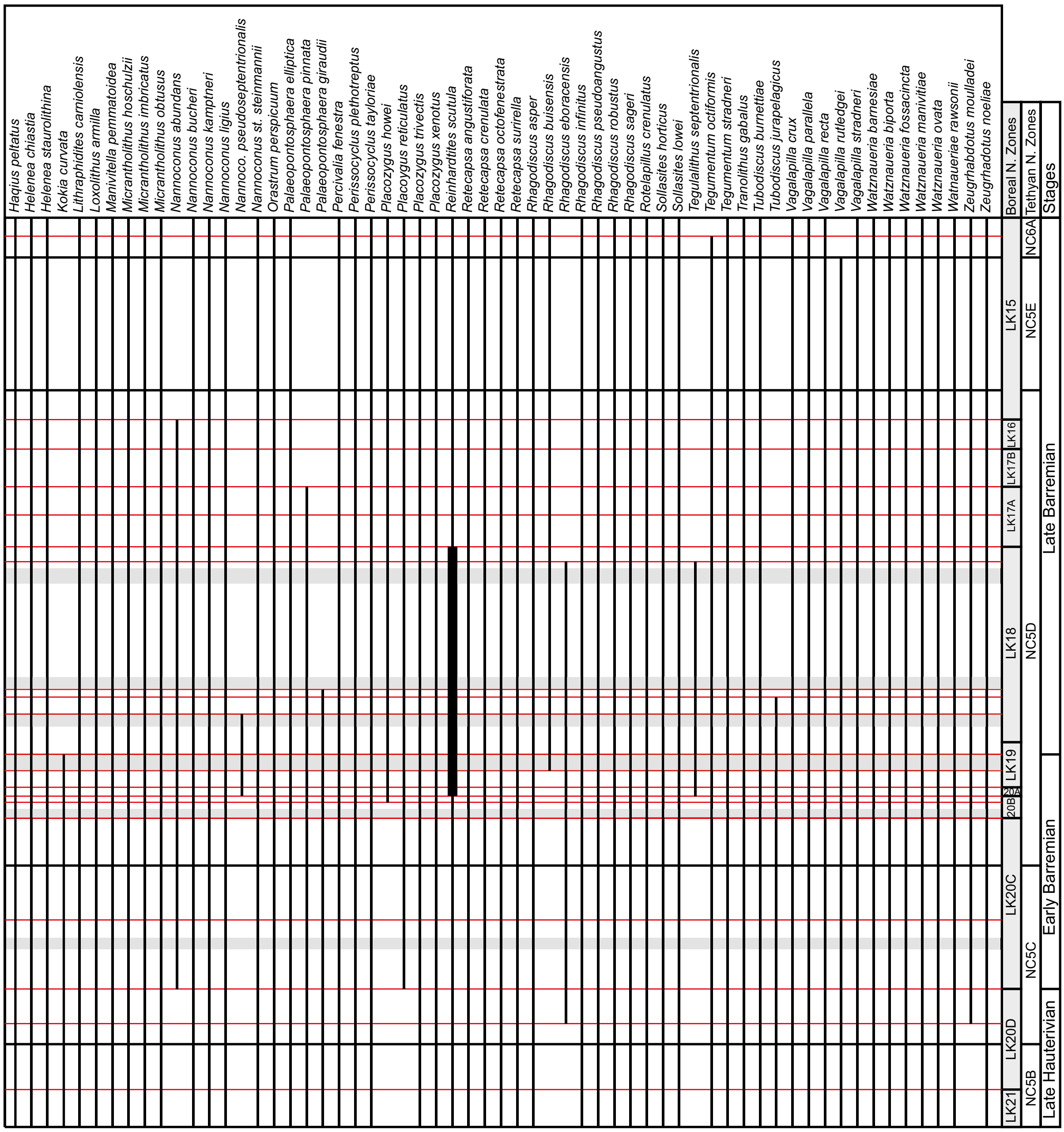


Fig. 6 continued

EC79 and in LSBMRu5/LSBMRu7/LSBMRu9 with a first occurrence above the Early/Late Barremian boundary marked by a sudden change of colour from dark grey to yellow (Fig. 14b), thus with a first occurrence in the lower Vandenheckii ammonite Zone and not higher in the Late Barremian (De Kaenel *in* Godet et al. 2010) or in the basal Aptian (Rutledge and Bown 1996). The top of *Ethmorhabdus hauterivianus* in the highest LSBMRu7-9 samples and in EC72b is placed in the Vandenheckii Zone and *Tubodiscus jurapelagicus* in LSBMRu9 indicates an age not older than the Late Barremian Vandenheckii ammonite Zone. LSBMRu9 and EC72b contain specimens of large *Nannoconus* indicating influxes of warm Tethyan water. *Nannoconus abundans* is a typical Boreal endemic species found in EC72b and LSBMRu1, this taxon restricted to the Barremian is very rare (or absent) in upper LK19 and lower LK18 nannofossil Zones.

The Late Barremian marker *Lucianorhabdus salomonii* Bergen 1994 is absent in LSBMRu5-9 and EC72b-79/ECMRu10 samples, and after revision of the material observed and figured by Godet et al. (2010, Table 2, fig. 14B.10) must be referred to the genera *Owenia* or *Orastrum*, and the age of EC72b-79/ECMRu10 is thus a little older than the upper Sartousiana Zone as previously reported by De Kaenel *in* Godet (2006) and Godet et al. (2010). According to these new data and considering the HO of *Tegulalithus septentrionalis* (NG) still present in LSBMRu9 and ECMRu10, the biostratigraphical range of the samples LSBMRu5-9 and EC72b-79/ECMRu10 extends from the Vandenheckii to the lower Sartousiana ammonite Zones. Incidentally, Aptian-Albian nannofossils reworked from huge palaeokarstic Late Eocene Siderolithic deposits (Fig. 14e, f, Hooker and Weidmann 2000) were also reported in some samples of the Marnes de la Russille at Eclépens (De Kaenel *in* Godet 2006, p. 373/380; Early Albian *Flabellites oblongus* of nearly 10 µm *in* Clavel et al. 2007, Pl. 8, fig. H).

Samples EC51 and EC55-57 are very similar to the other samples of Eclépens and La Sarraz–Les Buis, they contain also the markers *Assipetra terebrodentarius*, *Cyclagelosphaera margerelii*, *Nannoconus abundans* and *Zeugrhabdotus moulladei*. EC55 is placed in the LK20B nannofossil Zone (Hauptblätterton facies of the North Sea Basin, Jeremiah 2001; within the Mid-Barremian Event/MBE of the Boreal Realm, Møller et al. 2019) and the lower Compressissima Zone with the acme of *C. margerelii* (LIO), which is particularly abundant. EC51 was sampled in the marly discontinuity between the limestones of the upper Pierre jaune de Neuchâtel and the basal Urgonien Jaune, it belongs to the lower LK20C nannofossil Zone and the upper Hugii Zone, with LO of *Nannoconus abundans*, HO of *Palaeopontosphaera salebrosa*, HO of *Haqius ellipticus* (Fig. 5), and large typical Barremian *A. terebrodentarius* (8 µm) much younger than the first occurrence of this species in the Late Hauterivian.

Systematic taxonomy

This section includes all species observed in LSBMRu1, taxonomic discussion of key taxa, the description of five new species (*Biscutum jurensis*, *Flabellites eclepensensis, Palaeopontosphaera giraudii, Rhagodiscus buisensis* and *Vagalapilla rutledgei*) and eight new combinations (*Cyclagelosphaera sulcata, Glaukolithus choffatii*, *Palaeopontosphaera pinnata*, *Placozygus howei*, *Placozygus reticulatus*, *Placozygus trivectis*, *Placozygus xenotus*, and *Vagalapilla recta*). Taxa considered in this section are listed by generic epithet. Only references not cited in Perch-Nielsen (1985) and Bown et al. (1998) are included in the reference list. All pictures are in cross-polarized light or in phase-contrast. Most of the taxa observed are illustrated in Figs. 7, 8, 9, 10, 11 with 71 species. The magnification for all pictures is × 2500. Dimensions of some taxa are indicated on bottom of the pictures.

Genus *Assipetra* Roth 1973

Assipetra infracretacea (Thierstein 1973) Roth 1973
Figure 7.22

Discussion: Both small *A. infracretacea infracretacea* (< 7.5 µm) and large *A. infracretacea larsonii* (> 7.5 µm) (Fig. 7.22) were observed in sample LSBMRu1. Tremolada and Erba (2002) indicated that LO of *A. infracretacea larsonii* is of Aptian age, but these large forms are present in the late Early Barremian.

Assipetra terebrodentarius (Applegate, Bralower, Covington and Wise *in* Covington and Wise 1987) Rutledge and Bergen *in* Bergen 1994
Figure 7.18–20

Discussion: Few specimens of *A. terebrodentarius* were observed. Some specimens observed have petaloid to globular structures. A part of a specimen may have globular elements and the other part petaloid elements (Fig. 7.18). Large (> 8 µm) *A. terebrodentarius* specimens are present in sample LSBMRu1 (Fig. 7.20). Forms of *A. terebrodentarius* (> 7.5 µm) have been included in the subspecies *A. terebrodentarius youngii* by Tremolada and Erba (2002). They indicated that LO of this subspecies is Aptian, but these large forms are present in the late Early Barremian. LO of *A. terebrodentarius* is in the Late Hauterivian Balearis Zone (Fig. 5) and its HO is in Early Campanian.

Genus *Axopodorhabdus* Wind and Wise *in* Wise and Wind 1977

Axopodorhabdus dietzmannii (Reinhardt 1965) Wind and Wise 1983

Genus *Biscutum* Black 1959 emend. De Kaenel and Bergen 1993

Biscutum constans (Górka 1957) Black *in* Black and Barnes 1959
Figure 8.6–8

Discussion: Only small forms less than 4.5 µm were observed and are included in *B. constans*. The large forms (between 4.5–6.6 µm) of *Biscutum constans* assigned to the subspecies *Biscutum constans cavum* described by Jeremiah (2001) from the North Sea Basin were not observed in samples from the Eclépens or La Sarraz–Les Buis quarries. Specimens of large *Biscutum* observed (Fig. 8.9–12) in LSBMRu1 have a size of 6.7 and 7.0 µm but with a central area closed by a plate and they belong to the new species *B. jurensis*.

Biscutum jurensis De Kaenel, n. sp.
Figure 8.9–12

Derivation of name: Named after the Jura Mountains.

Diagnosis: A medium-sized, broadly elliptical species of *Biscutum* with a thick rim, and a medium-sized central area closed by several elements forming a plate.

Differentiation: *B. jurensis* is differentiated from all other *Biscutum* species by its larger size and closed central area.

Dimensions: Length (L) = 5.0–8.0 µm, Width (W) = 4–6.5 µm.

Holotype: Fig. 8.9–10, L = 6.7 µm, W = 5.4 µm.

Paratype: Fig. 8.11–12, L = 7.0 µm, W = 5.8 µm.

Type locality: Les Buis quarry near La Sarraz, western Swiss Jura Mountains (coord. 2528.240/1168.170, map 1:25′000 of Switzerland).

Type level: Marnes de la Russille (sample LSBMRu1).

Discussion: Specimens observed of *B. jurensis* are between 5.7 µm (sample EC51) and 7.0 µm (sample LSBMRu1). *P. elliptica* is smaller and with an open central area and *B. constans* has a small central area and a spine base. Similar forms are observed by Burnett (1998, Pl. 6.5, figs. 22–23) in the Albian-Maastrichtian.

Range: *B. jurensis* is observed from the bottom sample EC51 (Early Barremian Hugii ammonite Zone) to sample EC72 (Late Barremian Vandenheckii ammonite Zone).

Biscutum rotatorium (Bukry 1969) De Kaenel and Bergen 1996
Figure 11.22

Discussion: Most researchers still call this form *Discorhabus ignotus* (e.g. Bown et al. 1998). The holotype of the species *B. ignotus* from Górka (1957) is a placolith with a distal shield composed of 14 elements joined along oblique sutures lines. The forms observed in LSBMRu1 have radial suture lines and correspond to the species *B. rotatorium* described by Bukry (1969). *B. rotatorium* is a small circular species with a distal shield composed of 16–23 elements, and an imperforate centre. The shields exhibit faint birefringence and the central area is slightly birefringent.

Genus *Bownia* Varol and Girgis 1994

Bownia mutterlosei (Crux 1989) Varol and Girgis 1994
Figure 9.7

Discussion: *B. mutterlosei* is the type species of the genus *Bownia* described by Varol and Girgis (1994). This genus includes murolith species with a biclyclic rim structure showing a spiraled (zeugoid) rim extinction pattern and a central cross structure. In *B. mutterlosei* the central cross is slightly off-axis. *B. mutterlosei* is differentiated from *Vagalapilla* by its rim extinction pattern with two equally birefringent cycles. Very rare specimens of *B. mutterlosei* are recorded in LSBMRu1. Crux (1989) observed the HO of *B. mutterlosei* in North Germany sections in the middle Elegans ammonite Zone. Bown et al. (1998) placed the HO of *B. mutterlosei* in the lower Cenomanian.

Genus *Broinsonia* Bukry 1969

Broinsonia galloisii (Black 1973) Bown *in* Kennedy et al. 2000
Figure 9.11–12

Discussion: Very rare specimens of *B. galloisii* are recorded in LSBMRu1. *B. galloisii* is differentiated from *B. matalosa* by its smaller size (< 5.5 µm). In the sample from the Eclépens quarry, specimens are larger (> 6.5 µm). Specimen from LSBMRu1 (Fig. 9.11) and from the Eclépens quarry (Fig. 9.12) have the same structure with the same thin axial cross bar. Both specimens, small and medium-sized, are named *B. galloisii* in this study. Other names have been used in the literature for these forms. Thierstein (1973) and Crux (1989) used *Vagalapilla matalosa*. Bown (*in* Kennedy et al. 2000) tentatively classified the small form (< 5.5 µm) as *Broinsonia galloisii* and the medium-sized specimens as *Broinsonia* cf. *galloisii*. Jeremiah (2001) used *Acaenolithus galloisii* for small and medium-sized specimens. LO of *B. galloisii* is recorded by Jeremiah (2001) in middle LK19 Zone of the North Sea Basin. This is one of the key taxa to date the oldest age of LSBMRu1 together with the Tethyan species *Flabellites eclepensensis* (Fig. 5). *B. galloisii* occurs first in Boreal area and is reported later (base of the Aptian) in Tethyan area. Bown (1992) and Mutterlose (1992a) reported *Broinsonia matalosa* in the Indian Ocean down to the Valanginian of the Argo Abyssal Plain. This occurrence is unique to this region and *B. galloisii*/*B. matalosa* have not been observed in sediments older than late Early Barremian in North Sea Basin and in North Germany sections.

Genus *Bukrylithus* Black 1971

Bukrylithus ambiguus Black 1971
Figure 9.16

Genus *Calcicalathina* Thierstein 1971

Calcicalathina oblongata (Worsley 1971) Thierstein 1971
Figure 9.20

Discussion: *C. oblongata* is very rare but present in LSBMRu1. Specimens observed have the typical high, narrow rim and a wide central granular area. *C. erbae*, the other *Calcicalathina* species present in Barremian strata, was not observed. LSBMRu1 belongs to the NC5 nannofossil Zone. The NC5 zone of Roth (1978, 1983) has been subdivided in 5 subzones (NC5A to NC5E) by Bralower (1987). HRO of *C. oblongata* is the subzonal marker of the NC5C/NC5D boundary in the Tethyan nannofossil zonation. Based on Gradstein et al. (2012), HO of *C. oblongata* is at 130.08 Ma and is correlated with the upper Nicklesi Zone. Above this level *C. oblongata* is scarce but present. In many sections these scarce occurrences of *C. oblongata* are always taken of evidence of reworking (e.g. Bralower 1987). Von Salis (1998) correlated HO of *C. oblongata* in Italy with the upper Hugii Zone and in France with the base of Moutonianum Zone. Thierstein (1973) and Bergen (1994) correlated in SW-France the HO of *C. oblongata* with the middle of Compressissima Zone. HO of scarce occurrence of *C. oblongata* is at the top of the Mountonianum Zone and specimens recorded in LSBMRu1 represent the uppermost range of *C. oblongata* (Fig. 5). The calibration of Gradstein et al. (2012) corresponds to HRO of *C. oblongata*. The NC5C/NC5D subzonal boundary is not moved to HO of *C. oblongata* recorded at the top of Moutonianum Zone. To keep some consistency in zonal scheme, HRO of *C. oblongata* used widely in many sections is retained as marker event for the NC5C/NC5D boundary. New HO of *C. oblongata* position also allows to correlate better the low latitude (Tethyan) and high latitude (Boreal) nannofossil zonal schemes. Both HO and HRO of *C. oblongata* events could be used to better improve the Barremian biostratigraphy.

Genus *Conusphaera* Trejo 1969

Conusphaera mexicana Trejo 1969 ssp. *mexicana* (cf. Bralower et al. 1989)

Conusphaera rothii (Thierstein 1971) Jakubowski 1986

Discussion: Bralower et al. (1994) noted that *C. mexicana* and *C. rothii* may represent preservational morphotypes. These two species are differentiated by the extinction lines of the core segments. In *C. mexicana* the segments have axial extinction lines and in *C. rothii* the extinction lines are curving. Both taxa are observed in LSBMRu1. *C. rothii* is frequent in the Valanginian—Early Barremian of the North Sea area, whereas *C. mexicana* is extremely rare or absent. As noted by Jeremiah (2001) in Zone LK19, only rare *C. rothii* are observed. Both species range in the Aptian: Early Aptian by Varol and Bowman (2019) and Late Aptian by De Kaenel and Bergen (1996, Tables 3, 4).

Genus *Cretarhabdus* Bramlette and Martini 1964

Cretarhabdus conicus Bramlette and Martini 1964
Figure 9.25

Cretarhabdus inaequalis Crux 1987
Figure 9.24

Discussion: Very rare specimens of *Cretarhabdus* with an irregular central grill are observed in samples EC55 and LSBMRu1 and are assigned to the species *inaequalis*. Crux (1987) described *C. inaequalis* from the Otto Gott section in North Germany and recorded it from the Late Hauterivian Gottschei ammonite Zone to the Late Barremian. Jeremiah (2001) recorded it up the Early Albian in North Sea Basin.

Genus *Cyclagelosphaera* Noël 1965

Cyclagelosphaera margerelii Noël 1965
Figure 11.17

Discussion: Rare specimens of *C. margerelii* are observed in LSBMRu1. According to Jeremiah (2001), the top of the interval with common/abundant *C. margerelii* is correlated with the end of Zone LK20 in the lower Elegans Zone and the uppermost Hauptblätterton facies (organic-rich laminated clays) recorded in North Sea Basin and Lower Saxony basin. Rare *C. margerelii* indicate therefore that LSBMRu1 is slightly younger than LK20 (upper Elegans Zone) and belongs to the Zone LK19. Sample EC55 from the Eclépens quarry contains common/abundant *C. margerelii* and no *Reinhardtites scutula*. This sample belongs to the subzone LK20B of Jeremiah (2001) (Figs. 5, 13), which is defined at the base by the LIO of *C. margerelii* and at the top by the LFO of *Reinhardtites scutula*.

Cyclagelosphaera puncta Black 1973
Figure 11.18

Discussion: Specimens of *C. puncta* observed in LSBMRu1 are small, less than 5 µm, with a distinct small opening in the central area. The holotype of Black (1973) from the Middle Albian is 7.2 µm. *Cyclagelosphaera* species with small central opening ranges from the Bajocian to the Hauterivian (*C. lacuna*, *C. argoensis*) and then from the Albian with *C. puncta*. HO of *C. puncta* is not yet constrained. Specimens observed in the Barremian are assigned to *C. puncta* based on the thin structure of the distal shield cycle.

Cyclagelosphaera rotaclypeata Bukry 1969
Figure 11.19–20

Discussion: Specimens of *C. rotaclypeata* recorded in sample LSBMRu1 are small (between 3.0 and 4.9 µm), but they have the typical large central area filled by radial elements forming a plate. Bukry (1969) described *C. rotaclypeata* in Tethyan areas for forms between 5–8 µm. LO of these larger forms of *C. rotaclypeata* is placed in the Albian by Burnett *in* Gale et al. (1996). Crux (1989) recorded *C. rotaclypeata* from the Late Hauterivian to the upper Elegans Zone in NW-European basins. The Boreal upper Elegans Zone is correlated with the top of the Tethyan Moutonianum Zone (Mutterlose et al. 2014). Jeremiah (2001) reported some rare occurrence of *C. rotaclypeata* in Late Barremian and Aptian sediments from the North Sea Basin.

Cyclagelosphaera sulcata (Forchheimer 1972) De Kaenel, n. comb.
Figure 11.21

Basionym: *Markalius sulcatus* Forchheimer 1972, p. 36, Pl. 8, Fig. 5.

Discussion: *Cyclagelosphaera* species differ from *Markalius* species by the bright birefringence of the distal shield. In *Markalius* the distal shield is non-birefringent. *C. sulcata* differs from other *Cyclagelosphaera* species by its elevated large central plug with angular sutures forming the inner tube cycle which exhibits a yellow birefringence. The species *Cyclagelospheara shenleyensis* described by Black (1973) from the Early Albian is similar to *C. sulcata*. *C. sulcata* is a Boreal species described by Forchheimer (1972) from Barremian sediments in the North Sea Basin. *C. shenleyensis* is also a Boreal species (Black 1973). LO of *C. sulcata* is placed in the Late Hauterivian and its HO at the base of the Late Barremian (Fig. 5) in the Elegans ammonite Zone (Fig. 5).

Genus *Diazomatolithus* Noël 1965

Diazomatolithus lehmanii Noël 1965
Figure 11.16

Discussion: Only rare specimens of *D. lehmanii* are observed in sample LSBMRu1. Jeremiah (2001) indicated that this species is abundant from the Early Valanginian to the Early Barremian Fissicostatum Zone and rare to the top of Elegans Zone. In the Late Barremian, *D. lehmanii* occurs very sporadicaly in North Sea Basin. In NW-European basins, Crux (1989) recorded the HO of *D. lehmanii* at the top of Elegans Zone. So, rare specimens of *D. lehmanii* indicate that LSBMRu1 can be correlated with the upper Elegans Zone, but the abundance of this species is quite variable in core/outcrop samples. Thus, the low abundance of this species may have no age significance.

Genus *Diloma* Wind and Čepek 1979

Diloma placinum Wind and Čepek 1979

Diloma primitiva (Worsley 1971) Wind and Čepek 1979

Genus *Ethmorhabdus* Noël 1965

Ethmorhabdus hauterivianus (Black 1971) Applegate, Covington and Wise *in* Covington and Wise 1987
Figure 9.21

Discussion: Specimens observed of *E. hauterivianus* are the typical large forms, between 8 and 12 µm, with a finely perforated net and no central spine base. HO of *E. hauterivianus* was observed at the top of Hugii Zone in SE-France (Bergen 1994) and in the lower Denckmanii Zone of NW-European basins (Crux 1989). *E. gallicus*, the other similar species of *Ethmorhabdus* has a perforated net with only 4–5 cycles of perforations, but has also a central spine base. HO of *E. gallicus* is observed in the Late Tithonian (De Kaenel and Bergen 1996). According to recent and important calibrations of Boreal and Tethyan ammonites (Mutterlose et al. 2014), HO of *E. hauterivianus* in the Boreal lower Denckmanii Zone can thus be correlated with the Tethyan lower Vandenheckii Zone in the Jura Mountains (Fig. 5). *E. hauterivianus* is one of the key markers to date the top of the Marnes de la Russille in the La Sarraz–les Buis quarry. *E. hauterivianus* is present (rare to very rare) in almost all LSBM samples and is recorded to the top sample LSBMRu9 (Figs. 12, 14a). This indicates that the top of the MRu in the La Sarraz–les

Buis quarry is in the lower Vandenheckii Zone. In the Eclépens samples, *E. hauterivianus* is present in sample EC72b, but not in sample EC79, which contains the LO of *F. oblongus* (Fig. 13).

Genus *Flabellites* Thierstein 1973

Flabellites eclepensensis De Kaenel, n. sp.
Figure 8.20–25

Flabellites oblongus in Aguado et al. 2014a, fig. 4.25–29.

Derivation of name: Named after the Eclépens quarry (Eclépens, VD), W-Switzerland.

Diagnosis: A small (3 to < 5.0 µm), normally elliptical species of *Flabellites* with a narrow central area spanned by a blocky, low angle diagonal cross. The two bars of the cross may fuse together and forms a single bridge with a middle suture line

Differentiation: *F. eclepensensis* is differentiated from the only other species of *Flabellites*, *F. oblongus*, by its smaller size and its blocky diagonal cross, which appears in cross-polarized light in early form as a bridge with a median suture.

Dimensions: Length (L) = 3 < 5.0 µm, Width (W) = 2.5 to 3.8 µm.

Holotype: Fig. 8.20–21, L = 4.0 µm, W = 3.2 µm.

Paratype: Fig. 8.22–23, L = 4.4 µm, W = 3.3 µm.

Type locality: Eclépens quarry nearby Eclépens, western Swiss Jura Mountains (Godet et al. 2010, coordinates 2531.256/1167.183, map 1:25′000 of Switzerland).

Type level: Marnes de la Russille (sample EC79).

Discussion: The three specimens of *Flabellites oblongus* illustrated by Aguado et al. (2014a) are small (between 4.3 and 5 µm) with a blocky bridge and correspond to *Flabellites eclepensensis*. Aguado et al. (2014a) correlated LO of these forms with the middle part of the uppermost Early Barremian Moutonianum Zone in the section of Arroyo Gilico (Southern Spain). This basic correlation is one of the primary data defining very precisely the age of LSBMRu1, which is not older than the middle Moutonianum Zone.

Range: According to the Tethyan nannofossil biozonation, *F. eclepensensis* ranges from late Early Barremian (Zone NC5D of Roth, 1978, 1983) to Late Aptian (Zone NC8). Because most of the bioevents belong to the Boreal Realm, LO of *F. eclepensensis* is better defined by using the North Sea Basin zonation (Boreal) of Jeremiah (2001) and can be placed within the upper Zone LK19. This zone is defined by HIO of *Cyclagelosphaera margerelii* (base) and HRO of *Diazomatolithus lehmanii* (top). Presently *F. eclepensensis* is recorded up to the Late Aptian in samples from the Angles outcrop in SE-France (E. De Kaenel, unpubl. pers. obs.).

Flabellites oblongus (Bukry 1969) Crux *in* Crux et al. 1982
Figure 8.16–19

Discussion: *F. oblongus* was not recorded in LSBMRu1, but observed in samples from the Eclépens quarry. *F. oblongus* has a central area spanned by a thin low angle diagonal cross aligned with the short axis. The distal shield is asymmetric with one shield broader than the other. Typical forms measure between 5–10 µm. The two specimens illustrated in Fig. 8.16–19 are from Late Aptian samples of the Angles outcrop and measure 5.6 and 5.9 µm. *F. eclepensensis* is smaller (3 < 5 µm) µm) with a narrow central area and a very blocky diagonal cross. In the early forms, the two bars of the diagonal cross are touching and appear in cross-polarized light as a bridge with a middle suture line. Bergen (1994) indicated with his text-fig. 2 the presence of early morphotypes of *F. oblongus* in the Late Hauterivian. These early specimens have almost no flange and a higher angle diagonal cross (De Kaenel and Bergen 1996), they correspond to the species *Crucibiscutum trilensis* described by Bown and Concheyro 2004 from the same Late Hauterivian interval.

Genus *Glaukolithus* Reinhardt 1964

Glaukolithus bicrescenticus (Stover 1966) Bergen 1998

Glaukolithus choffatii (Rood, Hay and Barnard 1973) De Kaenel, n. comb.

Basionym: *Zeugrhabdotus choffati* Rood, Hay and Barnard 1973, p. 369–370, Pl. 1, fig. 7.

Discussion: The genus *Glaukolithus* [type species: *Glaukolithus diplogrammus* (Deflandre 1954) Reinhardt 1964] includes species with faint birefringent rim and transerve bar. *G. choffatii* is a small species of *Glaukolithus* with a faint birefringent rim and faint transverse bar. The genus *Zeugrhabdotus* (type specimen: *Z. erectus*) includes species with bicyclic rim with a bright inner cycle and a bright bridge.

Glaukolithus diplogrammus (Deflandre *in* Deflandre and Fert 1954) Reinhardt 1964
Figure 10.14–15

Genus *Gorkaea* Varol and Girgis 1994

Gorkaea pseudoanthophorus (Bramlette and Martini 1964) Varol and Girgis 1994
Figure 10.28–30

Discussion: *Gorkaea pseudoanthophorus* is the type species for the genus *Gorkaea* (Varol and Girgis 1994). The genus *Gorkaea* includes murolith species with a sigmoid outer distal cycle, a thick inner distal cycle, and a bridge spanning the central area. Many authors incorrectly placed *G. pseudoanthophorus* within *Zeugrhabdotus embergeri*. The holotype of *Zeugrhabdotus embergeri in* Noël (1958) has a unicyclic sigmoid rim. Jeremiah (2001) recorded a short increase of *G. pseudoanthophorus* (his *Parhabdolithus embergeri*) in Zone LK19 (middle-upper Elegans Zone). Few *G. pseudoanthophorus* recorded also place LSBMRu1 in the same part of Zone LK19. This increase is indicated in Figs. 5, 6 as LIO and HIO of *G. pseudoanthophorus* (NS).

Genus *Grantarhabdus* Black 1971

Grantarhabdus meddii Black 1971
Figure 9.26

Genus *Haqius* Roth 1978

Haqius circumradiatus (Stover 1966) Roth 1978
Figure 11.24

Haqius peltatus Bown 2005
Figure 11.23

Discussion: Bown (2005) described *H. peltatus* for small (< 6.5 µm), elliptical species of *Haqius*. The specimen illustrated (Fig. 11.23) has a length of 5.4 µm. Bown (2005) reported for *H. peltatus* a range from Berriasian to Albian. Larger forms are *Haqius ellipticus* (Grün *in* Grün and Allemann 1975) Bown 1992 emend. Bown 2005. In sample EC51, specimens of *H. ellipticus* are 9 µm. Bergen (1994) reported the HO of *H. ellipticus* in the bed ANG090 of the Barremian stratotype of Angles. This bed is located in the Colombiana Subzone at the upper part of the Hugii Zone (Reboulet et al. 2018, = Kiliani Zone *in* Vermeulen 2005). The HO of large forms, *H. ellipticus*, is placed at the top of the Early Barremian Hugii Zone. Also recorded in sample EC51 are specimens of *Nannoconus abundans*, which is used as subzonal marker by Jeremiah (2001) to define the base of subzone LK20C (Fig. 5).

Genus *Helenea* Worsley 1971 emend. Bown 2005

Helenea chiastia Worsley 1971
Figure 9.29–30

Helenea staurolithina Worsley 1971
Figure 9.27–28

Genus *Kokia* Perch-Nielsen 1988

Kokia curvata Perch-Nielsen 1988
Figure 7.26

Discussion: The specimen of *Kokia* observed in LSBMRu1 (Fig. 7.26) has a rosette-shaped structure with 10 elements joined along curving suture. The terminations of the rays are rounded. The diameter is 10.2 µm. In XP (cross-polarized) light, this specimen displays a grey-yellowish birefringence. *Kokia curvata* described by Perch-Nielsen (1988) from Early Valanginian North Sea sediments has 8–10 rays with grey to yellowish birefringence and a diameter between 10–13.3 µm. Perch-Nielsen (1988) also illustrated a form, *Kokia* sp. 1, from the Late Hauterivian with 10 rays. *Kokia* cf. *K. stellata* observed by Bown (2005) in Late Hauterivian in the northwest Pacific Ocean has 12 rays but is smaller (7.0–8.5 µm) and has a low birefringence in XP light. The observed specimen is better described as *K. curvata*. *Kokia curvata* is abundant in Berriasian sediments from the North Sea Basin (Jeremiah 2001) and rare to the Late Valanginian. *K. curvata* is a typical Boreal taxon as *T. septentrionalis*. Some Boreal species are absent from the Early Barremian, but return in the uppermost Early Barremian Elegans Zone. The Early Barremian re-entry of the Boreal species *T. septentrionalis* was observed by Crux (1989) in North Sea and NW-European basins. The return of Boreal species is due to a transgressive interval establishing marine connections to the North (Crux 1989). The presence of *Kokia* species in the uppermost Early Barremian LSBMRu1 sediments follows the same pattern and also indicates establishments of marine connections to the North.

Genus *Lithraphidites* Deflandre 1963

Lithraphidites carniolensis Deflandre 1963

Genus *Loxolithus* Noël 1965

Loxolithus armilla (Black *in* Black and Barnes 1959) Noël 1965
Figure 11.25

Genus *Manivitella* Thierstein 1971

Manivitella pemmatoidea (Deflandre ex Manivit 1965) Thierstein 1971
Figure 11.26

Genus *Micrantholithus* Deflandre *in* Deflandre and Fert 1954

Micrantholithus hoschulzii (Reinhardt 1966) Thierstein 1971
Figure 7.24

Micrantholithus imbricatus (Manivit 1966) Varol and Bowman 2019
Figure 7.23

Discussion: Small forms of *Micrantholitus*, less than 7 µm, are present in sample LSBMRu1. Typical *M. hoschulzii* specimens are larger, between 7 and 12 µm. On the smaller specimens the outline of the segments varies from straight to rounded and the position of the sutures between the segments is not always in the angles. Varol and Bowman (2019) illustrated similar small forms of *Micrantholithus* (between 4.8–5.2 µm) from the Late Valanginian in northwestern Atlantic Ocean on DSDP Leg 76, Site 534A.

Micrantholithus obtusus Stradner 1963
Figure 7.25

Discussion: *M. hoschulzii* and *M. obtusus* are considered as Tethyan taxa (Bown 2005). Both species are observed in LSBMRu1, but they are rare and most of them show overgrowth, especially the large specimens.

Genus *Nannoconus* Kamptner 1931

Nannoconus abundans Stradner and Grün 1963
Figure 7.16, 21

Discussion: Rare specimens of *N. abundans* are observed in sample LSBMRu1 and in samples from the Eclépens quarry (EC51, EC57, EC72b). Specimens illustrated in Fig. 7.16 (side view) and in Fig. 7.21 (proximal view) are from sample EC51. On the side view, *N. abundans* has a clear upper flange and a medium-sized central canal. Similar forms in cross-polarized light have been illustrated by Bown et al. (1998) and Rückheim et al. (2006). SEM pictures of *N. abundans* (holotype of Stradner and Grün 1963) shows that the central canal is wider on the distal end and very narrow on the proximal end. LM picture of the proximal view of *N. abundans* (Fig. 7.21) also shows the very narrow end of the proximal canal. *N. abundans* is an endemic species only observed in NW-European basins (Bown et al. 1998). Very rare specimens observed in LSBMRu1 indicate the presence of a connection with the North Sea area. The presence of this connection is additionally supported by the presence of few *T. septentrionalis*, a typical Boreal–Arctic taxon (Crux 1989). The LO of *N. abundans* is a well-calibrated event and has been used in different zonal schemes. Crux (1989) placed this event at the base of the Rarocinctum ammonite Zone in North Sea Basin and North Germany sections. Jeremiah (2001) also placed this event at the base of the Rarocinctum Zone and used it to define the base of its subzone LK20C. The occurrences in sample EC51 of *N. abundans* together with *P. salebrosa* and *H. ellipticus* are the key taxa to place the base of the Urgonien Jaune in the lower part of subzone LK20C and in the Tethyan Early Barremian Hugii ammonite Zone (Figs. 3, 5, 13).

Nannoconus bucheri Brönnimann 1955
Figure 7.29–30

Nannoconus kamptneri kamptneri Brönnimann 1955
Figure 7.27–28

Nannoconus ligius Applegate and Bergen 1988
Figure 7.17

Discussion: *N. ligius* is a small, delicate species with 8 petaloid elements with a small central canal. Applegate and Bergen (1988) reported a Late Hauterivian–Early Barremian range. Bergen (1994) indicated that HO of *N. ligius* is Late Aptian in the section Angles of SE-France.

Nannoconus pseudoseptentrionalis Rutledge and Bown 1996
Figure 7.12–15

Discussion: *N. pseudoseptentrionalis* was described by Rutledge and Bown (1996) from the Early Barremian Elegans Zone in North Sea Basin. This species is differentiated from *T. septentrionalis* by its margin without regular-spaced elements and by the absence of the weakly birefringent flange observed in some *T. septentrionalis* specimens. LO of *N. pseudoseptentrionalis* occurs at the base of the Elegans Zone and its HO in the lower Denckmanii Zone. Specimens of *N. pseudoseptentrionalis* observed and illustrated by Jeremiah (2001) from the Early Aptian LK14 Zone have a wide central diaphragm and correspond to *Farhania varolii* (Jakubowski 1986) Varol 1992. *N. pseudoseptentrionalis* has not been reported outside of the North Sea Basin.

Nannoconus steinmannii steinmannii Kamptner 1931

Genus *Orastrum* Wind and Wise *in* Wise and Wind 1977

Orastrum perspicuum Varol *in* Al-Rifaiy et al. 1990

Genus *Palaeopontosphaera* Noël 1965 emend. De Kaenel and Bergen 1993

Palaeopontosphaera elliptica (Górka 1957) De Kaenel and Bergen 1996
Figure 8.1–5

Discussion: The emendation of the genus *Palaeopontosphaera* by De Kaenel and Bergen (1993) is based on the type species of the genus, *Palaeopontosphaera dubia* Noël 1965. Biscutaceae species possessing an inner wall of non-imbricate elements with an imperforate, vacant, or spanned by a simple structure (cross or bar) are included in the genus *Palaeopontosphaera*. *P. elliptica* differs from other *Palaeopontosphaera* species by its distinct very thin inner wall and by the non-birefringent central plate. This plate can be observed in some specimens (Fig. 8.2). *Biscutum constans* is separated from *P. elliptica* based on the larger thickness of the rim and the smaller dark central area with a spine base.

Palaeopontosphaera giraudii De Kaenel, n. sp.
Figure 8.29–30

Crucibisctum salebrosum (Black 1971) Jakubowski 1986 (cf. Crux 1989, Pl. 8.10, figs. 29–30, non fig. 28).
Palaeopontosphaera salebrosa (Black 1971) Prins and Sissingh *in* Sissingh 1977 (cf. De Kaenel *in* Godet et al. 2010, fig. 14A.9-10).

Derivation of name: Named after Dr Fabienne Giraud (Université Grenoble-Alpes, France), a nannopalaeontologist.

Diagnosis: A medium-sized, broadly elliptical species of *Palaeopontoshaera* with a thick rim and a medium-sized central area spanned by a thick birefringent axial cross structure.

Differentiation: *P. giraudii* is differentiated from *P. salebrosa* by its larger size and prominent central cross. *Crucibiscutum hayi* is also a medium-sized species that may belong to the genus *Palaeopontosphaera*. *C. hayi* is very similar to *P. giraudii* but the central axial cross is thin and there is a large stratigraphical displacement between these two species. The LO of *C. hayi* is placed at the base of the Albian by Bown et al. (1998).

Dimensions: Length (L) = 4.5–8.0 µm, Width (W) = 3.5–6.5 µm.

Holotype: Fig. 8.29, L = 6.6 µm, W = 5.3 µm.

Paratype: Fig. 8.30, L = 7.6 µm, W = 5.5 µm.

Type locality: Les Buis quarry near La Sarraz, western Swiss Jura Mountains (coordinates 2528.240/1168.170, map 1:25′000 of Switzerland).

Type level: Marnes de la Russille (sample LSBMRu1).

Discussion: Specimens observed are between 4.5 µm and 8.0 µm (Fig. 8.29–30). The presence of these medium-sized specimens of *Palaeopontosphaera* was also observed by Crux (1989) and Jeremiah (2001) in Early Hauterivian-early Late Barremian from the North Sea Basin. Jeremiah (2001) also recorded *P. giraudii* in the upper LK19 Zone and the lower LK18 Zone. The larger specimens recorded from LSBMRu1 correspond to the specimens recorded by Jeremiah (2001) in the interval including upper LK19-lower LK18 Zones. The HO of *P. giraudii* is observed in sample EC79. Jeremiah (2001) recorded the HO of *P. giraudii* in the lower LK18 Zone (Fig. 5).

Range: LO in Early Hauterivian Boreal Amblygonium ammonite Zone. HO in early Late Barremian Tethyan Vandenheckii ammonite Zone (Boreal early LK18 nannofossil Zone).

Palaeopontosphaera pinnata (Black 1971) De Kaenel, n. comb.
Figure 8.26–27

Basionym: *Cruciplacolithus pinnatus* Black 1971, p. 397, Pl. 30, Fig. 5.

Crucibisctum salebrosum (Black 1971) Jakubowski 1986 (cf. Crux 1989, Pl. 8.2, fig. 9, non fig. 8).
Crucibiscutum hayi (Black 1973) Jakubowski 1986 (cf. De Kaenel *in* Godet et al. 2010, fig. 14A.4-5).

Discussion: The species *pinnatus* was recombined with the genus *Sollasites* by Perch-Nielsen (1984) and with the genus *Crucibiscutum* by Rutledge and Bown *in* Bown et al. (1998). Because of the structure of the rim with a thin bright inner distal cycle, this species is transferred to the genus *Palaeopontosphaera* following the emendation of the genus by De Kaenel and Bergen (1993). Two species of *Palaeopontosphaera* with central cross structure are present in LSBMRu1: *P. pinnata* and *P. giraudii*. *P. pinnata* is small, between 3 and 5 µm with a thin central cross weakly birefringent which does not fill the central area. Specimens observed are between 4.5 and 4.9 µm. *P. salebrosa* and *P. giraudii* are differentiated from *P. pinnata* by its larger central cross that practically fills the central area. *P. pinnata* was described by Black (1971) for large forms of *Cruciplacolithus*. The holotype, from the Hauterivian, is 12.6 µm. Crux (1989) illustrated a form (Pl. 8.2, fig. 9) from the Late Hauterivian of the North Sea Basin with a thin central cross and a length of 3.25 µm. Rutledge and Bown *in* Bown et al. (1998) used the specimen illustrated by Crux (1989) for their new combination *Crucibiscutum pinnatus*. The size of the holotype of Black (1971) is problematic and we are using the size, 3 to 5 µm, indicated by Young et al. (2019). Crux (1989) recorded *P. salebrosa* up to the Boreal upper Denckmanii ammonite Zone in NW-European basins, but he did not separate *P. salebrosa* from *P. pinnata*. HO of *P. pinnata* is placed in the Late Barremian Tethyan Sartousiana ammonite Zone (Fig. 5).

Palaeopontosphaera salebrosa (Black 1971) Prins and Sissingh *in* Sissingh 1977.
Figure 8.28

Discussion: Typical *P. salebrosa* specimens are small, between 3 and 5.5 µm with a birefringent central cross filling the central area. The holotype of Black (1971) is 5.4 µm and these forms are not observed above the basal Early Barremian Hugii Zone (Fig. 5). The HO of *P. salebrosa* is used by Jakubowski (1987) to define the top of the NLK13 Zone in North Sea area and is correlated with the middle Early Barremian Rarocinctum Zone by Crux (1989) and Bown et al. (1998). *P. salebrosa* is only observed in sample EC51 at the base of the UJ. The specimen illustrated in Fig. 8.28 is 4.4 µm with a narrow central area completely filled by the central cross. The presence of *P. salebrosa* in sample EC51 is one of the key taxa with *N. abundans* to place the base of the UJ in the lower part of subzone LK20C and in the Boreal Early Barremian Rarocinctum ammonite Zone, which corresponds to the Tethyan Early Barremian Hugii ammonite Zone. *P. salebrosa* is considered as a high-latitude bipolar species (Street and Bown 2000) and is typical of Boreal and Austral latitudes. *P. salebrosa* is very similar to *Crucibiscutum hayi*, but this latter species is Albian-Cenomanian (Burnett 1998).

Genus *Percivalia* Bukry 1969

Percivalia fenestrata (Worsley 1971) Wise 1983
Figure 10.12–13

Genus *Perissocyclus* Black 1971

Perissocyclus plethotretus (Wind and Čepek 1979) Crux 1989

Perissocyclus tayloriae Crux 1989

Genus *Placozygus* Hoffman 1970

Discussion: Species of the genus *Placozygus* are separated from species of the genus *Zeugrhabdotus* by their bicyclic structure of the rim exhibiting a spiral interference pattern. In Early Cretaceous species, the inner bright cycle is thin. In Late Cretaceous species, the inner and outer distal cycles of the rim have a more distinct spiral extinction pattern.

Placozygus howei (Bown *in* Kennedy et al. 2000) De Kaenel, n. comb.
Figure 10.22–24

Basionym: *Zeugrhabdotus howei* Bown *in* Kennedy et al. 2000, p. 643–644, fig. 31 i, j, e', f'.

Discussion: The species *howei* is transferred to the genus *Placozygus* based on the bicyclic extinction pattern of the rim. In early specimens from the Barremian or Aptian the bicyclic pattern of the rim is still diffuse (Fig. 10.23). In Albian specimen (*Lordia* sp. A *in* Bergen 1998) the bright inner distal is more characteristic. Rare specimens of *P. howei* are present in LSBMRu1. LO of *P. howei* is placed by Bergen (1994) in the uppermost Early Barremian Compressissima and Moutonianum Zones (= *Zygodiscus elegans in* Bergen 1994).

Placozygus reticulatus (Black 1971) De Kaenel, n. comb.

Basionym: *Zygodiscus reticulatus* Black 1971, p. 420, Pl. 34, fig. 9.

Discussion: The species *reticulatus* is transferred to the genus *Placozygus* based on the bicyclic and sigmoid extinction pattern of the rim. The holotype of Black (1971) is a proximal view of a specimen observed in Early

Barremian from the North Sea area with a transverse bridge supporting a finely perforated floor granular. Rare specimens of *P. reticulatus* are observed in LSBMRu1. In XP light, the floor on each sides of the bridge exhibits a bright extinction pattern, which differentiate this species from all other *Placozygus* species. Black (1971) indicated a range from Early Barremian to Late Albian in North Sea Basin.

Placozygus trivectis (Bergen 1994) De Kaenel, n. comb.

Basionym: *Zeugrhabdotus trivectis* Bergen 1994, p. 65, Pl. 1, figs. 26a-b, 27a-c.

Discussion: The species *trivectis* is transferred to the genus *Placozygus* based on the bicyclic and sigmoid extinction pattern of the rim. *P. trivectis* is differentiated from other *Placozygus* species by the structure of the transverse bridge composed of three fused elements. LO of *P. trivectis* is placed by Bergen (1994) in the Early Valanginian Campylotoxus Zone (=*Neocomiensiformis* and *Inostranzewi* Zones, Reboulet et al. 2014). Rare specimens of *P. howei* are observed in LSBMRu1. This species is described as being cosmopolite.

Placozygus xenotus (Stover 1966) De Kaenel, n. comb.
Figure 10.25–27

Basionym: *Zygolithus xenotus* Stover 1966, p. 149, Pl. 4, figs. 16–17, Pl. 9, fig. 2.

Discussion: The species *xenotus* is transferred to the genus *Placozygus* based on the bicyclic and sigmoid extinction pattern of the rim (Fig. 10.27). *P. xenotus* has a well-developed inner distal cycle showing a bright sigmoidal birefringence pattern. *P. xenotus* is differentiated from other *Placozygus* by the structure of the central bridge composed by two well-separeted elements. Rare specimens of *P. xenotus* are observed in LSBMRu1. LO of *P. xenotus* is placed by Bergen (1994) in the Early Valanginian Campylotoxus Zone (=*Neocomiensiformis* and *Inostranzewi* Zones, Reboulet et al. 2014).

Genus *Reinhardtites* Perch-Nielsen 1968

Reinhardtites scutula Bergen 1994
Figure 9.17–19

Discussion: *R. scutula* was identified as *Zeugrhabdotus sisyphus* by Crux (1989) and *Zeugrhabdotus scutula* by Jeremiah (2001). This species has a distinct elongated, diamond-shaped transverse bar and is the ancestral species of the genus *Reinhardtites* (Bergen 1994). A few (10 specimens per traverse) of *R. scutula* can be observed in LSBMRu1. Rare to few *R. scutula* are also observed in samples from the Eclépens quarry up to the top of the Marnes de la Russille (MRu), in sample ECMRu10 (Fig. 13). These observations are one of the key observations to date these samples. Both Crux (1989) and Jeremiah (2001) observed in North Sea Basin and NW-European basin an increase in abundance of this taxon from the base of Elegans Zone to the middle Denckmanii Zone. Jeremiah (2001) defined the base of LK20A Subzone and top of LK18 Zone by, respectively, LFO and HFO of *R. scutula* (Fig. 5). The increase in abundance of *R. scutula* in LSBMRu1 corresponds to the same increase event and therefore the Eclépens (EC) samples belong to the nannofossil LK18 Zone of Jeremiah (2001). The increase of *R. scutula* in the Boreal basins and MRu of the Jura Mountains is associated with influx of northern cold/more saline waters due to improvement of connections to the north (Crux 1989). HO of *R. scutula* is in the Early Santonian (Burnett 1998).

Genus *Retecapsa* Black 1971

Retecapsa angustiforata Black 1971
Figure 9.23

Retecapsa crenulata (Bramlette and Martini 1964) Grün *in* Grün and Allemann 1975

Discussion: The genus *Retecapsa* includes Cretarhabdids species with an axial cross and accessory lateral bars. Based on the original definition of the genus *Retecapsa* by Black (1971), only forms with eight openings are included in this genus. Grün *in* Grün and Allemann (1975) emended the genus to include forms with more than eight openings as *R. crenulata* (12 pores) or *R. surirella* (12–16 pores). *R. surirella* has a distinct central platform surrounded by 12–16 pores and has been included in the genus *Cretarhabdus* by Reinhardt (1970) or Thierstein (1971). The emendation of the genus *Retecapsa* by Grün *in* Grün and Allemann (1975) is followed in this study.

Retecapsa octofenestrata (Bralower *in* Bralower et al. 1989) Bown *in* Bown and Cooper 1998 or Bergen 1998 (N.B. Bown's publication at 31/8/1998 is a little earlier to Bergen's paper in the last volume of *Géologie Méditerranéenne* for 1998).
Figure 9.22

Retecapsa surirella (Deflandre and Fert 1954) Grün *in* Grün and Allemann 1975

Genus *Rhagodiscus* Reinhardt, 1967

Rhagodiscus achlyostaurion (Hill 1976) Doeven 1983
Figure 10.7

Discussion: *R. achlyostaurion* was neither observed in LSBMRu1 nor in the Eclépens quarry samples. The rim of *R. achlyostaurion* is weakly bicyclic with a thin inner bright distal cycle. A bright circular spine is present in the centre of the central area. *R. buisensis* is differentiated from *R. achlyostaurion* by the presence of a spine base and the absence of the bright spine. Specimens larger than 6.5 µm are *R. hamptonii* and have a distinct bicyclic rim with an outer grey cycle and a thin inner bright cycle. The central area is larger with a small spine base and no spine. LO of *R. achlyostaurion* (Fig. 5) is younger than samples from the Eclépens quarry and is correlated with the middle of Feraudianus Zone (= upper Sartousiana Zone). An Aptian specimen from the Angles outcrop is illustrated in Fig. 10.7 to show the different spine structure compared to *R. buisensis*.

Rhagodiscus asper (Stradner 1963) Reinhardt 1967
Figure 10.3–4

Rhagodiscus buisensis De Kaenel, n. sp.
Figure 10.5–6

Rhagodiscus cf. *achlyostaurion* (Hill 1976) Doeven 1983 (cf. Bown *in* Kennedy et al. 2000, fig. 32u).

Derivation of name: Named after Les Buis quarry (La Sarraz, VD), W-Switzerland.

Diagnosis: A medium-sized species of *Rhagodiscus* with a weakly birefringent rim. The central area is narrow with a weakly birefringent small circular spine base and no developed spine.

Differentiation: *R. buisensis* is differentiated from *R. achlyostaurion* by the absence of a bright circular spine. Bown (*in* Kennedy et al. 2000) recorded specimens of *R. buisensis* as morphotypes of typical *R. achlyostaurion*. *R. buisensis* is also described to better detected/placed the LO of *R. achlyostaurion*.

Dimensions: Length = 5–6.5 µm, Width = 3.5–5 µm.

Holotype: Fig. 10.5, L = 5.1 µm, W = 3.6 µm.

Paratype: Fig. 10.6, L = 5.3 µm, W = 3.8 µm.

Type locality: Les Buis quarry near La Sarraz, western Swiss Jura Mountains (coordinates 2528.240/1168.170, map 1:25′000 of Switzerland).

Type level: Marnes de la Russille (sample LSBMRu1).

Discussion: Early morphotype of *R. achlyostaurion* (*R. buisensis*) were also recorded in the Eclépens quarry samples and these occurrences are important for biostratigraphy. LO of *R. achlyostaurion* occurs in the upper Sartousiana Zone (Fig. 5) and the presence only of specimens of *R. buisensis* indicates older samples. *R. buisensis* is an intermediate form between *R. asper* (granular plate) and *R. achlyostaurion* (granular plate with a thick, bright circular spine base).

Range: *R. buisensis* is not observed below the uppermost Early Barremian. Bown (*in* Kennedy et al. 2000), Herrle and Mutterlose (2003) and Giraud et al. (2018) reported *R. buisensis* (*R. achlyostaurion* no spine) in the Late Aptian and Early Albian.

Rhagodiscus eboracensis Black 1971
Figure 10.1–2

Rhagodiscus gallagheri Rutledge and Bown 1996

Discussion: *R. gallagheri* is a small species of *Rhagodiscus* (< 5 µm) with slightly convex or straight longer sides. *R. gallagheri* is neither observed in sample LSBMRu1 or in samples from the Moutonianum Zone. Its LO is recorded in sample LSBMRu5 or one sample as EC72b above the HO of *C. oblongata* and is present to the top of the LSBMRu samples and in the Eclépens samples EC72b/EC79 (Figs. 12, 13), which are in the early Late Barremian LK18 Zone. Rutledge and Bown (1996) placed the LO of *R. gallagheri* at the base of the Aptian. Aguado et al. (2014b) recorded *R. gallagheri* in the upper Barremian Sarasini Zone (Zone NC5E). De Kaenel *in* Godet et al. (2010) illustrated *R. gallagheri* from sample EC79 of the Eclépens quarry.

Rhagodiscus infinitus (Worsley 1971) Applegate, Covington and Wise *in* Covington and Wise 1987

Rhagodiscus pseudoangustus Crux 1987

Rhagodiscus robustus Bown 2005
Figure 10.8–9

Rhagodiscus sageri Bown 2005
Figure 10.10–11

Genus *Rotelapillus* Noël 1973

Rotelapillus crenulatus (Stover 1966) Perch-Nielsen 1984
Figure 11.14–15

Genus *Sollasites* Black 1967

Sollasites horticus (Stradner, Adamiker and Maresch *in* Stradner and Adamiker 1966) Čepek and Hay 1969
Figures 8.14–15

Discussion: The two species of *Sollasites* present in Barremian can be identified by their size when the central area structures are not preserved. *S. lowei* is a very small to medium-sized species with a medium-sized central-area (Fig. 8.13). *S. horticus* is a medium-sized species with a narrow rim and a large central-area (Fig. 8.15). *S. horticus* is a Boreal taxon. A short increase of *S. horticus* is observed by Jeremiah (2001) in the upper Zone LK19 associated with LO of *B. galloisii*. Crux (1989) observed in North Sea Basin the re-entry of *S. horticus* and *T. septentrionalis*. Both species range from the Jurassic to the Late Cretaceous.

Sollasites lowei (Bukry 1969) Rood, Hay and Barnard 1971
Figure 8.13

Genus *Tegulalithus* Crux 1986

Tegulalithus septentrionalis (Stradner 1963) Crux 1986
Figure 7.1–11

Discussion: The re-entry of *T. septentrionalis* at the base of Elegans Zone was well observed and illustrated by Crux (1989) in North Sea Basin and NW-European basin. The same specimens are observed in sample from LSBMRu1 and are typical forms, similar to the holotype. The holotype of Stradner (1963) has a size of 7 µm with 18 elements. Many variations are observed. Smaller forms have a wider central tube and less elements (Fig. 7.6–8), but are still included in the same species. The smaller form has a size of 3.6 µm with 14 elements and a wide central tube (Fig. 7.8). These smaller specimens have been sometimes identified as *Diazomatolithus lehmanii*. Crux (1989, Pl. 8.2, fig. 7) illustrated a nice specimen of small *T. septentrionalis* (identified as *D. lehmanii*) from the middle Elegans Zone. On this SEM picture, the upper cycle (4 µm) and lower cycles (2.7 µm) are quite visible. The abundance of *T. septentrionalis* is relatively high (10 specimens per traverse) in LSBMRu1. Crux (1989) explained the re-entry of the Boreal species *T. septentrionalis* by the improvement of marine connections to the north during a transgressive period. He also associated this return with the increase of *R. scutula*. HO of *T. septentrionalis* in the Swiss Jura Mountains follows the calibration from Crux (1989) in the northwestern area of Europe (north Germany) and is placed in the middle Denckmanii Zone (Fig. 5) with very rare specimens observed in ECMRu10 sample (Fig. 13). The HFO of *R. scutula* is recorded by Crux (1989) just above the HO of *T. septentrionalis*. The total range of *T. septentrionalis* is recorded by some nannopalaeontologists as intra-Late Hauterivian, as per Bown et al. (1998) and Jeremiah (2001). And this is one of the best markers, with a very short range, used to zone the Late Hauterivian in many North Sea wells. For these nannopalaeontologists, the presence of *T. septentrionalis* in mid-Barremian is either due to reworking or attributable to the superficially similar *Nannoconus pseudoseptentrionalis*. Both species are present in sample LSBMRu1 (see also the last chapter "Discussion" below).

Genus *Tegumentum* Thierstein *in* Roth and Thierstein 1972

Tegumentum octiformis (Köthe 1981) Crux 1989
Figure 9.14–15

Discussion: *T. octiformis* is a typical endemic Boreal species not recorded in Tethyan areas. HO of *T. octiformis* is placed in the Late Barremian Bidentatum Zone (upper LK15 Zone) by Jeremiah (2001) in North Sea Basin.

Tegumentum stradneri Thierstein *in* Roth and Thierstein 1972

Genus *Tranolithus* Stover 1966

Tranolithus gabalus Stover 1966

Genus *Tubodiscus* Thierstein 1973

Tubodiscus burnettiae Bown *in* Kennedy et al. 2000
Figure 11.29–30

Discussion: *T. burnettiae* is a medium-sized species, between 6 and 8 µm. *T. burnettiae* is distinguished from *T. jurapelagicus* by the shape of the rim, broadly elliptical, its broader rim, and by its thicker inner distal cycle.

Tubodiscus jurapelagicus (Worsley 1971) Roth 1973
Figure 11.27–28

Discussion: Two species of *Tubodiscus* are present in LSBMRu1, *T. burnettiae* and *T. jurapelagicus*. *T. burnettiae* ranges from the Valanginian to the Albian and *T. jurapelagicus* from the Berriasian to the early Late Barremian (Fig. 5). Applegate and Bergen (1988) recorded the HO of *T. jurapelagicus* in the Barremian. *T. jurapelagicus* was

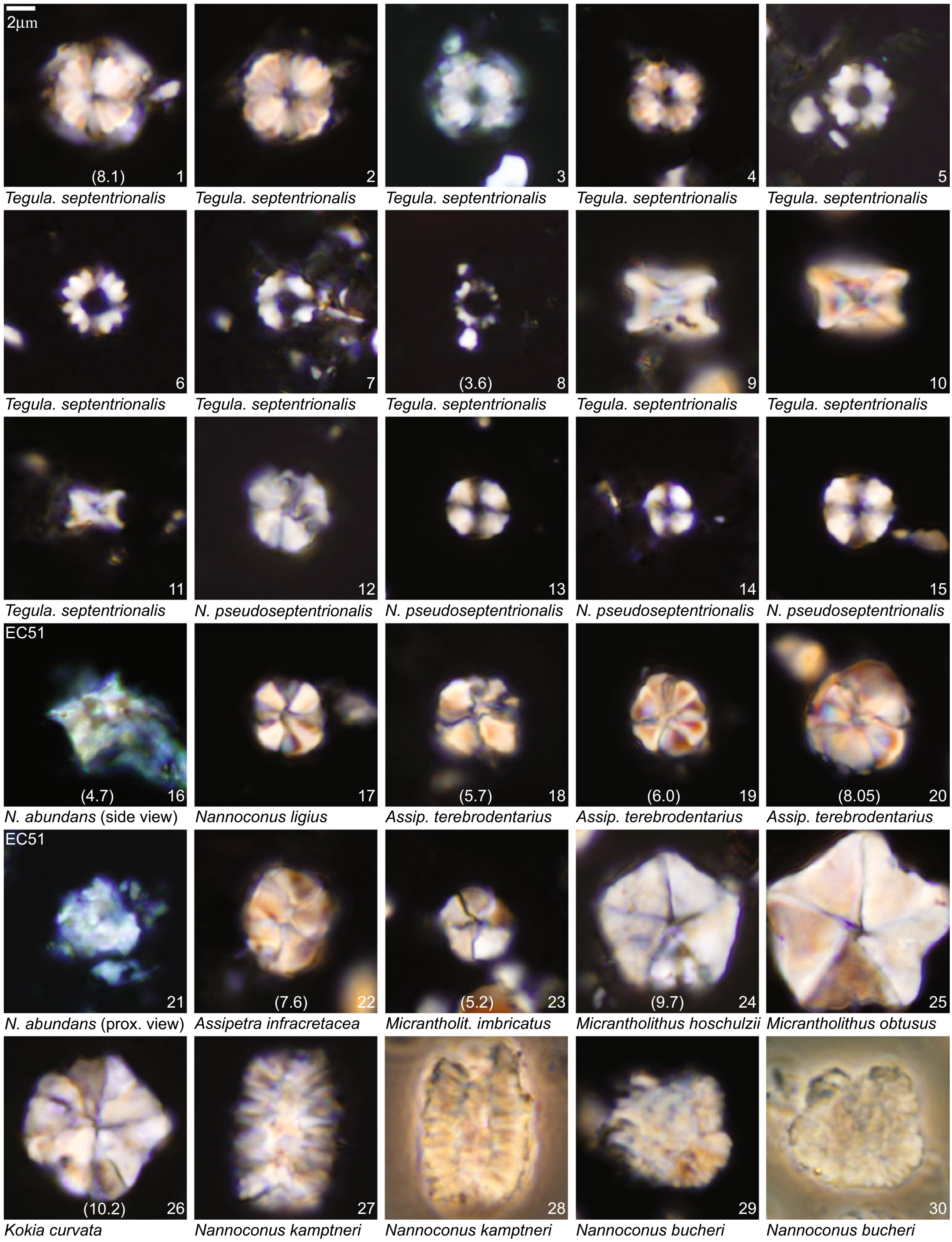


Fig. 7 Calcareous nannofossils from the Marnes de la Russille (Barremian) of the Swiss Jura Mountains. All LM pictures from La Sarraz–Les Buis quarry (without sample numbers: LSBMRu1) and Eclépens quarry (with sample numbers: EC)

(See figure on next page.)

Fig. 8 Calcareous nannofossils from the Marnes de la Russille (Barremian) of the Swiss Jura Mountains and from the Aptian of the section Angles (SE-France). All LM pictures from La Sarraz–Les Buis quarry (without sample numbers: LSBMRu1) and Eclépens quarry (with sample numbers: EC). LM pictures from Angles section: 16–17 (same specimen in different orientation) and 18–19 (same specimen in different orientation)

not observed in sample EC79 from the Eclépens quarry from the Vandenheckii Zone. HO of *T. jurapelagicus* in sample LSMRu9 occurs between the HO of *E. hauterivianus* and the LO of *F. oblongus* and is correlated with the early Late Barremian Vandenheckii Zone. These two species of *Tubodiscus* are considered as cosmopolite species.

Genus *Vagalapilla* Bukry 1969

Discussion: Several genera (*Staurolithites*, *Vekshinella* and *Vagalapilla*) have been used to combine this group of muroliths with a central cross. De Kaenel and Bergen (1996) used the genus *Vagalapilla* based on the detailed description of the type species of the genus (*V. imbricata* of Gartner 1968) by Bukry (1969). The holotypes for the genus *Staurolithites* (Caratini 1963) and for the genus *Vekshinella* (Loeblich and Tappan 1963) are dubious. Caratini (1963) includes in this genus all circular and elliptical forms with an open central area spanned by all kind of central structure crosses. The type species for the genus *Vekshinella* (*Ephippium acutiferrus* of Vekshina 1959) has a short, slightly convex proximal spine and a long sharp distal spine and represents a very different group of forms.

Vagalapilla crux (Deflandre and Fert 1954) Lyulyeva 1980
Figure 9.1–2

Discussion: Following the combination from Lyulyeva (1980), the genus *Vagalapilla* Bukry (1969) is used herein for this species because of the questionable type species and holotype of genus *Staurolithites*. *V. crux* is differentiated from other *Vagalapilla* species by its thin rim and very thin, simple axial cross. The inner distal cycle of the rim is not visible in XP light.

Vagalapilla parallela (Wind and Čepek 1979) De Kaenel and Bergen 1996

Vagalapilla recta (Black 1971) De Kaenel, n. comb.
Figure 9.3–4

Basionym: *Staurolithites rectus* Black 1971, p. 419, Pl. 34, fig. 6.

Discussion: Genus *Vagalapilla* Bukry (1969) is used herein for this species because of the questionable type species and holotype of the genus *Staurolithites*. The rim of *V. recta* is similar to the rim of *V. crux*, but the central axial cross is larger with distinct axial suture lines. Black (1971) described *V. recta* from the Barremian of the North Sea Basin. Young et al. (2019) considered *V. recta* as a junior synonym of *V. crux*. But the structure of the axial cross of specimens of *V. recta* observed in sample LSBMRu1 is different from the axial cross of *V. crux*. The structure of the axial cross with the median suture line is also distinct on the holotype of Black (1971) and supports the splitting of these two species.

Vagalapilla rutledgei De Kaenel, n. sp.
Figure 9.8–10, 13

Eiffelithus? sp. 2 Covington and Wise 1987, p. 630, Pl. 2, figs. 7, 8, 9.

Derivation of name: Named after Dr David Rutledge (PetroStrat Ltd, Wales, United Kingdom), a nannopalaeontologist.

Diagnosis: A medium-sized species of *Vagalapilla* with a birefringent bicyclic rim and a broad inner distal cycle. The central area is almost closed by a broad birefringent axial cross bar with flaring terminations and median suture when observed at 45°.

Differentiation: *V. rutledgei* is differentiated from other bicyclic species of *Vagalapilla* by its broad birefringent axial cross. In *V. mitcheneri*, the other bicyclic *Vagalapilla* present in Barremian, the axial cross structure is different, distinctly flaring from the centre with a median suture at 0°, that does not fill the central area.

Dimensions: Length = 5–6.5 μm, Width = 3.5–5 μm.

Holotype: Figs. 9.8–10, L = 5.9 μm, W = 4.2 μm.

Paratype: Fig. 9.13, L = 5.1 μm, W = 3.8 μm.

Type locality: Eclépens quarry nearby Eclépens, western Swiss Jura Mountains (Godet et al. 2010, coordinates 2531.256/1167.183, map 1:25′000 of Switzerland).

Type level: Marnes de la Russille (sample EC79).

Discussion: Applegate and Bergen (1988) placed *Eiffellithus* sp. 2 in synonymy with their new species *V.*


2µm
1
Palaeop. elliptica
2
Palaeop. elliptica
3
Palaeop. elliptica
4
Palaeop. elliptica
5
Palaeop. elliptica
(3.8) 6
Biscutum constans
(3.4) 7
Biscutum constans
(4.2) 8
Biscutum constans
Holotype
(6.7) 9
Biscutum jurensis
Holotype
10
Biscutum jurensis
Paratype
(7.0) 11
Biscutum jurensis
Paratype
12
Biscutum jurensis
(4.5) 13
Sollasites lowei
(6.1) 14
Sollasites horticus
(8.05) 15
Sollasites horticus
Aptian
(5.7) 16
Flabellites oblongus
Aptian
(6.1) 18
Flabellites oblongus
Holotype Eclépens-EC79
(4.0) 20
Flabellites eclepensensis
Paratype Eclépens-EC79
(4.4) 22
Flabellites eclepensensis
Eclépens-EC72b
(4.4) 24
Flabellites eclepensensis
Aptian
17
Flabellites oblongus
Aptian
19
Flabellites oblongus
Holotype
21
Flabellites eclepensensis
Paratype
23
Flabellites eclepensensis
25
Flabellites eclepensensis
(4.6) 26
Palaeop. pinnata
(4.6) 27
Palaeop. pinnata
Eclépens-EC51
(4.4) 28
Palaeop. salebrosa
Holotype
(6.6) 29
Palaeop. giraudii
Paratype Eclépens-EC55
(7.6) 30
Palaeop. giraudii

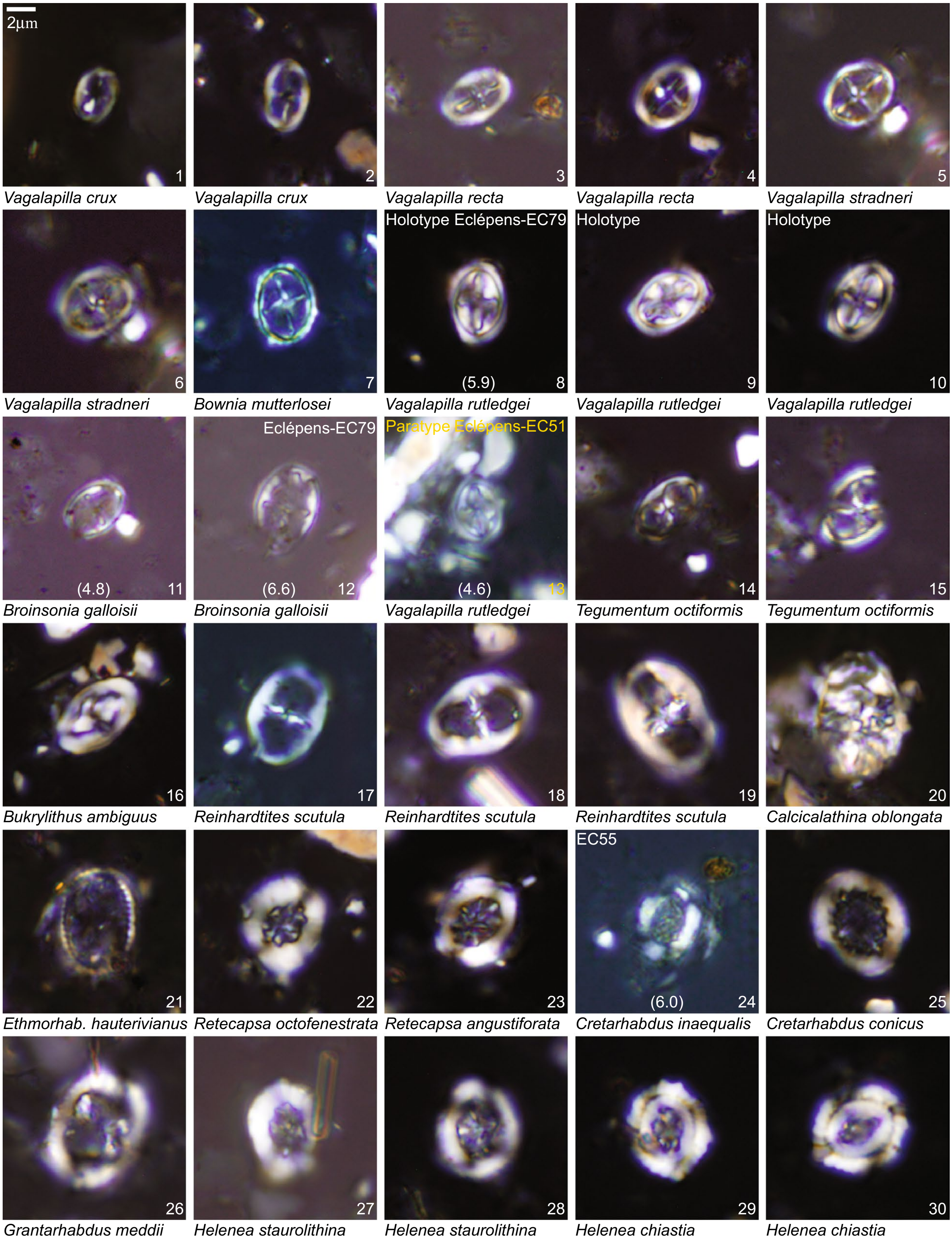


Fig. 9 Calcareous nannofossils from the Marnes de la Russille (Barremian) of the Swiss Jura Mountains. All LM pictures from La Sarraz–Les Buis quarry (without sample numbers: LSBMRu1) and Eclépens quarry (with sample numbers: EC)

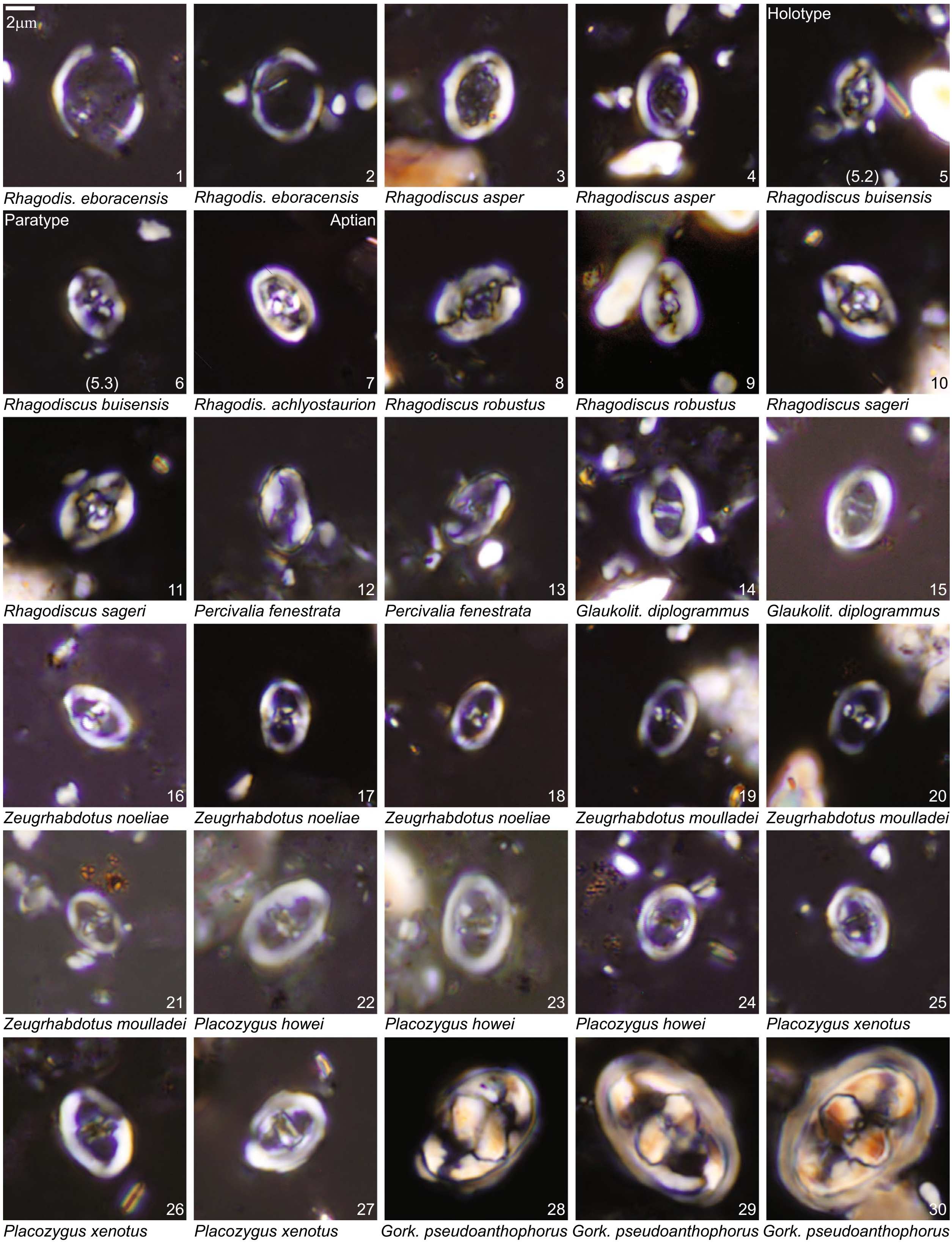


Fig. 10 Calcareous nannofossils from the Marnes de la Russille (Barremian) of the Swiss Jura Mountains and from the Aptian of the section Angles (SE-France). All LM pictures from La Sarraz–Les Buis quarry (without sample numbers: LSBMRu1). LM picture from Angles section: 7

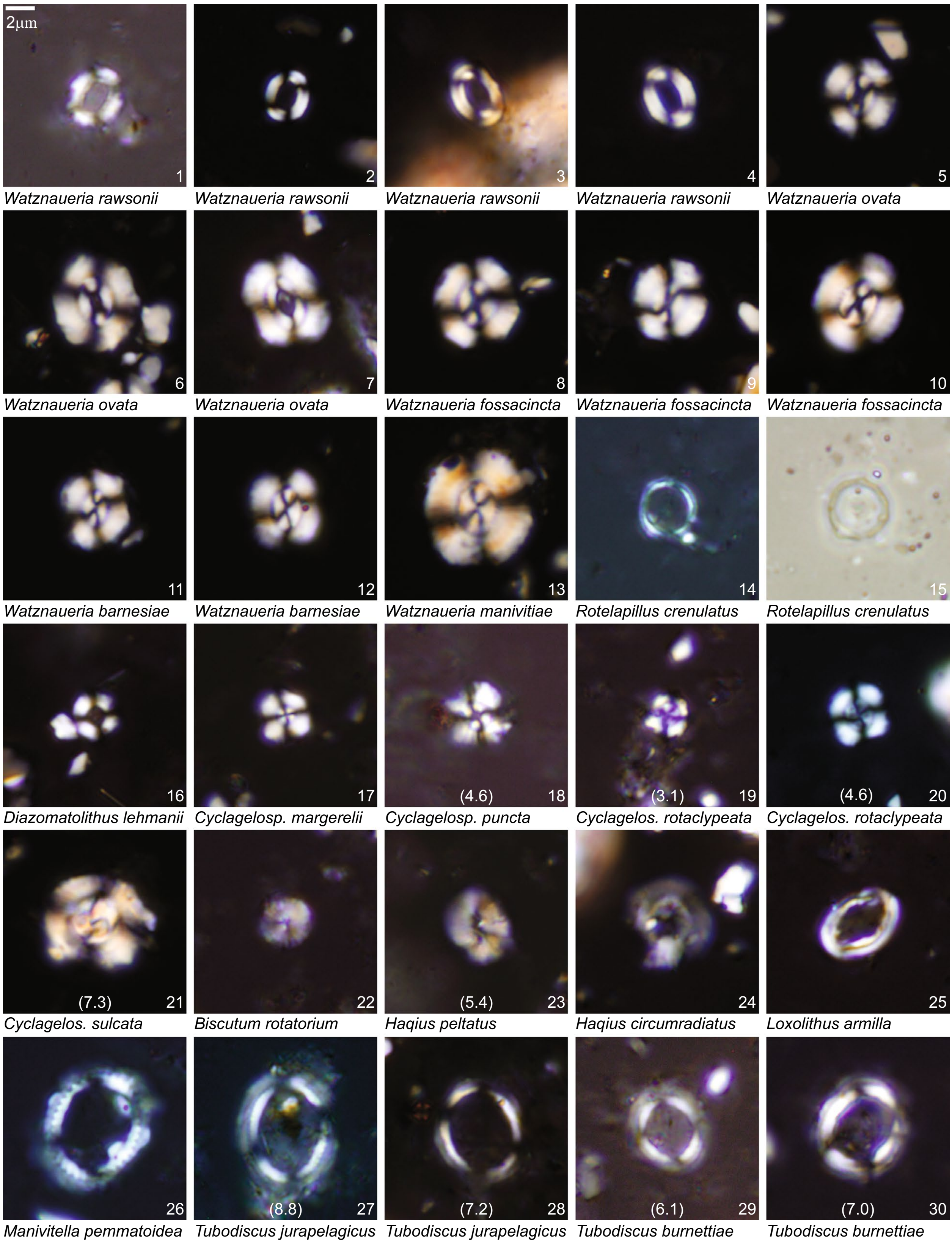


Fig. 11 Calcareous nannofossils from the Marnes de la Russille (Barremian) of the Swiss Jura Mountains. All LM pictures from La Sarraz–Les Buis quarry (without sample numbers: LSBMRu1)

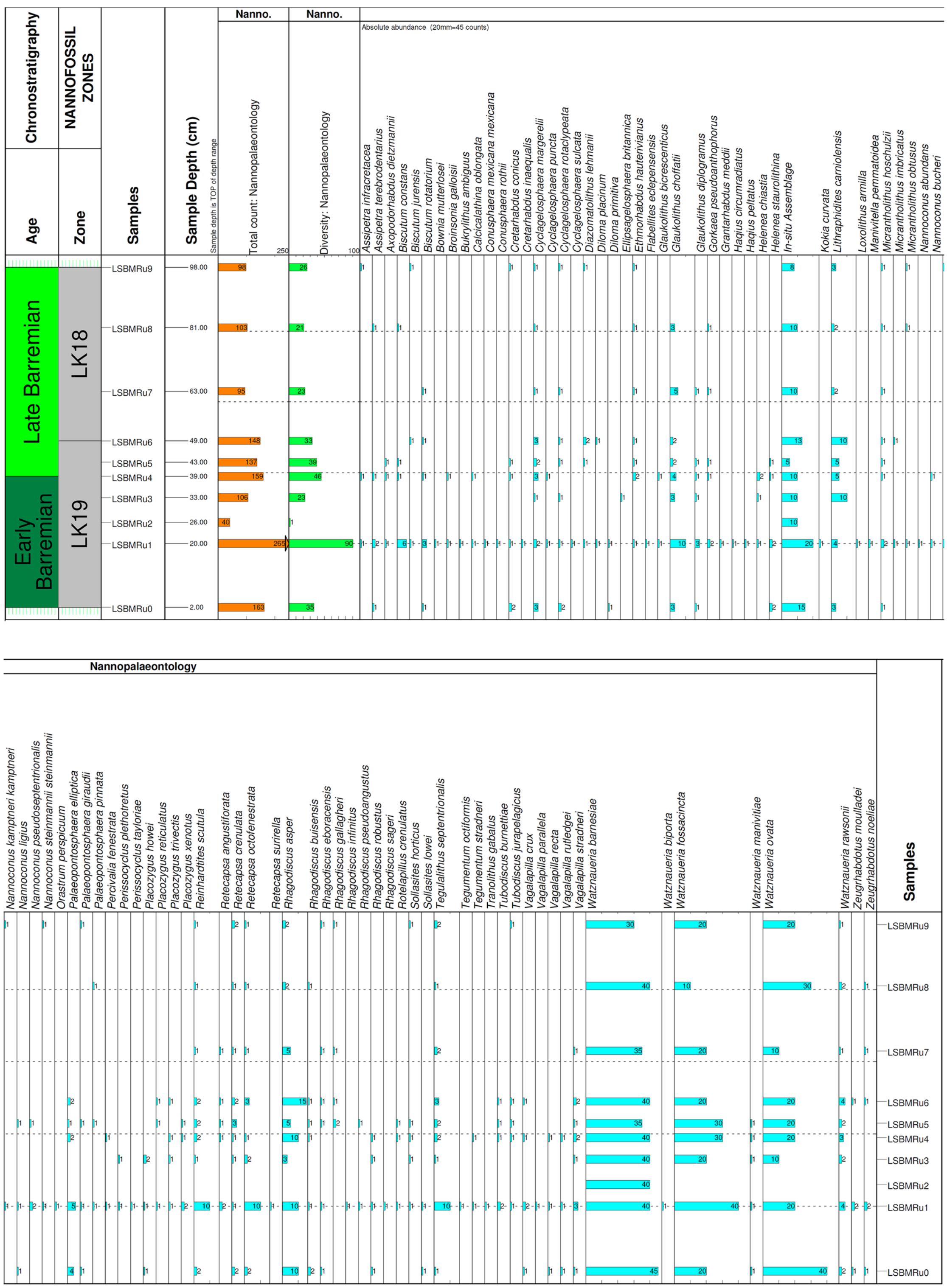


Fig. 12 Nannofloras from the Marnes de la Russille (MRu) in the La Sarraz–Les Buis quarry (LSB). In order to avoid very high numbers for nannofossil counts, a 0–100 based counting system is used. The numbers for individual species represent semi-quantitative count estimation of specimens/100 fields of view (FOV). Numbers from 1 to 20 represent the estimation of species per 100 FOV. Numbers above 20 are coded: 25 (one specimen/4FOV), 30 (one specimen/3FOV), 35 (one specimen/2FOV), 40 (one specimen/1FOV), 45 (two specimens/1FOV). The numbers for total abundance (in situ) estimation represent the number of specimens per 5 FOV

Fig. 13 Nannofloras from the Marnes de la Russille (MRu) in the Eclépens quarry (EC)

mitcheneri. The holotype of *V. mitcheneri* has a quite different central cross structure that specimens illustrated as *Eiffellithus* sp. 2 by Covington and Wise (1987). These specimens correspond to *V. rutledgei*.

Range: Rare specimens of *V. rutledgei* are recorded in LSB-MRu1 and from EC51 to EC79. *V. rutletgei* (=*Eiffellithus* sp. 2) is very rare in uppermost Hauterivian, common in Early Barremian and rare in Late Barremian from the northwestern Atlantic Ocean on DSDP Leg 93 (Covington and Wise, 1987). The HO is near the top of the Barremian (Fig. 5).

Vagalapilla stradneri (Rood, Hay and Barnard 1971) Thierstein 1973

Figure 9.5–6

Discussion: *V. stradneri* is differentiated from other Barremian *Vagalapilla* species with unicyclic rim by the shape of the rim, broadly elliptical and the thin axial cross supporting a bright spine base. The attachments of the axial cross to the rim show some enlargements.

Genus *Watznaueria* Reinhardt 1964

Watznaueria barnesiae (Black *in* Black and Barnes 1959) Perch-Nielsen 1968
Figure 11.11–12

Watznaueria biporta Bukry 1969

Watznaueria fossacincta (Black 1971) Bown *in* Bown and Cooper 1989
Figure 11.8–10

Watznaueria manivitiae Bukry 1973
Figure 11.13

Watznaueria ovata Bukry 1969
Figure 11.5–7

Watznaueria rawsonii Crux 1987
Figure 11.1–4

Discussion: *W. rawsonii* is a small (3.5–5 μm) species of *Watznaueria* with a normal width central area filled by a delicate and irregular grill. When preserved (Fig. 11.1), the grill is weakly birefringent. In sample LSBMRu1, *W. rawsonii* is relatively common, but much less than *W. barnesiae*, *W. fossacincta* and *W. ovata*. LO of *W. rawsonii* is placed by Crux (1989) in the Late Hauterivian Variabilis Zone in the Northern Germany basin. HO of *W. rawsonii* is not yet well constrained, but is present in the Late Barremian Sartousiana Zone (sample ECMRu10 from the Eclépens quarry).

Genus *Zeugrhabdotus* Reinhardt 1965

Zeugrhabdotus moulladei Bergen 1998
Figure 10.19–21

Discussion: LO of *Z. moulladei* (=*Zeugrhabdotus* sp. A) is placed by Bergen (1994) in the latest Hauterivian Angulicostata (=Ohmi) Zone (Fig. 5). *Z. moulladei* is differentiated from *Z. erectus* by the latitudinal extinction line on each sides of the transverse bar.

Zeugrhabdotus noeliae Rood, Hay and Barnard 1971
Figure 10.16–18

Discussion

The very rich and well-preserved nannoflora presented in this study combined with those published by Godet et al. (2010) confirm the Barremian age of the MRu intercalations and therefore allow to refute the Late Hauterivian age as proposed by Clavel et al (2007) according to a poor number of 8 recognized nannoplankton species and some erroneous determinations or inaccurate time distributions. In Clavel et al. (2007, Pl. 8, fig. H), *Crucibiscutum trilensis* Bown and Concheyro 2004 is confounded with a typical, very large-sized Early Albian *Flabellites oblongus* of nearly 10 μm (Bown 2005, p. 30) obviously reworked from a Late Eocene palaeokarst (Siderolithic deposits), whereas early smaller specimens of *F. oblongus* recognized by Aguado et al. (2014a) correspond to *Flabellites eclepensensis* De Kaenel, n. sp. *Crucibiscutum salebrosum* is recombined into the species *Palaeopontosphaera giraudii* De Kaenel, n. sp. and *Palaeopontosphaera pinnata*, not at all "extremely rare or absent in deposits younger than Late Hauterivian" (Clavel et al. 2007, p. 1038). Moreover, *Tegulalithus septentrionalis* is absolutely not "restricted in Sayni-Ligatus Zone" as asserted by Clavel et al. (2007), but likewise a typical Barremian species well represented in the North Sea and NW-European basins (Mutterlose and Harding 1987; Crux 1989).

According to the new biostratigraphical nannofossil data presented in this study, all the orbitolinids from the Urgonian facies at Eclépens and La Sarraz–Les Buis assigned to the Late Hauterivian by Clavel et al. (2007, 2014) are indeed Barremian, notably with Early to early Late Barremian species of biostratigraphic importance such as *Praedictyorbitolina busnardoi* Schroeder, Clavel, Cherchi and Charollais 1999, *Praedictyorbitolina claveli* Schroeder 1994, *Praedictyorbitolina carthusiana* Schoeder, Clavel and Charollais 1990 and *Valserina primitiva* Schroeder, Charollais and Conrad 1969. An Early to Late Barremian age is therefore mainly applicable to the associated assemblages of other fossils and microfossils from the UJ–MRu complex including echinoids, brachiopods, benthic foraminifera, dasycladacean algae, ostracods, dinokysts (Clavel et al. 2007, p. 1037–1038, Pl. 7; Ghasemi-Nejad *in* Godet 2006, p. 364–369, Pls. 1–3), and spores and pollens (Ghasemi-Nejad *in* Godet 2006, p. 370/Pl. 4).

The studied sections of Eclépens and La Sarraz–Les Buis differ strongly regarding thickness and facies distribution, and are separated by faults within the Mormont–La Sarraz fault system in the extension of the Pontarlier fault system (Fig. 1a). Their differences of thickness and facies distribution as well as the hiatus of the Late Hauterivian deposits can be explained by synsedimentary tectonics of tilted blocks with differential subsidence generated by oblique-slip faults of the Pontarlier fault system

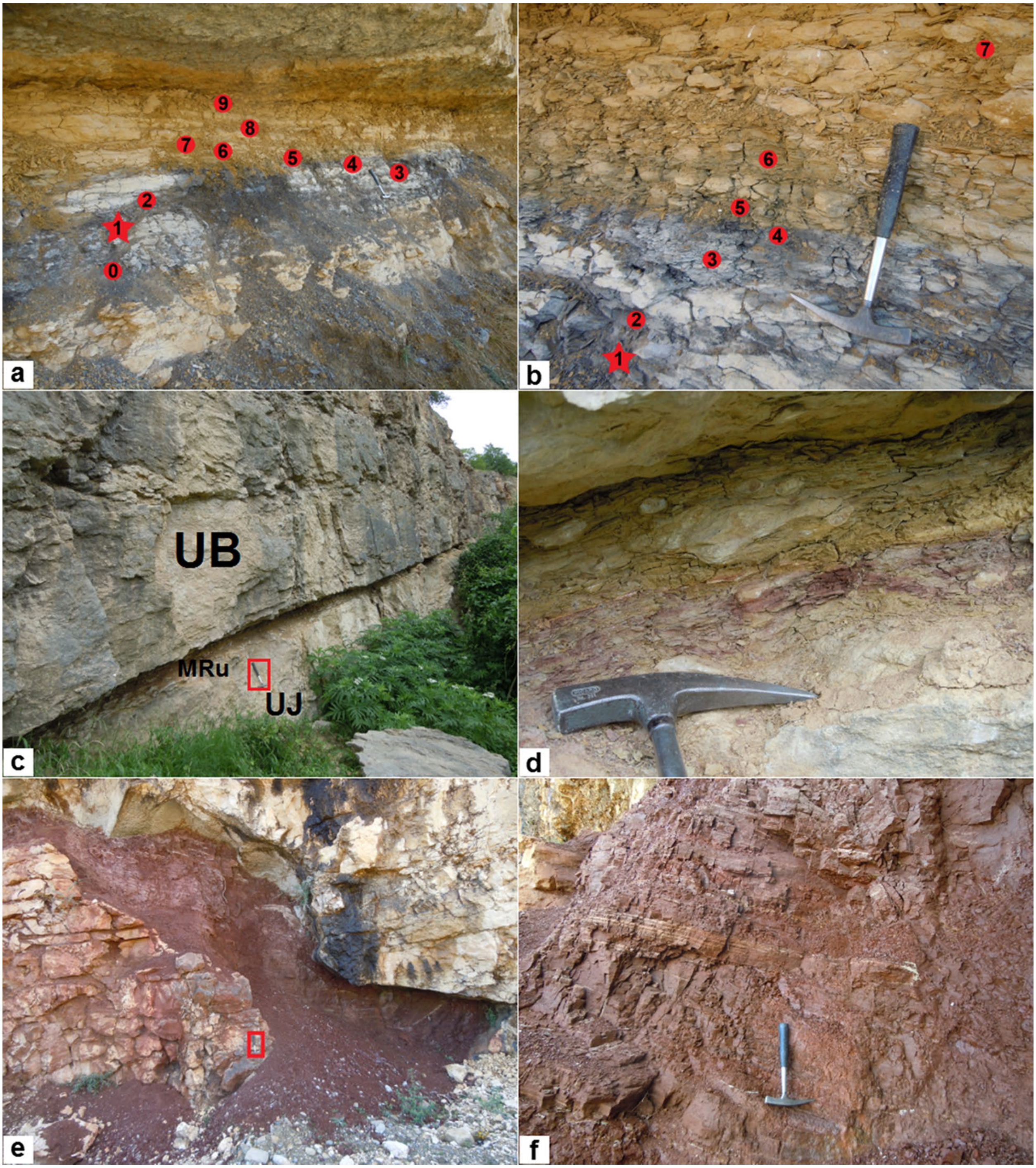


Fig. 14 **a, b** La Sarraz–Les Buis quarry Sect. (8/3/2020), channel infill of Marnes de la Russille (MRu) with LSBMRu0-9 samples positioned (red star and circles), the transitional change of colour between LSBMRu4 and LSBMRu5 indicates the Early/Late Barremian boundary. **c, d** Eclépens quarry Sect. (24/6/2018), transition of the highest Marnes de la Russille (MRu) between Urgonien Jaune (UJ) and Urgonien Blanc (UB) facies, with coloured marls partly rubefied (d, sample ECMRu10). **e, f** La Sarraz–Les Buis quarry Sect. (8/3/2020), paleokarst with Late Eocene infilling of red clays and marls (Siderolithic deposits) in the lower part of the massive UB limestones. Scale: hammer (red frame in c, e) = 31.5 cm long

(synsedimentary faults), a major and presumed very deep Late Palaeozoic Hercynian break until the crystalline basement of the Jura Mountains. This synsedimentary tectonic activity or "Barremian crisis" experienced his maximum activity with a "Hauterivian–Barremian tectonically enhanced unconformity" observed at the Hauterivian–Barremian transition in the Urgonian facies of the Western Alps of SE-France (Arnaud 1981: hauts-fonds du Trièves et du Vercors méridional, *in* Résumé, p. 2–3; Arnaud 2005, p. 13–15; Arnaud-Vanneau et al. 2005, p. 98, 123). Accordingly, the reddish cross-bedding of the sequence Ha7 at La Sarraz–Les Buis (Fig. 1b, f-g) can be interpreted as eroded and reworked Late Hauterivian ferruginous palaeosols or "terra rossa" developed in a hot and wet climate on emersion surfaces of tilted blocks. Similarly, coeval bauxite deposits with lacustrine sediments of this "Barremian crisis" are also known on the western and eastern Tethyan margins forming an extensive archipelago, in NE-Spain (Mojon 1996, 2002) and in NW-Romania (Dragastan et al. 1988), respectively.

The difference in thickness (35 m) of the UJ–MRu complex between Eclépens (47 m) and La Sarraz–Les Buis (12 m) seems considerable, but is misleading according to differential subsidence in fault-bounded compartments and deposition of very fine-grained and pyrite/organic-rich marls (MRu) with nannoflora at La Sarraz–Les Buis that certainly took place much slower (cf. Gallego-Torres et al. 2015 for comparable paleoenvironment of deposition) when compared to the very thick bioclastic UJ limestones with stromatoporoids well developed at Eclépens. Thus, the 44 m of late Early to early Late Barremian UJ with MRu deposits in the Eclépens quarry (with EC72b-79/ECMRu10 samples) overall correspond to the channel infilling of the La Sarraz–Les Buis quarry with a little more than 1 m thickness deposited in about 1.2 million years (Fig. 5), and characterized by a very slow MRu sedimentation rate as well as rich nannofloras (LSBMRu0-9 samples). The topmost interval EC79-ECMRu10 is not represented in the La Sarraz– La Sarraz–Les Buis quarry section, probably eroded and reworked by the prograding Urgonien Blanc (UB) facies.

Sedimentological and sequential interpretation of the La Sarraz–Les Buis section compared to the Eclépens section

According to the sedimentological and micropalaeontological features, the channel of the La Sarraz–Les Buis quarry with its very fine-grained marly MRu infilling (Fig. 1c) is interpreted as a deep tidal channel in an estuarine palaeoenvironment with turbid waters, well-known to be very rich in clayey sediments (Reynaud and Dalrymple 2011) and nutriments ideal for increased growth of nannoplankton (Cloern et al. 2014). MRu infillings of smaller channels in the NW cliff of the quarry (Fig. 1h-i) are interpreted as proximal linear dendritic ramifications (cf. Hughes 2011) of the distal larger channel analysed in this study (Figs. 1c, d and 3), observed approximately 20 m below and 250 m laterally at the base of the opposite SE cliff (slope around 8% and 3.5°). The depth can be estimated with the photic zone necessary for the nannoplankton photosynthesis, generally optimal down to a depth of 130–150 m in open marine environment (Gundersen et al. 1976; Winter et al. 2002), but only down to 1 to 50 m in estuaries or turbid coastal waters (Harding et al. 1987, p. 404).

The storm wave base indicates a maximum depth for sediment erosion and reworking, in the case of shallow epicontinental seas such as the Urgonian platform of the Jura Mountains, down to 50 ± 20 m according to Immenhauser (2009). As the UJ–MRu complex was deposited in a small coastal area particularly protected by offshore oolithic/bioclastic carbonate sand bars and stromatoporoid bioconstructions/rudist reefs, the MRu infilling of the channel at La Sarraz–Les Buis probably lied at an estimated palaeodepth of 40–50 m, coherent with other field observations reported.

The channel itself was incised on an erosional shallow surface by tidal currents at the beginning of the 3rd order sequence Ba2 in the late Early Barremian Moutonianum Zone (Fig. 3), then rapid subsidence generated a significant deepening with deposition of the very fine-grained MRu infilling corresponding to the Ba2 transgressive interval. This dynamic process of subsidence was still active in the beginning of the 3rd order sequence Ba3 (Vandenheckii Zone) and its boundary with sequence Ba2 is included within the MRu. Finally, the MRu infilling is overlaid by the middle Late Barremian prograding Urgonien Blanc (UB) facies of the Ba3 highstand system track (Godet et al. 2010).

The stratigraphical scheme of the Eclépens quarry section can be transposed to the La Sarraz–Les Buis quarry section (Figs. 1b, 3). Our sequence stratigraphy interpretation includes the sequences E2 and E3 previously defined by Godet et al. (2010) at Eclépens and located between the early Late Hauterivian Ha4 and early Late Barremian Ba3 sequences introduced by Arnaud (2005). The nannofossil datings clearly indicate two sequences Ba1′ and Ba2 within the interval corresponding to the highstand system track (HST) of sequence E2 introduced by Godet et al. (2010), in a series influenced by synsedimentary tectonics. Maximum flooding surface (MFS) E2 of Godet et al. (2010) distinctly denotes a sedimentary change, but we consider the massive bioclastic limestone bed with cross-stratification placed below as a shallow tidal bar preceding marly sediments with Early Barremian nannofloras EC55-57 in the transgressive system track (TST) of sequence Ba1′ (Pulchella and

Compressissima Zones). Thus, we rather interpret mfsE2 as a sedimentary discontinuity or sequence boundary (SB) corresponding to SbB1′. Nannofossil dating of the marly sample EC72b also unequivocally shows the beginning of the early Late Barremian (Vandenheckii Zone) corresponding to the TST of Late Barremian sequence Ba3, above more calcareous beds of the presumed HST of late Early Barremian sequence Ba2.

According to the nannofossil data, the sequence boundary SbB3 therefore must be placed a little lower than the equivalent SbE3 positioned by Godet et al. (2010), and the two massive bioclastic limestone beds with cross-stratification below the early Late Barremian sample EC79 can also be interpreted as shallow tidal bars in the TST of sequence Ba3. Without precise nannofossil datings in this Early to early Late Barremian UJ series of Eclépens, there are objectively no absolute sedimentological criteria available to recognize and to interpret sequences with certainty.

At La Sarraz–Les Buis section, two marly superimposed Barremian sequences Ba2 and Ba3 including each an alternation of marls and more calcareous layers can be reported in the channelized MRu infilling. The late Early Barremian sequence Ba2 is well developed with very fine, dark grey and organic-rich marls and the nannofossil-rich key sample LSBMRu1 illustrating perfectly the Mid-Barremian Event (MBE) recognized in SE-Spain and the Tethyan Realm by Aguado et al. (2014a). The lower part of the UJ limestones with two massive beds (sequences Ha7 and Ba1) overlay the PJN facies above a major 3rd order discontinuity marked by a bioperforated hardground incrusted by large oysters. Two thick, whitish, roughly bioclastic/oolithic layers at the top of the sequences Ha7 (latest Hauterivian-earliest Barremian) and Ba1 (earliest Barremian) are interpreted as lagoonal deposits of highstand system tracks (HST) during stable sea level, and reddish cross-bedding in the middle part of Ha7 indicate a transgressive system track (TST) with reworked red palaeosols from emerged areas nearby (Fig. 1f-g, i).

The key marker *Tegulalithus septentrionalis* and the Barremian age of the Marnes de la Russille

Previous data

In the Boreal Realm, the key marker *Tegulalithus septentrionalis* is well represented and abundant in the lower Late Hauterivian Speetonensis–Gottschei ammonite Zones (Crux 1989; Rutledge 1994; Jeremiah 2001) and LK24A-LK23-LK22 nannofossil Zones with an acme in a very small interval between 132.5–133 Ma corresponding to LK22 (upper Speetonensis and Gottschei Zones). In the Early Barremian of the northern Boreal basins (North Sea, Barents Sea), this species is absent (Rutledge 1994), or very rare in the upper-Early Barremian (transition Fissicostatum-Elegans ammonite Zones and LK20A-LK19 nannofossil Zones) and latest Hauterivian (Variabilis ammonite Zone, LK20D nannofossil Zone) and considered as reworked (Jeremiah 2001, p. 52, fig. 7 and p. 67–68, fig. 19). Mutterlose and Harding (1987, p. 199) first observed *T. septentrionalis* with *Nannoconus abundans* in the Early Barremian (Hauptblätterton facies, uppermost Fissicostatum and Elegans ammonite Zones, LK20B-LK20A-LK19 nannofossil Zones) from the Lower Saxony Basin of North Germany. Then, Crux (1989) clearly reported the mid-Barremian re-entry or return of *T. septentrionalis* (excluding reworkings) in the same Early Barremian interval of Boreal basins closer to continental margins (Lower Saxony Basin of North Germany, cf. Mutterlose and Harding 1987 and Mutterlose 1984; North Sea Basin with Speeton section in Eastern England, cf. Rawson and Mutterlose 1983; Norwegian coast).

In the Lower Saxony Basin, *T. septentrionalis* is present over a thickness of several meters and sometimes common (Moorberg, Gott, Aegi and Letter sections in Mutterlose and Harding 1987; Otto Gott brick pit at Sarstedt, samples in Crux 1989 according to Mutterlose 1984, p. 38, fig. 18), Mutterlose and Harding (1987, p. 188) even asserted that "*Lithastrinus septentrionalis*, which has been found in most samples, is probably another good marker species, possibly restricted to the Lower Barremian, for it has not been found further down in the uppermost Hauterivian", because the abundance of *T. septentrionalis* indeed reached 10% to 30% of the nannofossils present in samples from Gott, Aegi and Letter sections studied by these authors. The specimens of *T. septentrionalis* observed in both Speeton and Lower Saxony sections are typical but often not as well preserved than those from the early Late Hauterivian, thus Rutledge (1994) introduced the name *Nannoconus pseudoseptentrionalis* to include roughly similar nannoconids possibly confused in the corresponding Speeton section.

In the Tethyan Realm, *T. septentrionalis* is rare and reported in the early Late Hauterivian (Sayni and Ligatus ammonite Zones, Tethyan NC4B-NC5A nannofossil Zones), but not from the Early Barremian (Silvia Gardin pers. comm., Rutledge 1994, p. 122, 274; Gardin in prep., Mutterlose et al. 1996, p. 22; Gardin et al. 2000, short meeting abstract without pictures or detailed informations, quoted by Clavel et al. 2007 as a proof for the Late Hauterivan age of the Marnes de la Russille in the Jura Mountains; Gardin *in* Godet 2006, Annexe 5, fig. 1, p. 385), and was not mentioned by Bergen (1994).

New data

In the Urgonien Jaune (UJ) and Marnes de la Russille (MRu) facies of the studied sections at Eclépens (EC) and La Sarraz–Les Buis (LSB) in the central Jura Mountains, *T. septentrionalis* is absent in the basal UJ and MRu levels (samples EC51, EC55-57) and its re-entry is observed just above in younger MRu intercalations (samples LSBMRu0-9), the specimens observed are well preserved and identical to the early Late Hauterivian Boreal material. Moreover, typical Late Hauterivian nannofossil markers (cf. Bergen 1994) were not observed in the MRu intercalations, but *T. septentrionalis* can be associated with Early Barremian species as *Broinsonia galloisii* and *Nannoconus abundans* in the lower MRu intercalations (LSBMRu0-9). In the early Late Barremian, *T. septentrionalis* is associated with typical *Flabellites oblongus* in the upper MRu intercalations (samples EC79-ECMRu10). So, *T. septentrionalis* from the MRu must be reported to Barremian and not to early Late Hauterivian, as in the Lower Saxony Basin and in the Speeton section.

Considering the palaeontology, an Early Barremian age for the basal MRu is supported by a Tethyan ammonite of the genus *Pseudometahoplites* firstly occurring in the Compressissima Zone and determined with certainty according to Vermeulen (2007, p. 91–92, Pl. 1). No Late Hauterivian ammonites have such a small size and very particular morphology. According to the regional geology and sedimentology in the Jura Mountains, there is no possibility of reworked Late Hauterivian nannofloras in the MRu intercalations, because the underlying Early–?Late Hauterivian Pierre jaune de Neuchâtel (PJN) is mostly constituted by massive limestones with shallow oolithic and bioclastic facies of high energy. These deposits with glauconite and rare marly layers are not at all favourable to the development and good preservation of nannofloras (cf. Godet et al. 2010 and Mojon et al. 2013 for the sedimentology and stratigraphy at the Hauterivian–Barremian transition between PJN and UJ). The two Hauterivian ammonites *Lyticoceras nodosoplicatum* Busnardo and Thieuloy 1989 and *Cruasiceras cruasense* (Torcapel 1884) recorded in this study from the basal UJ facies (marly layer with earliest Barremian nannoflora EC51 and limestones with glauconite directly above) are undoubtedly reworked from the shallow-water Early–Late Hauterivian PJN carbonates due to their identical infill.

A Late Hauterivian age for LSBMRu1 (in deposits locally generated by synsedimentary tectonic shifts) implies that only one metre of MRu with LSBMRu0-9 at La Sarraz–Les Buis would cover a period of more than 4 million years from the early Late Hauterivian to the early Late Barremian, absolutely without any apparent sedimentary discontinuity in a perfectly similar and regular deposit with the early Late Barremian sample LSBMRu5 located only 40 cm above LSBMRu1. Also, very problematic are notably the much greater MRu thickness of 44 meters at Eclépens (Fig. 3, only 2 km nearby) or several tens of metres in other parts of the central Jura Mountains, and the contradiction with the Early Barremian age of the ammonite *Pseudometahoplites* sp. juv. from the basal MRu intercalation.

The sudden re-entry of the species observed by Crux (1989) in the Early Barremian of the southern Boreal Realm can also perfectly be explained in the MRu of the central Jura Mountains by its absence in the basal Barremian (EC 51, 55–57) followed by a sudden occurrence and frequency higher up in the Early Barremian (LSBMRu0 and LSBMRu1, respectively). Palaeoecological and palaeoenvironmental changes could maybe explain its unexpected re-entry in the Early Barremian of the southern Boreal Realm and its sudden abundance in the MRu of the Jura Mountains, geographically located not far away in the northwestern Tethyan area.

Early Barremian occurrences of *T. septentrionalis* in Boreal basins far away from each other (Lower Saxony Basin/North Germany, North Sea Basin/Eastern England, Norwegian coast) correspond to a biological event (and not to reworkings), as also observed by this study in the Jura Mountains. According to these data, *T. septentrionalis* had never completely disappeared from the Boreal Realm after its acme in the early Late Hauterivian and always remained present but very rare with a highly dispersal and a very low frequency, almost undetectable in drill cores of open sea basins. A new proliferation at the end of the Early Barremian indicates palaeoenvironmental changes with a return of better ecological conditions for this species, becoming adapted preferably to higher temperate and shallower waters of more confined basins along the continental margins of the Boreal Realm. The HO of *T. septentrionalis* according to Crux (1989, fig. 8.7, p. 158–159 and figs. 8.12–8.13, p. 166–167) and Jeremiah (2001, fig. 7, p. 52) is also not exactly the same was recognized at Eclépens the uppermost LK19 nannofossil Zone/Elegans ammonite Zone (North Sea Basin/Speeton section) and the LK18 nannofossil Zone/lower Denckmanii ammonite Zone (Lower Saxony Basin). Our study likewise indicates that the species disappeared a little later (middle Denckmanii Zone or lower Sartousiana Tethyan ammonite Zone) at the NW-Tethyan margin.

These interpretations are highly coherent with the Mid-Barremian Event (MBE) reported herein and following the tectonic synsedimentary activity of a "Barremian crisis" at the Hauterivian–Barremian transition (Adatte et al. 2005, p. 13–15, 98, 123). Therefore, the total biostratigraphical range of *Tegulalithus septentrionalis* is from the early Late Hauterivian to the early Late Barremian (albeit discontinuous from a practical biostratigraphy perspective) over more than 4 million years, its geographical distribution in Europe covers mainly the Boreal Realm and the NW-Tethyan area (Jura Mountains), it is typically a Boreal and also Austral

(Late Hauterivian from Irian Jaya/Indonesia, Varol 1992) species.

Conclusions

The Urgonien Jaune (UJ) and Marnes de la Russille (MRu) facies can be dated locally in the central Swiss Jura Mountains to the earliest to early Late Barremian with abundant nannofloras including a mixture of Tethyan and Boreal taxa, as well as a Tethyan ammonite. The basal marls and limestones of the UJ have provided at Eclépens an Early Barremian nannoflora (Boreal LK20C and Tethyan NC5C nannofossil Zones) with reworked late Early to early Late Hauterivian ammonites as *Lyticoceras claveli* (Busnardo and Thieuloy 1989) and *Cruasiceras* cf. *cruasense* (Torcapel 1884). At Montcherand (Gorges de l'Orbe), the lowermost marly layer of the MRu located 20 m below the UJ facies top have yielded a Mid-Barremian ammonite *Pseudometahoplites* sp. juv. (Compressissima to Vandenheckii Zones, Early to Late Barremian transition), and several MRu marl layers at Eclépens and La Sarraz–Les Buis are characterized by Early to early Late Barremian nannofloras (Boreal LK20B to LK18 and Tethyan NC5C-NC5D nannofossil Zones).

At La Sarraz–Les Buis section, these nannofloras allow very accurate and reliable correlations with the Tethyan and Boreal biozonations of ammonites and nannofossils from the late Early Barremian to early Late Barremian, and as a consequence, the Tethyan Moutonianum to Sartousiana ammonite Zones within NC5D nannofossil Zone can be very precisely correlated to the Boreal Elegans/Denckmanii ammonite Zones and LK19-LK18 nannofossil Zones. The MRu nannofloras are dominated by Boreal species indicating active water circulation and exchanges between the southern temperate Tethys Ocean and northern colder Boreal basins, through presumed straits crossing a northern "Rheno-Bohemia" landmass outlined by Mutterlose (1992b, fig. 5) and Wulff et al. (2020, fig. 1). The very fine dark grey and organic-rich MRu marly layers with nannofossil-rich key samples EC55 and LSB-MRu1 belong to the late Early Barremian sequences Ba1′ and Ba2 (cf. sequence stratigraphy of Arnaud 2005 and Godet et al. 2010) and characterize the Mid-Barremian Event (MBE) identified in Europe and Middle East (Coccioni et al. 2003; Aguado et al. 2014a, b; Mahanipour and Eftekhari 2017; Wulff et al. 2018; Møller et al. 2019). The biostratigraphical and sequential data of the MRu imply that the overlaying Urgonien Blanc (UB) facies of the central Jura Mountains starts in the middle Late Barremian (Sartousiana Zone). In the southern Jura Mountains (SE-France), the deeply karstified UB top is overlied by the Poet Beds of the Perte-du-Rhône, which delivered a Tethyan ammonite *Martelites* sp. juv. (Sarasini Zone) of the Latest Barremian (Pictet et al. 2019).

The "Hauterivian–Barremian tectonically enhanced unconformity" in the Western Alps of SE-France (Adatte et al. 2005) was recognized at Eclépens/La Sarraz–Les Buis corresponding to a hiatus of Late Hauterivian sediments due to erosion (and formation of red palaeosols with "terra rossa" on emerged tilted blocks), reworked in the basal Early UJ deposits or not having been deposited. This event marked the climax of a "Barremian synsedimentary tectonic crisis" with low sea level, linked to global tectonics marked by active strike-slip and oblique-slip faults inducing block tilting during the Late Hauterivian-Early Barremian. The Marnes de la Russille (MRu) facies document the MBE locally at Eclépens and La Sarraz–Les Buis sections. Finally, the MBE (MRu within UJ) and the early Late Barremian UB facies of the Jura Mountains can now be correlated with the Helvetic shelf (northern Swiss Alps, Eastern Switzerland), where the MBE (Pictet et al. 2018) occurs in the Moutonianum Zone of the Drusberg Member/Tierwis Formation (SbB2, sequence Ba2) and the Schrattenkalk Formation begins in the Vandenheckii Zone with massive UB facies of the Lower Schrattenkalk Member (SbB3, sequence Ba3) according to Bonvallet et al. (2019).

Acknowledgements

The authors thank a lot Mr Rui Esteves and Mr Matthieu Honorat (Lafarge-Holcim, Eclépens) for the ammonites collected in the Urgonien Jaune of the Eclépens quarry, Dr Didier Bert (Réserve naturelle nationale géologique de Haute-Provence, Digne-les-Bains) and Dr Jean Vermeulen (Barrême) for the identification of the ammonites from the Urgonien Jaune, Prof. Dr Peter Oliver Baumgartner (UNIL, Lausanne) and Dr André Piuz (Natural History Museum, Geneva) for the optical and SEM microphotography, as well as Prof. Dr David Watkins (University of Nebraska, Lincoln), Dr Jason Crux (San Antonio, Texas) and Dr David Bord (Houston, Texas) for their comments and improvements about the content and the text of the manuscript. Many thanks also to the editor Dr Daniel Marty, the associate editor Dr Susanne Feist-Burkhardt and the journal reviewers Dr David Rutledge (PetroStrat Ltd, Wales, UK), Prof. Dr Thierry Adatte (UNIL, Lausanne), Dr Alain Morard (Swisstopo, Wabern) and Dr Fabienne Giraud (University Grenoble-Alpes), who have kindly revised our manuscript. To all of them, we are very grateful and express our heartfelt thanks.

Authors' contributions

All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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Received: 15 May 2020 Accepted: 21 September 2020
Published: 1 December 2020

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