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Reply to the discussion by Charollais et al. on "Reconciling strontium-isotope and K–Ar ages with biostratigraphy: the case of the Urgonian platform, Early Cretaceous of the Jura mountains, Western Switzerland" by Godet et al. (2011), Swiss Journal of Geosciences, 104, 147–160

Alexis Godet · Karl B. Föllmi · Stéphane Bodin · Thierry Adatte

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1 Introduction

In their discussion, Charollais et al. (2013) challenge our recently published ages for the Urgonian formation of the western Swiss Jura (Godet et al. 2011), which were derived by a chemostratigraphic approach. In our paper, we integrated strontium-isotope analyses on well-preserved rhynchonellids and K–Ar analyses on well-preserved glauconite grains with existing biostratigraphic data (Godet et al. 2011). The dating of ancient shallow-marine platform carbonates is often a challenging task, due to the lack of adequate biostratigraphic data, as well as the incompleteness of the stratigraphic record, and the important diagenetic overprint obliterating original chemical signatures. Often, only an integrated stratigraphical approach helps in advancing our knowledge on the timing of carbonate depositional processes in such archives. A good example of the utility of such a methodology is given by the Urgonian platform carbonates of the Jura Mountains, as will be shown in the following.

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A. Godet (✉) · K. B. Föllmi · T. Adatte
Institute of Earth Sciences, University of Lausanne,
Unil-Mouline, building Géopolis, 1015 Lausanne, Switzerland
e-mail: Alexis.Godet@unil.ch

S. Bodin
Institute for Geology, Mineralogy and Geophysics,
Ruhr-Universität Bochum, Universitätsstrasse 150,
44801 Bochum, Germany

Present Address:
A. Godet
Department of Geological Sciences, The University of Texas at San Antonio, One UTSA Circle, San Antonio, TX 78249, USA

During the Early Cretaceous, a broad, shallow marine carbonate platform developed along the northern Tethyan margin. Its vestiges are presently preserved in the Helvetic Alps (e.g., Funk et al. 1993; Föllmi et al. 1994, 2006, 2007; Föllmi and Godet 2013), the Vercors region (e.g., Arnaud-Vanneau and Arnaud 1990; Charollais et al. 2003; Clavel et al. 2007) and the western Swiss Jura (e.g., Blanc-Alétru 1995; Godet 2006), amongst other regions. In eastern France and the western Swiss Jura, the age of such a sedimentary edifice, the so-called Urgonian platform has been the subject of controversy for more than two decades. Clavel et al. (2007), Conrad et al. (2012) and Charollais et al. (2013) assign a late Hauterivian age to a large part of the Urgonian deposits. This age interpretation is refuted by Arnaud et al. (1998), Huck et al. (2011, 2013) and ourselves (Adatte et al. 2005; Godet, 2006; Godet et al. 2010, 2011, 2012), who showed that important reworking and stratigraphic hiati are located at and near the base of the 'Urgonien Jaune', and inferred a late Barremian age for the Urgonian platform deposits in the Swiss Jura mountains ('Urgonien Blanc').

It should be noted here that this is the first time that such an integrated stratigraphic approach has been used in this region for these formations, and that the ages obtained for the 'Urgonien Jaune' and the 'Urgonien Blanc' are coherent with previously published ages based on a combination of nannofossil biostratigraphy, sequence stratigraphy and chemostratigraphy (Godet et al. 2010). In this reply to the criticisms of Charollais et al. (2013), we will first recall the main stages in the history of the controversy surrounding the age of the 'Urgonien Jaune' and 'Urgonien Blanc'. We will then show that the arguments brought forward by Charollais et al. (2013) are lacking substance and, specifically, (1) that the benthic organisms used by Charollais et al. are poorly calibrated and/or stratigraphically wrongly placed, (2) that our chemostratigraphic interpretations and subsequent integrated stratigraphic framework for the Jura Mountains permit long-distance correlation, and (3) that, more in general, the development of Urgonian-type platform ecosystems required peculiar palaeoenvironmental conditions, which were not encountered during any time period of the Hauterivian, but only from the late Barremian onwards.

2 Historical framework of a long-lasting dilemma

The historial framework of the "Urgonian" controversy is summarized in Fig. 1. In 1847–1849, D'Orbigny defined the Urgonian Formation at Orgon (south of France), as a massive calcareous facies rich in rudists. Based on the finding of similar fauna, Desor and Gressly (1859; see Fig. 1, column 2) attributed the term "Urgonian" to the limestones that follow on the top of the 'Pierre Jaune de Neuchâtel' in the western Swiss Jura. It thus replaced part of the "Terrain Crétacé du Jura" of de Montmollin (1835; see Fig. 1, column 1), which was also known as 'Néocomien' (Thurmann 1835) and correlatable with the chalk or the greensands from other European areas. The view of Desor and Gressly was later confirmed by Jaccard (1869; see see Fig. 1, column 3). The Urgonian Formation from the Neuchâtel area was then split into two members, the lower and the upper Urgonian ('Urgonien Jaune' and 'Urgonien Blanc', respectively), although Desor and Gressly (1859) stated that there were no clear differences in terms of fossils content between these two members.

The question of the age of the historical 'Néocomien' has always been a source of debate. Although most geologists from the second part of the nineteenth century rapidly agreed that the formations first described by de Montmollin (1835) certainly belong to the Cretaceous, it was only in 1874 that Renevier attributed a Hauterivian age to the formations located between the Valanginian 'Calcaire roux' and the 'Urgonien' formations (Fig. 1, column 4). On the other hand, Baumberger (1901; see Fig. 1, column 5) introduced the term "Barremian" of Coquand (1862) to characterize the age of the 'Urgonien Jaune', whereas the 'Urgonien Blanc' would be Aptian in age. By replacing the term "Urgonian" previously used in the vicinity of Neuchâtel (e.g., Jaccard 1869) by "Barremian", Baumberger (1901) attributed a chronostratigraphic name to a lithostratigraphic unit, without any biostratigraphical evidence such as ammonites. His conclusions are only based on the occurrence of similar fauna—especially rudists—between the south of France and the western Switzerland. Moreover, Baumberger (1901) recognized no break in the sedimentation, so that the lower and the upper 'Pierre Jaune de Neuchâtel' would be early and late Hauterivian in age, respectively.

The next main step in the evolution of ideas on the stratigraphy of this historical succession was made by Remane et al. (1989), who compiled all the available data, as well as new ones (Fig. 1, column 6). Some divergences arose: Conrad and Masse (1989, p. 322) concluded that the Hauterivian–Barremian boundary may fall somewhere within the 'Urgonien Blanc', whereas Arnaud-Vanneau and Masse (1989, p. 272) attributed the main part of the same formation to the Barremian or even to the late Barremian. Their conclusion is mainly based on the presence of *Paracoskinolina reicheli* at the base of the rudist-bearing 'Urgonien Blanc' at Eclépens (Zweidler 1985).

In a series of papers published since the beginning of the 1980s, and especially after 1989, two main schools of thought emerged concerning the age of the Urgonian Formation, not only in Switzerland but also in the south of France. On one hand, a research team mainly based at Geneva analysed sections from the Vocontian Trough to the Vercors and the western Swiss Jura. They succeeded in establishing an orbitolinid biozonation (e.g., Schroeder et al. 1968, 2000, 2002), which is based on the evolution of four phylogenetical lineages of these benthic foraminifers calibrated against ammonites from the Ardèche region. Other benthic organisms such as rudists were calibrated against the ammonite biozonation with the help of this biostratigraphic scheme (Masse et al. 1998). Along with the biostratigraphical approach, sequence stratigraphy was performed in sections from the south of France to the Western Swiss Jura. The results highlighted the progradation of the Urgonian platform, from the early Hauterivian to the early Barremian (Clavel et al. 1995; Charollais et al. 2003). As a consequence, the above-mentioned authors attributed a "continuous" character to the sedimentation during the Early Cretaceous in the Western Swiss Jura, since they did not recognize any subaerially-exposed sequence boundary. This implies that the Hauterivian–Barremian boundary would fall within the 'Urgonien Blanc' (Clavel et al. 1995; Fig. 1, column 8).

On the other hand, Arnaud-Vanneau and Arnaud (1990; see Fig. 1, column 7) and Arnaud et al. (1998) used the same tools—i.e., orbitolinids and sequence stratigraphy. Contrary to Schroeder et al. (2002), Arnaud et al. (1998) used the association of these large benthic foraminifera present in rocks rather than the phylogenetical lineages. Their orbitolinids zonation was calibrated with respect to ammonite biozones in sections from the Vercors where ammonite-dated formations surround orbitolinids-bearing sediments. Moreover, these authors highlighted phases of emersion associated with sequence boundaries, which may thus represent significant hiati. In particular, a major break in sedimentation may be located at the top of the 'Pierre Jaune de Neuchâtel', implying that sediments from the late Hauterivian to the latest early Barremian are absent. They thus postulated that both the 'Urgonien Jaune' and the 'Urgonien Blanc' are late Barremian in age (Arnaud et al. 1998; Arnaud 2005: 7 in Fig. 1).

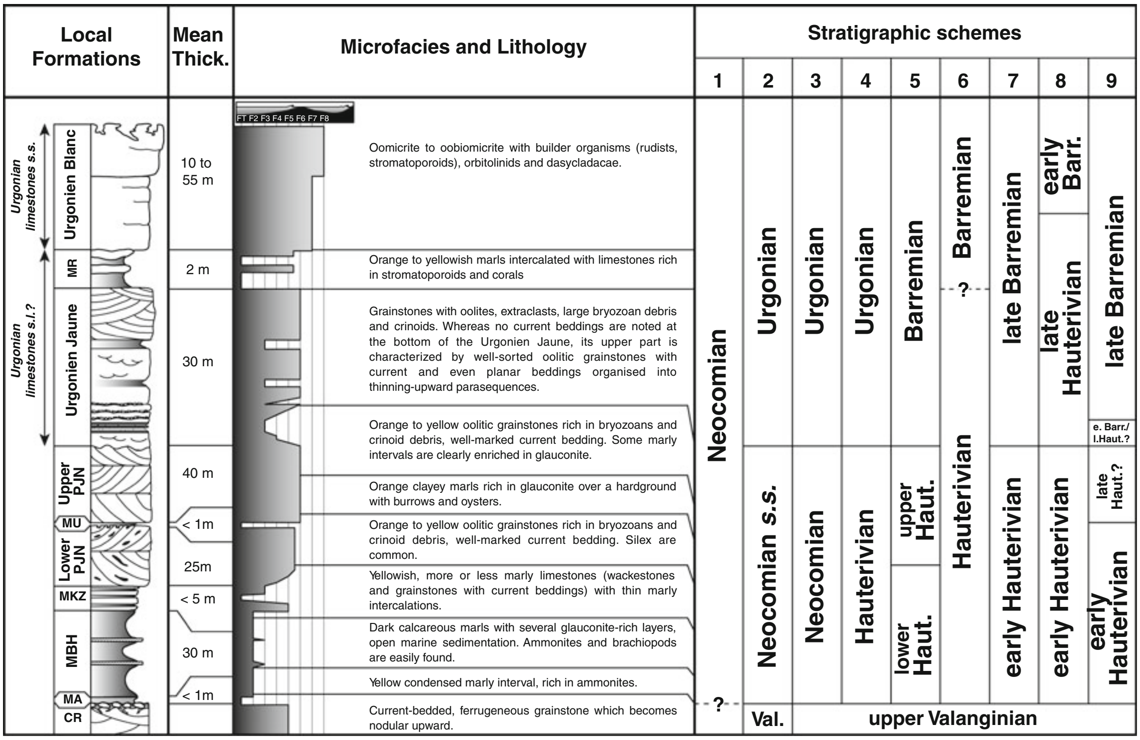

Fig. 1 Historical succession of the Hauterivian stage defined in the Neuchâtel area (modified from Godet 2006). The main lithologies are briefly described. The evolution of microfacies is compiled from Blanc-Alétru (1995) and Godet (2006), following the nomenclature of Arnaud-Vanneau and Arnaud (2005). The different stratigraphic schemes (*right-hand side* of the figure) correspond to: **1** Thurmann 1835; **2** Desor and Gressly 1859; **3** Jaccard 1869; **4** Renevier 1874; **5** Baumberger 1901; **6** Remane 1989 (modified); **7** Arnaud-Vanneau and Arnaud 1990; **8** Clavel et al. 1995; **9** Godet et al. 2010, 2011, this work. Abbreviations of the names of the formations: *CR* Calcaire Roux, *MA* Marnes à Astieria, *MBH* Marnes Bleues d'Hauterive, *MKZ* Mergelkalk zone, *PJN* Pierre Jaune de Neuchâtel, *MU* Marnes d'Uttins, *MR* Marnes de la Russille

From this brief historical overview, it is clear that the term "Urgonian" is used in three different contexts. Firstly, "Urgonian Formation" designates shallow-marine carbonate facies rich in rudists, following the original definition of D'Orbigny (1847–1849). Secondly, "Urgonian" in the terms 'Urgonien Jaune' and 'Urgonien Blanc' (Fig. 1) designates local lithostratigraphic divisions of the Urgonian Formation *s.l.* in the western Swiss Jura; whereas rudists are encountered in the 'Urgonien Blanc', which thus exhibits the typical facies of Urgonian limestones, these organisms are absent from the 'Urgonien Jaune'. Thirdly, these facies were deposited in shallow marine environments of the northern Tethyan margin, generally called the Urgonian platform.

3 Biostratigraphy

3.1 The problem of the scarcity of ammonites in the western Swiss Jura

In shallow marine carbonate environments, biostratigraphical dating mainly relies on the finding and identification of benthic organisms such as large foraminifera, algae, echinoids, bryozoans or rudists. The robustness of shallow water, biostratigraphic ages strongly relies on the calibration of the stratigraphic ranges of the species under consideration against fossil groups, for which their biostratigraphic utility is well established, such as ammonites and calcareous nannofossils. These latter groups are only present in certain horizons and members of the western Swiss Jura platform succession. Ammonites, for example, were identified in the 'Marnes Bleues d'Hauterive' and the 'Marnes d'Uttins', where they provided important biostratigraphic anchor points (Busnardo and Thieuloy 1989; Godet et al. 2010). Unfortunately, the stratigraphic positions of particularly important ammonites have been shifted from one publication. An ammonite of particular concern is *Lyticoceras* sp. (FSL 89933), which was originally found by Mouty (1966) at Confort (eastern France). Mouty (1966, p. 82) himself described this ammonite (identified as *Leopoldia*? sp.) from a 2.5 m thick marly and calcareous interval, which ends 3.35 m below the limit between the 'Pierre Jaune de Neuchâtel' and the Urgonian Formation, at "Grand Essert", on the southern side of the Valserine River. Mouty (1966) himself did not cite a single ammonite from the Urgonian, which he placed entirely in the Barremian. Busnardo and Thieuloy (1989) subsequently reinterpreted this specimen as a *Lyticoceras* sp., but still from within the 'Pierre Jaune de Neuchâtel', thus indicating the *L. nodosoplicatum* to the *S. sayni* ammonite zone (Godet et al. 2010). Clavel et al. (2007), however, moved the stratigraphic position of this ammonite into the overlying 'Urgonien Jaune', without any argument or specification. In their present comment, Charollais et al. (2013) quote the ammonite finding as follows: "*Lyticoceras* sp. (FSL89933): a specimen was "found by A. Mouty at the top of the Pierre Jaune at Confort" […] Re-determined as "gr. *Lyticoceras*/*Cruasiceras* sp.", this ammonite dates the lowermost part of the UJ either from the top of the Early Hauterivian or the bottom of the Late Hauterivian (*Cruasense* Subzone of the *Sayni* Zone; Clavel et al. 2007)". Our visit to the outcrop confirms that the ammonite was originally found in a more marly interval within the 'Pierre Jaune de Neuchâtel', which may correspond to the 'Marnes d'Uttins'. We therefore stay with the original description by Mouty (1966). This ammonite thus dates the upper 'Pierre Jaune de Neuchâtel' and, potentially, part of the 'Marnes d'Uttins', as the late Hauterivian *Subsaynella sayni* ammonite zone, following the redetermination of Busnardo and Thieuloy (1989) and Clavel et al. (2007). This age assignment by no means implies that the base of the 'Urgonien Jaune' is of the same age, as suggested by Charollais et al. (2013).

3.2 Calibrating the stratigraphic repartition of orbitolinids

The repartition of orbitolinids is widely used when assessing the age of shallow marine carbonate successions. During the last two decades, much effort has gone into the refinement of the stratigraphic calibration of this group against ammonite biozonation by Annie Arnaud-Vanneau and Hubert Arnaud (University of Grenoble). Their pioneering work provided the foundation for such a calibration with the detailed study of the Glandasse and Urgonian Limestone Formations from the Vercors and the Chartreuse (Arnaud-Vanneau 1980). In addition, Arnaud (1981) provided an in-depth and well documented biostratigraphic scheme for contemporaneous slope deposits from the Devoluy massif. Further syntheses appeared in Arnaud-Vanneau and Arnaud (1990), Arnaud et al. (1998), and Arnaud (2005). In parallel with these works, an alternative orbitolinid range chart was developed by a second group of researchers (e.g., Clavel et al. 1987, 2007, 2010; Schroeder et al. 2002; Charollais et al. 2003). Due to differences in the calibration of orbitolinids against ammonite zones, this alternative orbitolinid scheme is offset by a half to a whole stage, compared to that of Arnaud (2005; see also Föllmi 2008). For instance, Arnaud (2005) and Clavel et al. (2007, 2010) calibrated the onset of *Praedictyorbitolina carthusiana* to the late Barremian (*Gerardthia sartousiana* ammonite zone), and to the late Hauterivian (late *Plesiospitidiscus ligatus* ammonite zone), respectively. Moreover, according to Schroeder et al. (2002), the range of this species begins at the boundary between the transgressive and highstand systems tracts Ha5, whereas Clavel et al. (2010) places the same bio-event at the base of the depositional sequence Ha6, thereby suggesting discrepancies in the calibration of this species within the same research group.

The stratigraphic calibration of orbitolinids by Clavel and co-authors has been challenged several times. For instance, in the Helvetic Alps, orbitolinids found in the upper Schrattenkalk Formation were ascribed to the late Aptian by Schroeder et al. (2007). Ammonites found in the Plaine Morte Bed, which lies within the Grünten Member on top of the Schrattenkalk Formation, have been identified and attributed to the *Deshayesites deshayesi*—*Deshayesites weissi* ammonite zones boundary, which falls in the early Aptian (Föllmi and Gainon 2008). The latter dating thus contradicts the one derived from orbitolinids biostratigraphy, and is coherent with the dating of the drowning of Urgonian-type carbonate platforms in various peri-Tethyan settings (Arnaud-Vanneau and Arnaud 1990; Peybernès et al. 2000; Castro et al. 2001, 2008; Föllmi et al. 2007; Föllmi 2008; Burla et al. 2008; Huck et al. 2012; Leonide et al. 2012; see also Fig. 2).

Finally, not only Arnaud-Vanneau and Arnaud (1990), Arnaud (2005), Föllmi (2008) and Föllmi and Gainon (2008), but also Schroeder et al. (2010) have challenged the orbitolinid biostratigraphic scheme of Clavel et al. (2010). The stratigraphic distribution of large benthic foraminifera in sections from the eastern Arabian Plate reveals some significant offsets. For instance, the range of *Eopalorbitolina charollaisi* begins in the early Barremian for Schroeder et al. (2010), whereas Clavel et al. (2010) extended it into the late Hauterivian *Balearites balearis* ammonite zone, apparently without any supporting ammonite fauna. Similarly, the *Eopalorbitolina transiens* zone of Schroeder et al. (2010) ranges from the *Coronites darsi* to the *Avramidiscus vandenheckii* ammonite zones (late early and early late Barremian, respectively), whereas it may already begin in the early Barremian *Nicklesia nicklesi* ammonite zone for Clavel et al. (2010). Here again, it is important to stress that the calibration proposed by Clavel et al. (2010) lacks significant backup by ammonite biostratigraphy. It is for these reasons that we suggest that the orbitolinid biostratigraphic scheme of Clavel et al. (2010) should be treated with great caution. This is also valid for any biostratigraphic scheme that has been calibrated against ammonite biozones via the aforementioned orbitolinid calibration sensu Clavel (e.g., rudists, dasycladacean green algae, echinids). For instance,

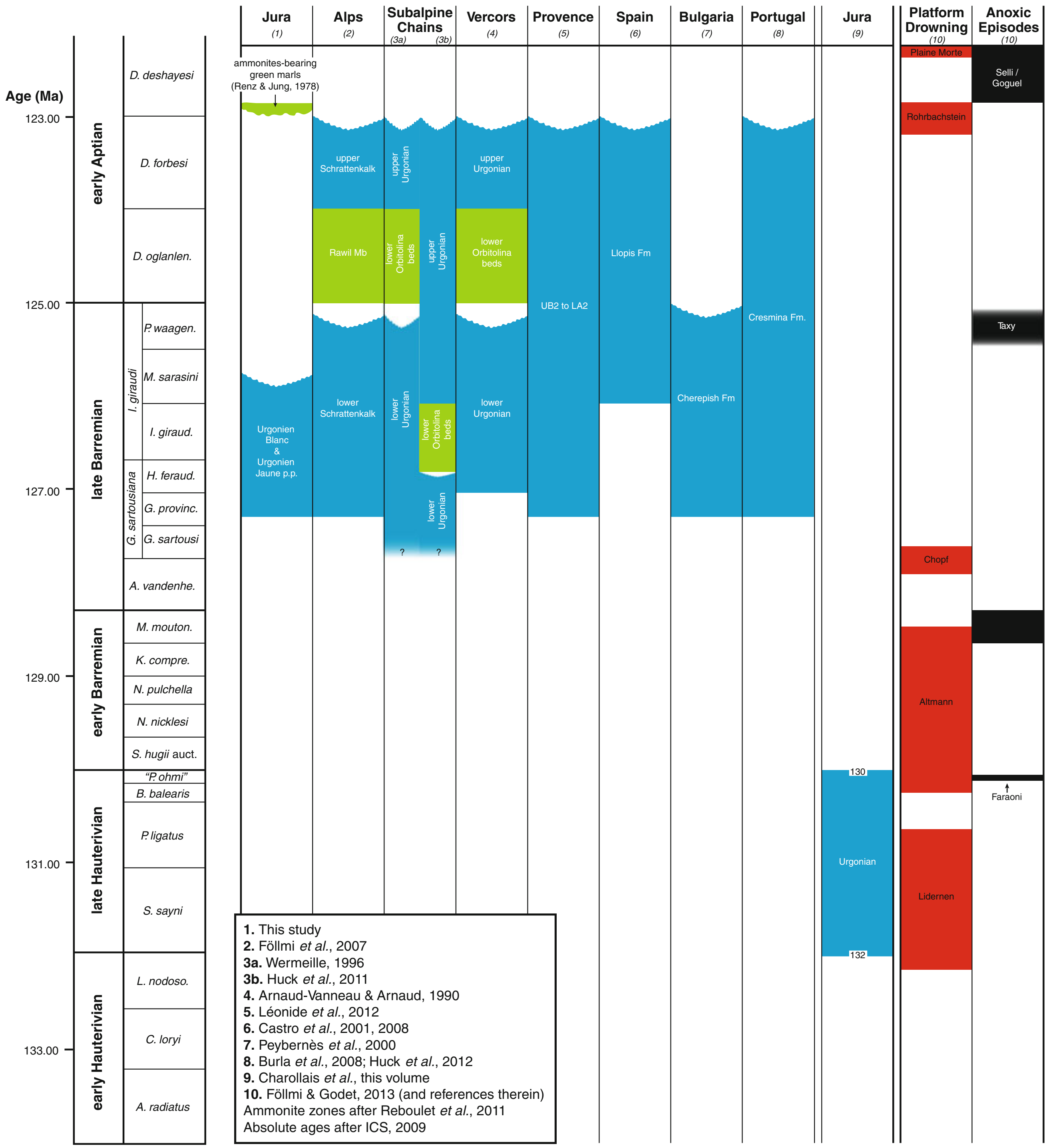

Fig. 2 Dating of Urgonian-type limestone in various peri-Tethyan locations. Whereas its attribution to the late Barremian seems commonly agreed, a late Hauterivian age, as proposed by Charollais et al. (2013) is shifted by nearly 3 Ma

Charollais et al. (2013) use the dasycladacean green algae *Falsolikanella* (*Praturlonella*) *danilovae* as a marker for the Hauterivian and early Barremian in their Fig. 2, whereas Masse and Fenerci-Masse (2011) stated that "the dasycladale *Falsolikanella danilovae* (Radoicic) and "*Neotrocholina*" *friburgensis* Reichel as well, are present in these beds, data which imply that the corresponding interval is Barremian". In fact, these authors place most of the rudist-bearing, Urgonian-type shallow marine limestone from the Marseille area in the Barremian and even in the late Barremian (Masse and Fenerci-Masse 2011, p. 682). Leonide et al. (2012) also report the occurrence of

F. danilovae in beds belonging to the late Barremian *Gerardthia sartousiana* ammonite zone, whereas the range of this species ends at the lower limit of the *G. sartousiana* after Charollais et al. (2013). Other biostratigraphical data led Leonide et al. (2012) to attribute rudist-rich limestones belonging to the Urgonian platform to the late Barremian–early Aptian.

3.3 Sedimentological and biostratigraphic evidence for reworking

The issue concerning calcareous nannofossils was already discussed in Godet et al. (2012). Within the same samples, three different experts observed both late Hauterivian and late Barremian nannofloras (see Clavel et al. 2007; Conrad et al. 2012; Godet et al. 2010, 2012 for details). It is important to note—and this is overlooked by Charollais et al. (2013)—that the sedimentological context of the lower part of the 'Urgonien Jaune' may explain this apparent juxtaposition of ages. The calcareous nannofossils have been sampled 11 and 16 m above the 'Pierre Jaune de Neuchâtel'/'Urgonien Jaune' boundary as defined in Godet et al. (2010). This limit is characterized by erosive pockets filled in by calcareous conglomerates and by boring traces. Moreover, perforated and oyster-encrusted pebbles and blocks were encountered in the same levels where the calcareous nannofossils have been observed (Godet et al. 2010), suggesting an intense reworking induced by strong currents. We thus believe than the occurrence of two sets of calcareous nannofossils, one indicative of the late Hauterivian and one indicative of the late Barremian, is not incompatible given the sedimentological context. It only reflects at the nanno-scale the reworking that is observed in the outcrop and within thin sections. In the latter, extraclasts are common and are suggestive of reworking, as is demonstrated by the presence of *Tintinnopsella longa* (Tithonian–Hauterivian) within an extraclast, as stated and illustrated in Blanc-Alétru (1995). Bryozoan fauna also indicate strong reworking: Walter (1993) studied a faunistic assemblage located in grey marls within the 'Urgonien Jaune' at Vaulion (in north of the canton of Vaud). He deduced an early Hauterivian age but also strongly underlines the occurrence of some species that are characteristic of the early and late Barremian of the Drôme and Ardèche departments of southeastern France, respectively. This mixing of fauna thus supports an intense degree of reworking, which has been previously evidenced by sedimentological features (calcareous conglomerate with perforated and oyster-encrusted blocks, channelizing structures) reported in the first 18 m above the Pierre Jaune de Neuchâtel/'Urgonien Jaune' boundary of the Eclépens section by Godet et al. (2010). A similar conclusion can be drawn from ostracods identified in samples from the Vaulion, Boveresse and La Russille sections, where a late Hauterivian/Barremian assemblage has been described by Clavel et al. (1994).

Stating that we reject most fossil groups is too simplistic. Instead, we applied a critical and integrated approach to all available datasets in order to construct a robust stratigraphic model. This includes describing the sedimentology of biostratigraphic samples, in order to assess whether they provide a depositional or reworking age. By adopting this scientific approach we were able to understand why late Hauterivian and late Barremian nannoflora were found in the same samples, and subsequently to propose an adequate interpretation of our Sr-isotope data.

4 Sr-age model: the advantage of an integrated stratigraphic approach

With the development and improvement of new stratigraphic techniques in the last three decades, it became important to integrate as much information as possible in order to provide the scientific community with the most accurate stratigraphic model. This led to exciting scientific challenges. This is the case of the Barremian–Aptian sedimentary succession of the Arabian Plate, which has been recently extensively studied for its biostratigraphy, sequence stratigraphy and chemostratigraphy (van Buchem et al. 2010). Such an approach becomes even more challenging when applied in shallow-marine carbonate environments, where time gaps and associated meteoric diagenesis potentially had a strong impact on the completeness and preservation state of sedimentary archives (Vail et al. 1977, 1987; James and Choquette 1984; Tucker and Wright 1990; Schlager 2005; Catuneanu 2006). It is with such scientific concepts in mind that we interpreted our $^{87}Sr/^{86}Sr$ dataset. Although sequence stratigraphic issues have been already discussed in a former set of Discussion/Reply articles (Godet et al. 2010, 2012; Conrad et al. 2012), they provide valuable insights which need to be included when dealing with Sr-model ages.

The main criticisms of Charollais et al. (2013) are reported below, together with an explanation of our view:

- For the 'Marnes bleues d'Hauterive', Charollais et al. (2013) make the following comments: "Godet et al. (2011) used these five consolidated values to calculate an "absolute" numerical age". The latter "corresponds particularly well to the age range to be extended from the biostratigraphical indications calibrated against the most recent time table compiled by the International Commission on Stratigraphy" (ICS 2009). "To us, however, this seems to be more the results of a circular calculation". We firmly contest this allegation. We first plotted our $^{87}Sr/^{86}Sr$ data against our reference curve, which was calibrated against ammonite biostratigraphy. We subsequently derived a mean numerical age using ICS (2009). Alongside, we examined the range of available biostratigraphical data for the 'Marnes bleues d'Hauterive' (*L. nodosoplicatum* to lowermost *C. loryi*) and derived a range of absolute ages. These ages are thus based on ammonite stratigraphy in this particular formation in the western Swiss Jura (e.g., Busnardo and Thieuloy 1989), whereas the $^{87}Sr/^{86}Sr$ reference curve was calibrated with ammonite faunas found in the Vocontian Basin (see Bodin et al. 2009 and references therein). Those two biostratigraphies are independent, especially since endemism may have affected ammonites from the western Swiss Jura (see p.140 in Busnardo and Thieuloy 1989), and there is no risk of circular reasoning whatsoever.

- For the 'Marnes d'Uttins' and 'Pierre Jaune de Neuchâtel', Charollais et al. (2013) came to a conclusion which is slightly different from our. They proposed to shorten the duration of the 'Marnes d'Uttins' to the *L. nodosoplicatum* ammonite zones whereas we extended it into the *S. sayni* ammonite zone, based on (i) $^{87}Sr/^{86}Sr$ ratios of $0.707464 \pm 10 \times 10^{-5}$ (2σ, sample MC3a), (ii) the recommendation made by the ammonite specialist who determined the specimen discovered in the 'Marnes d'Uttins' of the Eclépens quarry (Thieuloy, pers. com. 2006), and (iii) the original position of the ammonite discovered by Mouty (1966) in the 'Grand Essert' section (see Chapter 3 for a detailed discussion). Moreover, Charollais et al. (2013) reported that three samples (MC1a, MC3a and MC4) were used to derive Sr-model age for the 'Marnes d'Uttins'. In fact, only the $^{87}Sr/^{86}Sr$ for samples MC3a and MC4 were kept because these rhynchonellids passed all screening tests for diagenetic overprint, and because their $^{87}Sr/^{86}Sr$ falls within the range of $^{87}Sr/^{86}Sr$ values for belemnites from the *L. nodosoplicatum—S. sayni* ammonite zone. In other words, the $^{87}Sr/^{86}Sr$ value for MC1a was discarded because even if the shell seemed to be nicely preserved, its Sr-isotope ratio was too high to represent a reliable age date.
- For the 'Urgonien Jaune', Charollais et al. (2013) put forward a late Hauterivian age. Our own conclusion was based on $^{87}Sr/^{86}Sr$ values obtained from rhynchonellids sampled in the upper part of this formation at Pourtalès; they range from $0.707437 \pm 26 \times 10^{-5}$ to $0.707477 \pm 15 \times 10^{-5}$ (2σ). Although we only used the raw Sr-isotope data to construct our Fig. 6, we transferred the 2σ into uncertainties on the Sr-model age in our Table 3. Based on sedimentological, sequence stratigraphic and biostratigraphical information (strong reworking in the basal part of the 'Urgonien Jaune', several stacked sequence boundaries and mixed, late Hauterivian to late Barremian calcareous nannofossils above this; Godet et al. 2010, 2011), we reduced the potential Sr-model age to 127.94 Ma for this part of the 'Urgonien Jaune', where rhynchonellids were sampled.
- For the 'Marnes de la Russille', we agree with the statement of Charollais et al. (2013): the attribution of this formation to the late Barremian is driven by the fact that the 'Urgonien Jaune' was previously dated as such. Moreover, if we discard the highest value of $0.707513 \pm 36 \times 10^{-5}$ (2σ), which seems to represent an issue for Charollais et al. (2013), then an updated age for this formation would be 126.7 Ma. This latter mean age fits even better with our age model.
- Finally for the 'Urgonien Blanc', we would like to reiterate our conclusion that more data are needed to obtain an adequate age indication. We only included this data in our Table 3 in order to strengthen this conclusion, a fact that was overseen by Charollais et al. (2013).

The usefulness of $^{87}Sr/^{86}Sr$ to derive a model age for Urgonian carbonate sediments was also demonstrated in the case of the Cluses section near Geneva (department of Haute-Savoie, France; Huck et al. 2011). At this location, the evolution of both carbon isotope composition and $^{87}Sr/^{86}Sr$ measured on rudist shells indicate a Barremian to early Aptian age for the Urgonian platform sediments (Huck et al. 2011; see also p. 1129 in Godet et al. 2012 for further details). As we always maintained, $^{87}Sr/^{86}Sr$-based chemostratigraphy applied to the Early Cretaceous succession of the western Swiss Jura needs to be combined with other stratigraphic approaches in order to build a robust and coherent stratigraphic framework. This includes the integration of this part of the northern Tethyan margin into a broader palaeoceanographic, palaeoenvironmental and palaeoclimatic context, as explained below.

5 Ecological and palaeoenvironmental considerations in favour of a late Barremian age for the rise of the Urgonian platform

The composition and diversity of carbonate-producing organisms are highly variable through geological time and mostly depend on changes in ocean environments. Under subtropical climates, increases in nutrient availability may trigger a switch from oligotrophic to mesotrophic associations (Mutti and Hallock 2003). Consequently, comparing the type of organisms constitutive of Urgonian-type carbonates with Hauterivian to Barremian palaeoenvironmental and palaeoceanographic conditions may provide a strong constraint on the age of the rise of the Urgonian platform along the northern Tethyan margin.

The carbonate composition and the type of carbonate microfacies evolved through the 'Urgonian Jaune', 'Marnes de la Russille' and 'Urgonien Blanc'. The bryozoan and crinoidal packstone to grainstone is progressively replaced by oolitic grainstone from the base to the top of the 'Urgonien Jaune', then corals appear within the 'Marnes de la Russille' whereas the 'Urgonian Blanc' is mainly characterized by the occurrence of rudists, stromatoporoids, dasycladacean green algae and large benthic foraminifera (see Godet et al. 2010, for a detailed description). This stratigraphic evolution reflects the temporal evolution from mesotrophic to oligotrophic conditions, from the time period of the deposition of the 'Urgonien Jaune' to that of the 'Marnes de la Russille' and 'Urgonien Blanc'. Phosphorus (P) represents one of the most important and limiting factors in terms of trophic levels for shallow marine ecosystems (Föllmi 1996). Interestingly, variations in phosphorus mass accumulation rates (PMAR) throughout the Hauterivian and the Barremian show a long-term negative trend from mesotrophic (early Hauterivian) to oligotrophic (late Barremian) conditions (Bodin et al. 2006). A similar trend is observed in P concentrations measured in Early Cretaceous sediments from the western Swiss Jura, with high contents in the 'Marnes Bleues d'Hauterive' and extremely low concentrations in the upper part of the 'Urgonien Jaune' and the 'Urgonien Blanc' (see Fig. 16 in Godet et al. 2010, and discussion on the topic in Conrad et al. 2012, and Godet et al. 2012). The dominance of mesotrophic conditions during the Hauterivian, which culminated in the development of regionally important oceanic anoxia (the Faraoni episode; e.g., Bodin et al. 2006), renders it highly improbable that Urgonian-type photozoan limestone would be produced during this time period. This is further supported by the long-term evolution of rudist species: their involvement in the life of shallow marine ecosystems increased from the Valanginian onward, reaching an important phase of diversification during the latest Barremian and the early Aptian (Skelton and Gili 2012). This may be linked to increased Ca^{2+} and high CO_2 levels (Pomar and Hallock 2008), which may be encountered under hot and humid climates. Such intertropical conditions have been inferred from the clay mineral composition of the insoluble residue of the 'Urgonien Blanc', as well as of late Barremian sedimentary rocks from the Angles section (Godet et al. 2008). On the other hand, during the Hauterivian, the dominance of smectitic minerals in the clay fraction suggests the establishment of a seasonally-contrasted climate, which was not prone to the development of diversified rudist ecosystems.

Aside the climate, palaeoceanographic conditions also excluded the rise of Urgonian-type ecosystems during the Hauterivian along the northern Tethyan margin. In the Helvetic Alps, the late Hauterivian–early Barremian (from the *B. balearis* to the *C. darsi* ammonite zone; Bodin et al. 2006) is characterized by a major phase of carbonate platform drowning, materialized by the phosphate-rich Altmann Member and associated hardground. Triggering mechanisms for this drowning episode and associated condensation include upwelling currents that winnowed the sediments and brought nutrients onto the platform. Other evidence for upwelling currents in the western Tethys is given by the evolution of $\delta^{13}C$ and $\delta^{18}O$ in the highly condensed Combs sur Artuy section (department of Var; Godet 2013). There, the entire early Barremian *Kotetishvillia compressissima* ammonite zone is represented by a 25 cm-thick bed, in which both $\delta^{13}C$ and $\delta^{18}O$ exhibit a bell-shaped trend. In the same bed, the glauconite content is relatively high (>20 %). Both these isotopic and sedimentological data are coherent with the onset of upwelling currents during this period of time, which would have prevented the development of healthy oligotrophic assemblages on the northern Tethyan margin.

This sedimentological and palaeoenvironmental pattern has been encountered in peri-Tethyan locations other than the western Swiss Jura and the Helvetic Alps. The onset of rudist-rich, Urgonian-type limestone in those areas is systematically dated as late Barremian (Fig. 2), including the Vercors (e.g., Arnaud-Vanneau and Arnaud 1990), the Gard and Ardèche Department of southern France (Arnaud-Vanneau, Arnaud and Vermeulen, pers. com. in Godet et al. 2011; see also Lafarge 1978; Cotillon et al. 1979). The deposition of rudist-bearing, Urgonian-type oligotrophic limestone is also dated to the late Barremian in the Subalpine Chains of Haute-Savoie (Huck et al. 2011, 2013). In Provence, a peculiar tectonic setting may have allowed the inception of rudist-bearing sediments in the late Hauterivian, but the platform reached its maximal development in the late Barremian–early Aptian (Leonide et al. 2012). In Spain, the Los Villares Formation is dated from the Valanginian to the earliest late Barremian and is characterized by hemipelagic facies with condensation indicated by glauconite and iron oolites. Abundant ammonite findings support this age assignment, and the overlying, late Barremian-early Aptian Llopis Formation exhibits a typical Urgonian facies with corals and rudists (Castro et al. 2001, 2008). Finally in Bulgaria, Urgonian-type deposits are also dated as Barremian (Peybernès et al. 2000).

6 Conclusions

Our integrated stratigraphy of the Urgonian deposits from the western Swiss Jura enables the integration of this region and stratigraphy within the palaeoenvironmental evolution of the northern Tethyan margin: In their conclusions, Charollais et al. (2013) state that 'no contradiction exists between the conclusions drawn from our palaeontological data on one side and the few consolidated data derived from chemostratigraphy or geochronology on the other side'. We regard this as a single-sided conclusion, which does not hold true in the light of the combined bio-, sequence and chemostratigraphic data obtained by our research group. For instance, sedimentological features clearly demonstrate the intensity of the reworking (perforated and/or oysters-encrusted pebbles, channelized features, calcareous conglomerates) and condensation (glauconitisation, phosphate-rich sediments) in the key, basal interval of the 'Urgonien Jaune', not only at Eclépens but also in the Vaumarcus and Gorge de l'Areuse sections (Godet et al. 2010). This key interval corresponds to a time period of major platform drowning along the northern Tethyan margin (e.g., Föllmi et al. 2006; Godet et al. 2010). The rise of Urgonian-type, oligotrophic facies during this time period, as is postulated by Charollais et al. (2013) is unlikely because the sum of stratigraphical and palaeoceanographical information strongly counter-indicates this interference. With the improvement and multiplication of available proxies in geosciences, it becomes essential to develop multidisciplinary and integrated stratigraphic approaches such as the one that we have applied for more than a decade on the Urgonian sediments of the Jura Mountains and elsewhere. This is the reason why we are convinced that our age-model, which is based on our interpretations of biostratigraphy and chemostratigraphy, but also takes into account the sedimentological, sequence stratigraphic and palaeoenvironmental framework of these deposits, and which implies a late Barremian age for Urgonian deposits of the western Swiss Jura, is more logical and realistic than the one put forward by Charollais et al. (2013). The latter is out of phase with the general palaeoceanographic and palaeoclimatological context of the Hauterivian. To this comes that comparable Urgonian sediments from other peri-Tethyan locations have been dated as (late) Barremian by experts, which are presently not involved in the western Swiss Jura problematic. They all point to the development of photozoan ecosystems with rudists and/or corals during the late Barremian. A late Barremian age as such ensures a better stratigraphic integration of the western Swiss Jura area within the history of the northern Tethyan margin.

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