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Duration of the Early Bajocian and the associated $\delta^{13}\text{C}$ positive excursion based on cyclostratigraphy

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Abstract:

The Early Bajocian, about 172 Ma ago, was a period of tectonic changes, a global carbon-isotope positive excursion, and biological diversification of marine invertebrates (e.g., ammonites, radiolarians and coccolithophores). Unfortunately, both duration of the Early Bajocian and associated palaeoenvironmental changes are still poorly constrained. We propose here an estimate of the duration of this sub-stage based on a cyclostratigraphic analysis of the carbonate content from the Chaudon-Norante section, French Subalpin Basin, France. The Chaudon-Norante succession has been correlated with Les Dourbes section using greyscale variations in order to detect possible local hiatuses. The duration estimated here of the entire Early Bajocian is 4.082 Myr. Two intervals were identified in the positive $\delta^{13}\text{C}$ excursion; an increase of carbon isotope values lasting 1.36 Myr and climax isotope values for 2.72 Myr. A cooling at high latitudes and warming at low latitudes may have enhanced the Earth temperature gradient leading to an increase in humidity, which triggered in turn ocean eutrophication at the origin of the $\delta^{13}\text{C}$ positive excursion.

During the Early Bajocian (~172 Ma; Middle Jurassic), a $\delta^{13}\text{C}$ positive excursion with global impact is recorded in the carbonate sediments and it is concomitant with the diversification of various oceanic groups such as coccolithophores (Cobianchi *et al.* 1992; Mattioli and Erba 1999; Bown *et al.* 2004), radiolarians (Bartolini *et al.* 1996) and ammonites (O'Dogherty *et al.* 2006). This carbon isotope excursion (CIE) has been identified in several places in Europe (Corbin 1994; Bartolini *et al.* 1996; Bartolini *et al.* 1999; Jenkyns *et al.* 2002; O'Dogherty *et al.* 2006; Brigaud *et al.* 2009), and is characterised by an amplitude of +1 ‰ recorded in bulk carbonates (well documented in O'Dogherty *et al.* 2006) and +2 ‰ in belemnites (e.g., Jenkyns *et al.* 2002). However, the positive CIE is not observed sanguinely on coal and

organic matters deposits from Yorkshire (Hesselbo *et al.* 2003). It is therefore unclear if the excursion affected all the carbon reservoirs. This perturbation is explained as being the result of an increase in primary productivity due to ocean fertilization (Bartolini *et al.* 1999). Despite the major perturbations affecting both the biosphere and geosphere as recorded in sedimentary rocks of that age, no accurate time frame has been offered for the collective end-Aalenian/Early Bajocian period. As radiochronology for this time interval is still highly uncertain (Pálffy *et al.* 2000; Hall *et al.* 2004), the current duration of 2 Myr proposed for the Early Bajocian was based on the supposition that the ammonite subzones were of equal duration, each lasting 200 kyr in the Bajocian (Gradstein *et al.* 2004).

Since the recognition of cyclic deposition in the sedimentary record from the calcium carbonate content related to orbital cycles (Gilbert 1895), the cyclostratigraphic method has been widely used to constrain durations for several Mesozoic stages (e.g., Claps *et al.* 1995; Giraud *et al.* 1995; Boulila *et al.* 2008b; Suan *et al.* 2008b; Huang *et al.* 2010). Based on cyclostratigraphic analysis of calcium carbonate content obtained from hemipelagic deposits of the Chaudon-Norante section (France), we present here a new estimate of the duration of the Early Bajocian. Moreover, the new $\delta^{13}\text{C}_{\text{carb}}$ data presented here allows a good identification of the carbon cycle perturbation and an estimation of its duration.

Geologic and palaeogeographic settings

Two sections were studied for this work: Chaudon-Norante and Les Dourbes. Both of these sections are located in the French Subalpine Basin which was delimited northward by the Jura platform, westward by the Central Massif and the Ardèche platform, and southward by the Provence platform (Fig. 1A). These two sections belong to the Digne tectonic Nappe (Southern Alps), emplaced during the Mio-Pliocene (Lemoine 1973; Gidon and Pairis 1992). Chaudon-Norante was used here as a reference for the calculation of the Early Bajocian duration. A comparison was made with the hemipelagic Les Dourbes succession, the thickest section for the Early Bajocian interval from the French Subalpine Basin, in order to highlight possible hiatuses in the sedimentary succession in Chaudon-Norante. Les Dourbes section was also used to retrieve the long-term sedimentation rate.

Chaudon-Norante

The Chaudon-Norante section, located in the Ravin de Coueste near Digne (Fig. 1B), presents a continuous succession from the Toarcian (Early Jurassic) to the base of the Bathonian (Middle Jurassic). This section was proposed for the Aalenian/Bajocian GSSP (Erba and Pavia 1990). The Chaudon-Norante succession is well-exposed and the ammonite biostratigraphy for the Bajocian (Pavia 1973, 1983) as well as the nannofossil biostratigraphy have high temporal resolution (Erba 1990; Mattioli and Erba 1999).

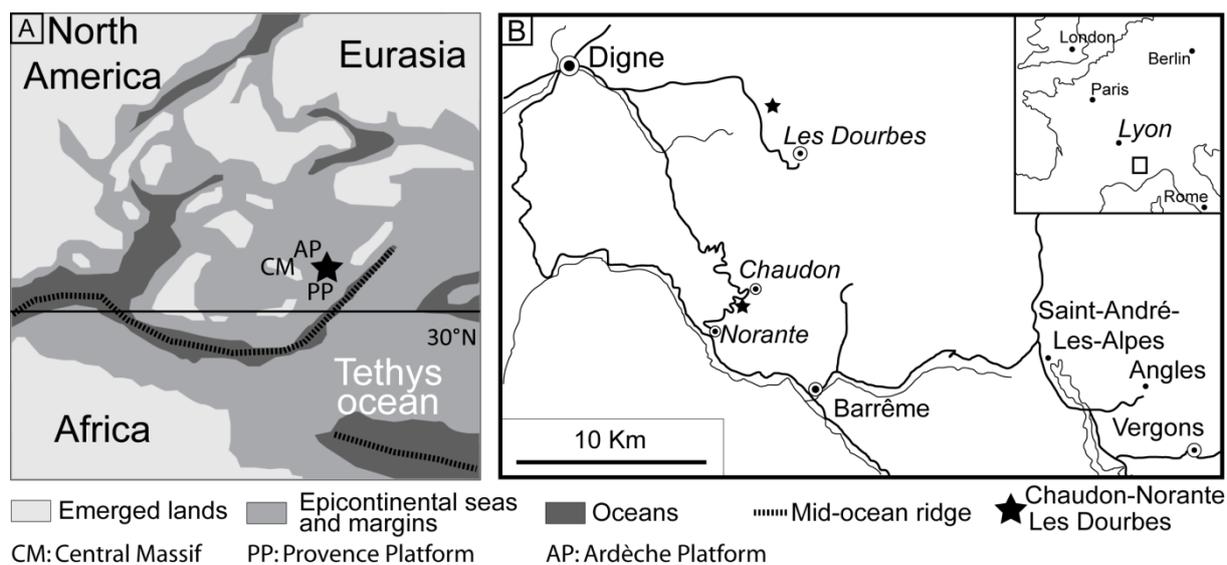


Figure 1: A: Geographical location of Les Dourbes and Chaudon-Norante in France; B: Palaeogeography of Europe during the Middle Jurassic, modified from Blakey (2005) and Scotese (2001). The map shows the distribution of the emerged lands, epicontinental seas, deep oceans, and mid-ocean ridges. The black star represents the location of Les Dourbes and Chaudon-Norante in the French Subalpine basin.

The part of the section studied here spans from the end of the Aalenian to the end of the Early Bajocian (Fig. 2). The succession comprises decimetric hemipelagic marlstone/limestone alternations. The limestones are mainly wackestones to packstones with some bioclastic remains of *Bositra* (*Bivalvia*), radiolarians, rare benthic foraminifera and rare siliceous sponge spicules (Pavia 1983).

The latest Aalenian is assigned to the latest part of the Concavum ammonite Zone. This 39.6 metre-thick interval is composed of fairly regular marlstone-limestone alternations except for the uppermost part, which is marl-dominated. The 129 metre-thick Early Bajocian succession corresponds to four ammonite zones. The Discites Zone at the base is dominated by marlstone. The *Laeviuscula* Zone displays regular marlstone-limestone alternations. The Sauzei Zone is limestone-dominated, whilst the *Humphriesianum* Zone displays regular marlstone-limestone alternations (Fig. 2).

Les Dourbes

The Les Dourbes section is located in the Ravin de Feston, near Digne (Fig. 1B). This section generally presents the same sedimentary succession as in the Chaudon-Norante section. It is characterized by metre-scale hemipelagic limestone-marlstone alternations over 235 m for the Early Bajocian (Fig. 3). At Les Dourbes, a high-resolution ammonite zonation was only proposed for the part ranging from the boundary between Sauzei and *Humphriesianum* Zones, to the Early Bajocian-Late Bajocian boundary (Pavia 1983). The biochronology of the lower part of the section (*Discites* and *Laeviuscula* Zones) is derived from Ferry and Mangold (1995) but without any precise identification of the zone limits.

Analytical Methods

Analysis of calcium carbonate content and of sediment greyscale

For the calcium carbonate content, the Chaudon-Norante section has been regularly sampled every 15 cm, which represents 251 samples for the uppermost Aalenian and 873 samples for the whole Early Bajocian. Each of the 1124 samples has been analyzed using a Dietrich-Frühling calcimeter to determine the wt%CaCO₃ contents by measuring evolved CO₂ after acidification of the sample.

We compared the low-frequency greyscale representations in order to correlate precisely the two sections, which are also correlated by means of ammonite biostratigraphy, and thus detect possible hiatuses in the thinner Chaudon-Norante section. Due to the abundant vegetation present on both sections, and the difficulty of overcoming the problem of shadows altering the greyscale intensity in pictures, we performed the greyscale representation on precise drawings of the sections with bed by bed measurements. The Chaudon-Norante section was previously described (Pavia 1983) with great accuracy, including a precise thickness measurement of each bed and the associated lithology. Four lithological groups were recognized (i.e., marlstone, calcareous marlstone, argillaceous limestone and limestone) and each of them was associated with a grey level on an 8 bits greyscale (256 grey levels). Hence we obtained a general greyscale representation of the section with 0 for marlstone, 85 for calcareous marlstone, 170 for argillaceous limestone and 255 for limestone, exhibiting grey level alternations congruent to field observations of carbonate content. The Les Dourbes section was previously studied (Ferry and Mangold 1995) following the same methodology described by Pavia (1983). So a similar greyscale representation was obtained for this section using our protocol.

Based on these artificial greyscale representations of the sections, we extracted the grey value of each pixel along each section to obtain scatter plots (greyscale/thickness of the section). We obtained 2371 values for the Chaudon-Norante section and 4319 values for the Les Dourbes. As the aim of these greyscale representations was to correlate the sections we applied a smoothing filter to each plot to retrieve the low-frequency (long-term) signal of the sedimentary deposits. The smoothing has been performed using a moving average calculation padded with the last values on 150 points for Les Dourbes and 75 points for Chaudon-Norante using the Stratigraphic Analysis Software Strati-Signal 1.0.5 (Ndiaye 2007). The smoothing process leads to loss in value number (N) due to averaging. The padding method is a mathematical methodology which fills the value loss by interpolation.

Carbon isotope compositions of bulk samples have been measured using an auto sampler Multiprep coupled to a GV Isoprime® mass spectrometer. For this bulk carbon isotope analysis, we selected 101 samples among the whole sample set, all having a weight CaCO₃ percentage $\geq 80\%$ in order to limit possible problems due to differential diagenesis in marlstones and limestones. For each sample, an aliquot of 300 to 375 μg of rock proportional to the CaCO₃ concentration was reacted with anhydrous oversaturated phosphoric acid at 90°C during 20 min. Isotopic compositions are quoted in the delta notation in permil relative to VPDB. All sample measurements were duplicated and adjusted to the international reference NIST NBS19. External reproducibility was in average $\sim 0.05\%$ (2σ) for $\delta^{13}\text{C}_{\text{carb}}$ values.

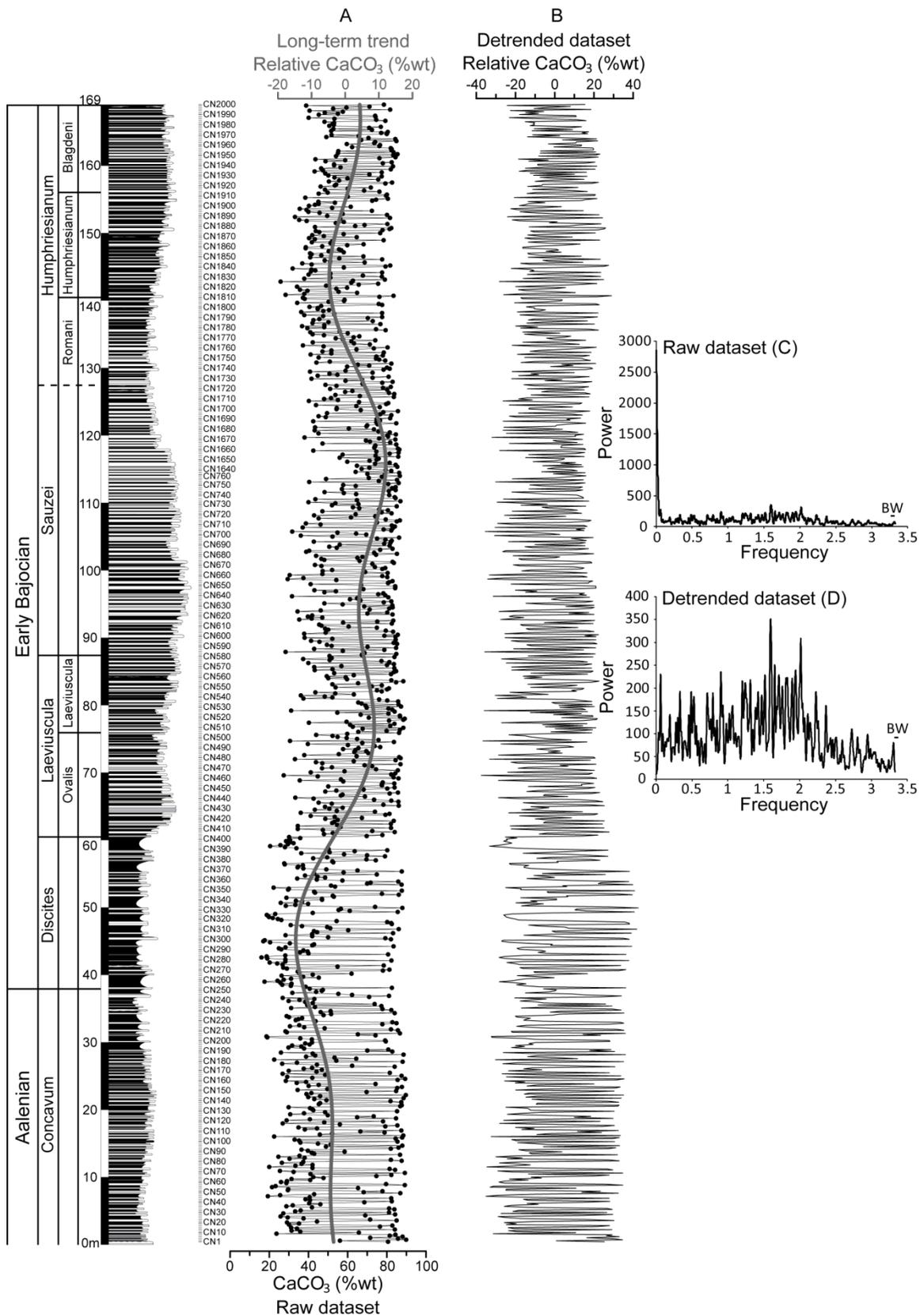


Figure 2: The Chaudon-Norante section modified from Pavia (1983). A: The raw dataset. The Blackman-Tuckey (BT) analysis 'raw dataset' (C) is highly influenced by a long-term frequency. This frequency extracted, which has a period of $77 \text{ m} \pm 39 \text{ m}$, is represented in grey (A) as well as the residuals obtained called detrended dataset (B), and represented in relative CaCO₃. The BT analysis 'Detrended dataset' (D) shows the main frequencies observed on the residuals dataset without the influence of the long-term variations. The bandwidth (BW) for spectral analyses is 0.03.

Spectral analysis techniques

Different spectral analysis methods have been used although algorithms employed for each technique are not discussed in this study. We refer to Weedon (2003) for the basic mathematics and to Paillard *et al.* (1996) for algorithms as far as all spectral analyses were performed using AnalySeries (Paillard *et al.* 1996).

The Blackman-Tuckey (BT) method was first used on the grey values extracted for Chaudon-Norante and Les Dourbes (Figs. 3 and 4), and for Chaudon-Norante wt%CaCO₃ time series (Fig. 2A). The lowest frequency spectral peak of the wt%CaCO₃ time series from Chaudon-Norante, representing 77 m ± 39 m long-term trend, has been band-pass filtered using AnalySeries (Fig.2A). The resulting new time series represented in relative CaCO₃ (wt%; Fig.2B), has been analyzed using the BT method with a Bartlett window and 0.03 m long and 0.08 m long bandwidths (Fig. 5B and C). Confidence levels were determined by the robust method of Mann and Lees (1996), determining the red-noise function by a least-square approach using the software R 2.12.0 (R Development Core Team, Vienna, Austria). On the same time series, a Multi-Taper Method (MTM) with 6 tapers was also performed with the inferior and superior error bars (Fig. 5A). Finally, a Morlet wavelet analysis (Torrence and Compo 1998) was also performed in order to highlight possible variations in short-term sedimentary wavelengths. This analysis is presented with frequencies $\omega_0 = 6$ and $\omega_0 = 24$.

Results

Greyscale spectral analysis and correlation between Les Dourbes and Chaudon-Norante

At Les Dourbes, the grey levels fluctuate between 100 and 170 until the middle of the Sauzei Zone where the grey level increases up to 220 to the end of the Sauzei Zone. The Humphriesianum Zone displays low greyscale values before an increase at the end of this zone. At Chaudon-Norante, the grey levels are low, between 50 and 100, in the Discites Zone. Grey level increases up to 180 in Laeviuscula Zone and reach 180 at the end of the Sauzei Zone. Eventually, the Humphriesianum Zone displays low grey level values before an increase at the end of this zone.

The variations in the carbonate content deduced from grey level variations at Les Dourbes (235 m thick) and Chaudon-Norante (131 m thick) sections show very similar stratigraphic trends (Fig. 3). Thus, the thickness ratio between comparable intervals of the two successions is the relative sedimentation rate. The ratio of relative sedimentation rate for the Early Bajocian between these two sections is 1.79 which corresponds to the ratio of thickness (in metre) for the whole Early Bajocian between the two studied sections. We recognized 6 intervals on the basis of their grey level correlations and calculated the relative sedimentation rate for each of them. From the base to the top of the Early Bajocian, the relative sedimentation rates for each interval are respectively 1.44, 2.13, 2.28, 1.49, 1.48 and 2.07. The correlations based on ammonite zones cannot be used straightforwardly to establish the relative sedimentation rate in these two sections, because at Les Dourbes only the upper part of the section (i.e., Humphriesianum Zone and the upper part of the Sauzei Zone) was precisely dated by ammonites (Pavia 1983). No hiatuses were identified in Chaudon-Norante or Les Dourbes by using the grey levels correlation technique, but only variable accumulation rates.

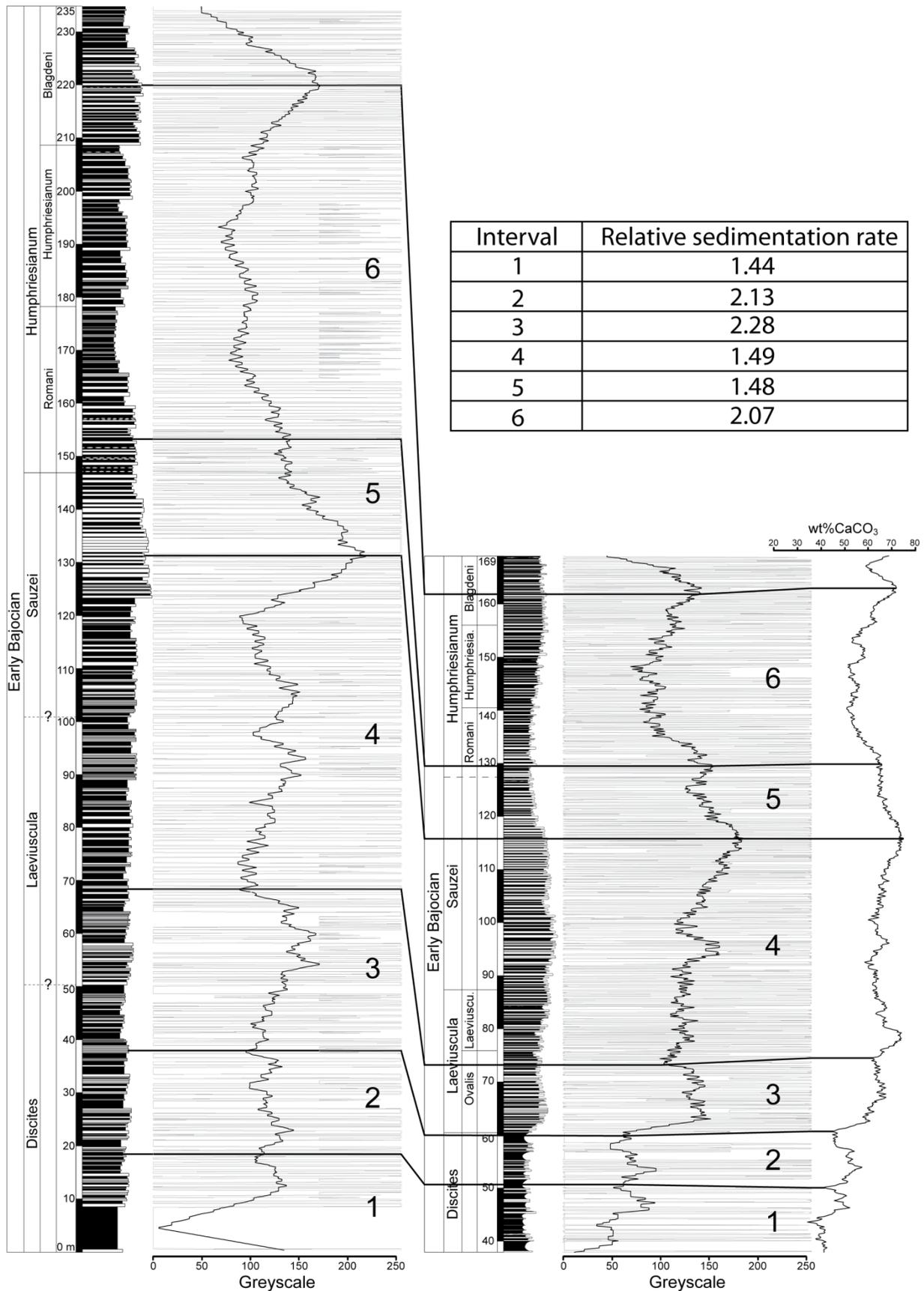


Figure 3: Grey level representations on 8 bit greyscales of the Les Dourbes sections (Left, based on Pavia, 1983 and Ferry and Mangold 1995) and of the Chaudon-Norante section (Right, based on Pavia 1983). Both results have been smoothed using a moving average with padding method from StratiSignal with a 150 point interval for Les Dourbes and a 75 point interval for Chaudon-Norante. Re-sampled CaCO_3 content is also 7 represented smoothed with a 25 point interval. Good correlations with the grey level graphs are observed. Based on the greyscale correlations, 6 intervals are proposed with relative sedimentation rate between Les Dourbes and Chaudon-Norante reported in the table.

Both spectral analyses on the grey level variations reveal two main groups of frequency supported by confidence intervals over 99 % (Fig. 4). The ranges of these groups of peak periods are linked to variations in sedimentation rate. In both sections, these peaks represent the limestone-marlstone alternations. The ratio of mean frequencies over 99% observed between Les Dourbes and Chaudon-Norante is ~ 1.6 (Fig. 4). Thus, this ratio of carbonate alternations is close to the relative sedimentation rate estimated above based on the correlations. This observation allows us to consider the difference of thickness in limestone-marlstone alternation in both sections due to a variable sedimentation rate rather than the presence of hiatuses in the Chaudon-Norante deposits (Fig. 3).

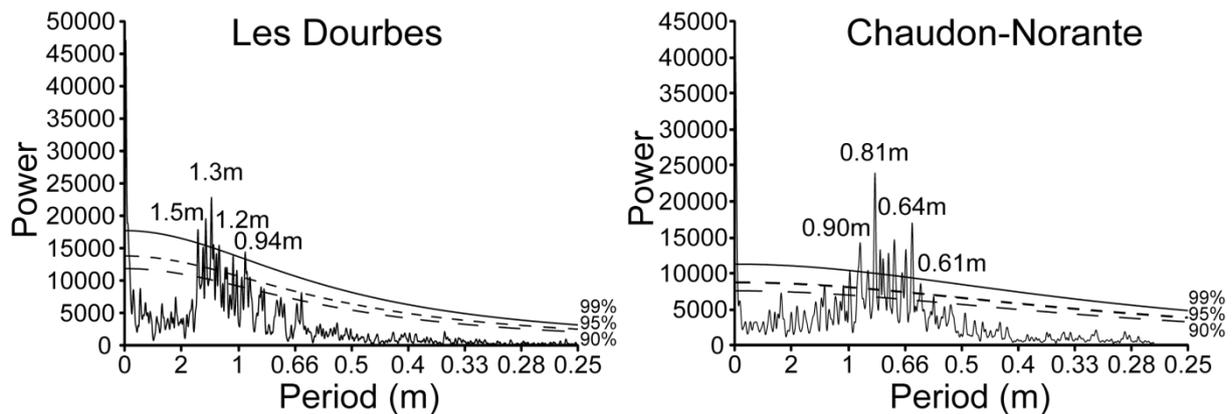


Figure 4: Two spectral analyses based on greyscale extracted from Les Dourbes (left) and Chaudon-Norante (right). The confidence levels have been calculated using the method of Mann and Lees (1996). At Les Dourbes, periods ranging from 1.5 m to 0.94 m are supported with confidence interval over 99 %. At Chaudon-Norante, periods ranging from 0.9 m to 0.64 m are supported with confidence interval over 99 %. These periods from both sections represent the limestone-marlstone alternations.

Calcium carbonate content at Chaudon-Norante

At the base of the section, in the Concavum and Discites Zones, the range of the CaCO_3 content is wider than in the rest of the section (Fig. 2). Fluctuations between 20 wt% and 85 wt% are observed. In the Concavum Zone, CaCO_3 mostly ranges from 30 wt% to 85 wt%. Within the long-scale variations, there is a rise between 10 m and 20 m with a slight reduction of the range of the small-scale fluctuations of the CaCO_3 contents. Then, there is a decrease in the large-scale variations of CaCO_3 content from 20 m to 40 m. In the Laeviuscula Zone, the range of CaCO_3 content decreases and varies between 40 % and 85 %. In the Sauzei Zone, the range of CaCO_3 content decreases even more and varies locally between 50 wt% and 85 wt%. This decrease is linked to a long-scale overall rise in the CaCO_3 content. Finally, in the Humphriesianum Zone, the CaCO_3 range is 40 wt% wide. In this zone, there is a decrease of the CaCO_3 content from 128m to 142m then followed by an increase from 142 m to 165 m. The long-scale variations are less prominent after the extraction of the long period cycle observed through the spectral analysis (see Material and Methods) but this filtering does not affect the small-scale CaCO_3 variations and ranging in different intervals.

Carbon isotope curve of Chaudon-Norante

The $\delta^{13}\text{C}_{\text{carb}}$ plot can be divided into three parts (Fig. 6). The first part, ranging from the base of the section to the Aalenian/Bajocian boundary, has $\delta^{13}\text{C}$ values fluctuating between 1‰ and 1.5‰ with three values below 1‰ but without any clear long-term pattern. The second part, from the Aalenian/Bajocian boundary to the end of the Laeviuscula ammonite Zone, shows a progressive increase from 1.3‰ to 2.5‰. The third part, from the end of the Laeviuscula ammonite Zone to the end of the Early Bajocian, displays quite steady values fluctuating between 2.3‰ and 2.7‰ with three points below 2.2‰. In this part, there is a weak trend towards a reduction of 0.3‰.

CaCO₃ spectral analysis at Chaudon-Norante

Based on the results from the MTM and BT spectral analyses, different groups of spectral peaks are recognized (Fig. 5). On the 0.3 m bandwidth BT analysis, the cycles with a period of 16 m, 1.1 m, 0.83 m, 0.76 m, 0.52 m are supported with a confidence level over 95 %. 0.62 m, 0.51 m, 0.49 m cycles are supported with a confidence level over 99 %. 0.62 m and 0.49 m cycles are again supported on the 0.8 m bandwidth BT analysis over 95 %. All the main frequencies obtained with the BT method are also obtained with the MTM method (Fig. 5). The 0.62 m and 0.49 m cycles correspond to the marlstone-limestone alternations observed in the field and on the greyscale spectral analysis.

We propose to interpret the different groups of peaks based on the hierarchical organization of the Milankovitch cycles (i.e., eccentricity 405 kyr and ~100 kyr, obliquity 41 kyr and precession 23 kyr and 19 kyr), which can be summarized from precession to eccentricity as 1:2:5:20. In prior geological times, the duration of obliquity and precession was probably shorter than in the Quaternary and can be approximate (Berger and Loutre 1994) and estimations for the eccentricity behaviour for the last 250 Myr has been proposed (Laskar *et al.* 2004; Laskar *et al.* 2011a) even if chaotic behaviour of large asteroids in Solar system make a precise evolution of Earth's eccentricity never possible (Laskar *et al.* 2011b). Nevertheless, the hierarchical organization of orbital cycles should have been consistent through time and can still be used (Berger and Loutre 1994). The shorter cycle observed with periods from 0.48 m to 0.84 m, is attributed to precession. The second one, with period ranging from 0.98 m to 1.43 m, is assigned to obliquity. The third one, with periods from 2.8 m to 3.84 m is assigned to the high-frequency eccentricity while the last range of periods (12-16 m) corresponds to the low-frequency eccentricity. Unfortunately, these hypotheses about cycle identification cannot yet be supported by absolute dating from radiochronology.

Filtering, age quantification and sedimentation rate

In Figure 6 are reported the filtered variations of CaCO₃ wt% contents for the periods corresponding to the precession (periods from 0.84 m to 0.48 m), obliquity (periods from 1.43 m to 0.98 m), and 100 kyr (periods from 3.84 m to 2.77 m) and 405 kyr eccentricity (periods from 10 m to 20 m) cycles. We observe, on the basis of these filtered data, that most of the variations of CaCO₃ contents may be explained by the precession and obliquity cycles. The effects of the 405 kyr-eccentricity cycle are not as strongly recorded as in the CaCO₃ signal, despite the high confidence level for the associated period in the spectral analysis. Eccentricity is acknowledged to be the only orbital cycle to have most likely remained close

to steady state from the Mesozoic to the Quaternary (Laskar *et al.* 2004). The 100 kyr-eccentricity cycle, which is not supported in the spectral analysis, is more represented during the uppermost Aalenian and the beginning of the Early Bajocian and then fades away in the Sauzei and Humphriesianum ammonite Zones. Moreover, the obliquity cycle, highly represented in the uppermost Aalenian, seems to fade away in the upper part of the Discites ammonite Zone and the rest of the Early Bajocian. This cycle is well-recorded in the CaCO_3 content variations at the transition between the Laeviuscula and the Sauzei ammonite Zones.

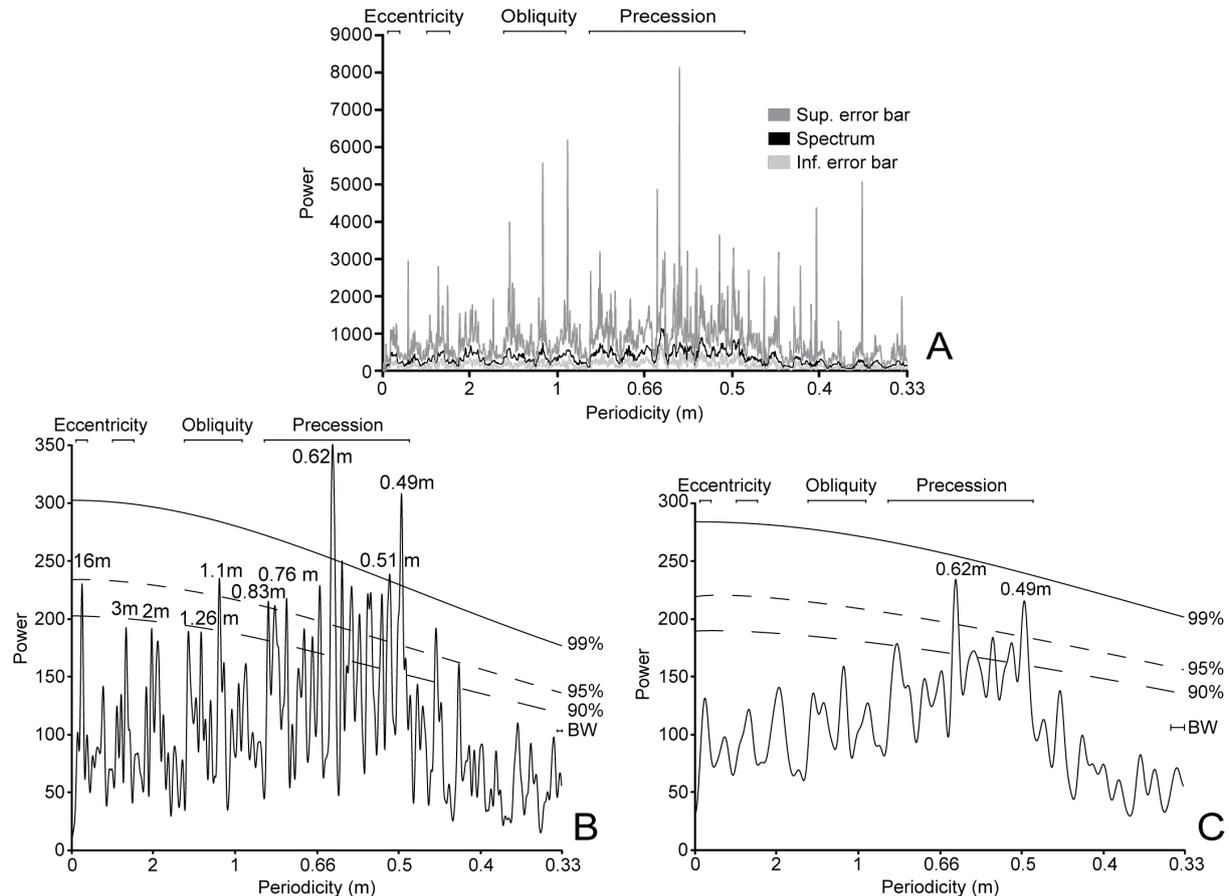


Figure 5: Spectral analyses of $\text{wt}\%\text{CaCO}_3$ from Chaudon-Norante. A: Multi-taper analysis is represented. B and C: Two Blackman-Tuckey (BT) analyses are represented with a bandwidth (BW) of 0.03 (B) and 0.08 (C). The confidence intervals have been calculated on BT analyses based on the Mann and Lees (1996). Based on the hierarchical organization of the periods observed, range for the Eccentricity, Obliquity and Precession cycles are presented.

The 405 kyr-eccentricity cycle for the past 250 Myr is the more stable cycle in the Phanerozoic (Laskar *et al.* 2004) and has been used for the quantification of the duration of the different stratigraphic interval studied. Nevertheless, due to the poor representation of the 405 kyr-eccentricity cycle, the duration quantification of the Early Bajocian, ammonite zones as well as of the $\delta^{13}\text{C}$ excursion has also been made based on the 100 kyr-eccentricity cycle, the obliquity and the precession. Obliquity cycle is supposed to have a period of 37 kyr and precession cycle is supposed to have a period of 20 kyr (Berger and Loutre 1994). The results

are presented in the Table 1. We propose for each time interval a duration value (Mean in the Table 1) which is the mean of durations calculated from each Milankovitch cycle. We are more confident in this mean duration values than durations calculated only from the 405 kyr-eccentricity cycle, commonly used for such time estimation, but which is not well-defined in our succession. The standard deviation associated with a mean value is proposed as error (2σ). The uppermost Aalenian part of the section lasted 1.092 ± 0.204 Myr but this duration is not equivalent to the entire Concavum Zone as far as its lower limit was not recorded at Chaudon-Norante. The Early Bajocian lasted 4.082 ± 0.144 Myr. All durations proposed in this study and associated errors are summarized in Table 1.

The sedimentation rates have been calculated at Chaudon-Norante using a tuning method based on correlations with the modelled eccentricity cycle La2010d proposed by Laskar *et al.* (2010a) and our filtered 405 kyr-eccentricity and 100kyr-eccentricity cycles. The sedimentation rate does not display long term trend and presents minimum and maximum values of 2 cm/kyr and 5 cm/kyr. Most of the high sedimentation rate intervals correspond to more carbonate-rich intervals and most of the low sedimentation rate intervals correspond to less carbonate-rich intervals.

Figure 6 here (whole page)

Time interval	Duration 405kyr-filtered (kyr)	Duration 100kyr-filtered (kyr)	Duration 37kyr-filtered (kyr)	Duration 20kyr-filtered (kyr)	Mean (kyr)	2σ (kyr)
<i>Sub-Stage</i>						
Late Aalenian (partly)	940	1130	1137,75	1160	1092	204
Early Bajocian	4100	4080	3986,75	4160	4082	144
<i>Ammonite zones</i>						
Concavum (partly)	940	1130	1137,75	1160	1092	204
Discites	510	770	693,75	660	658.5	218
Laeviuscula	910	770	795,5	880	839	134
Sauzei	1600	1270	1295	1300	1366	313
Humphriesianum	1080	1270	1202,5	1320	1218	208
<i>Isotopic steps</i>						
Increase	1240	1410	1378,25	1400	1357	158
Plateau	2860	2670	2608,5	2760	2724.5	219

Table 1: Sub-stages, ammonite zones and isotopic steps duration estimations based on the four filtered Milankovitch cycles

Wavelet analysis

The cycles corresponding to precession are relatively continuous in Chaudon-Norante, with weak signal between 35 m and 40 m, 75 m and 85 m, and from 161 m upward the end of the section (P in Fig. 7). The cycles corresponding to obliquity are less consistent. They are especially strongly expressed between 30 m and 60 m (O in Fig. 7). The cycles corresponding to 100 kyr-eccentricity are inconsistently expressed, especially between 10 m and 30 m and from 100 m upward the end of the section (e in Fig. 7). Lastly, the cycle corresponding to the 405 kyr-eccentricity is almost continuous except between 85 m and 105 m, and from 135 m upward the end of the section (E in Fig. 7).

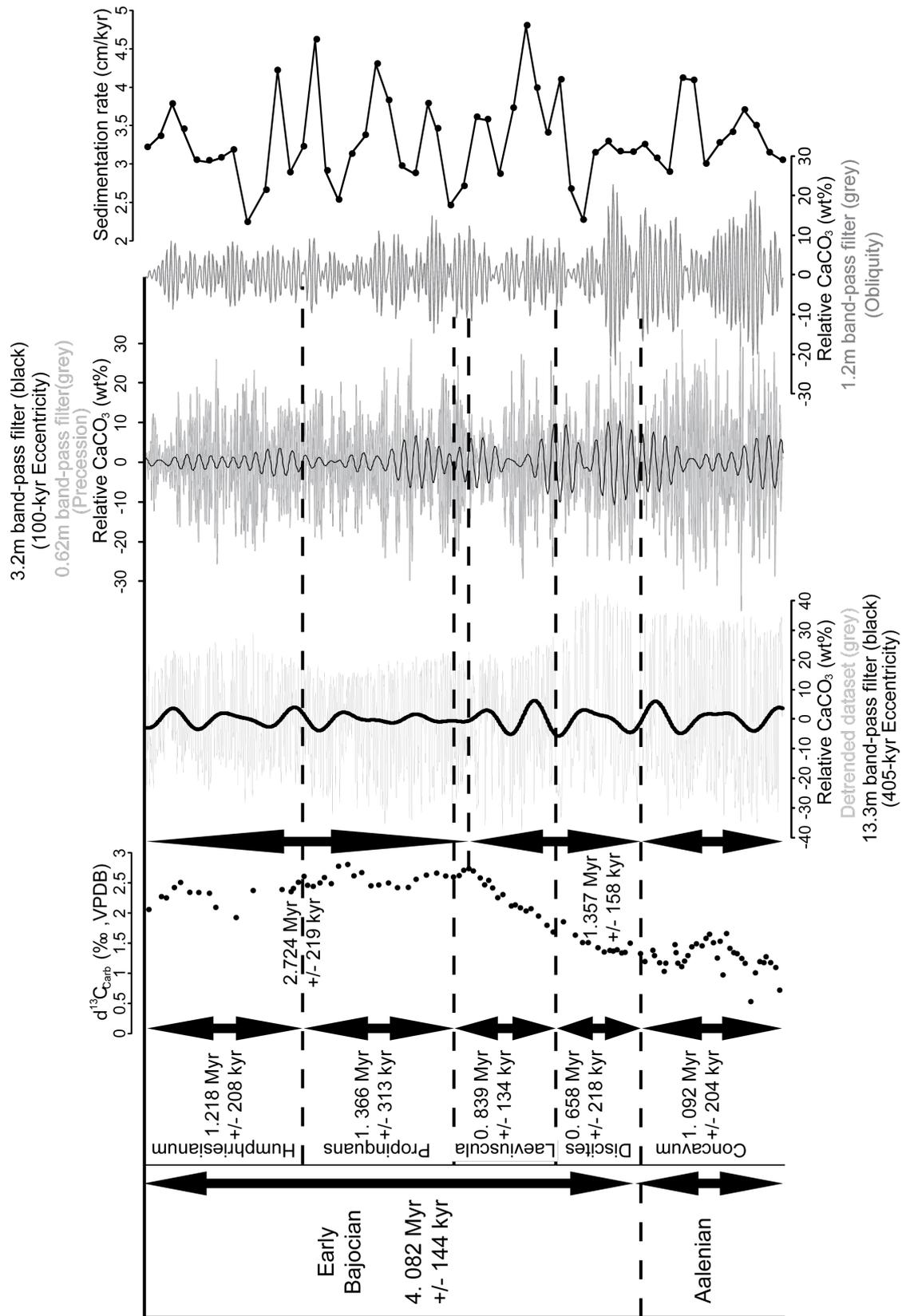


Figure 6: Filtered Milankovitch cycles from the CaCO_3 at Chaudon-Norante. The CaCO_3 detrended dataset (grey) is represented with the 13.3m (width from 20m to 10m) band-pass filter (black; 405-kyr eccentricity) on the left, the 3.2m (width from 3.85m to 2.78m) band-pass filter (black; 100-kyr eccentricity) and the 0.62m (width from 0.84m to 0.48m) band-pass filter (grey; precession) cycles in the middle, the 1.2m (width from 1.43m to 0.98m) band-pass filter (black; obliquity) cycle on the right. Proposed durations for the Early Bajocian, its four ammonite zones and the $\delta^{13}\text{C}_{\text{carb}}$ positive excursion are presented for each interval.

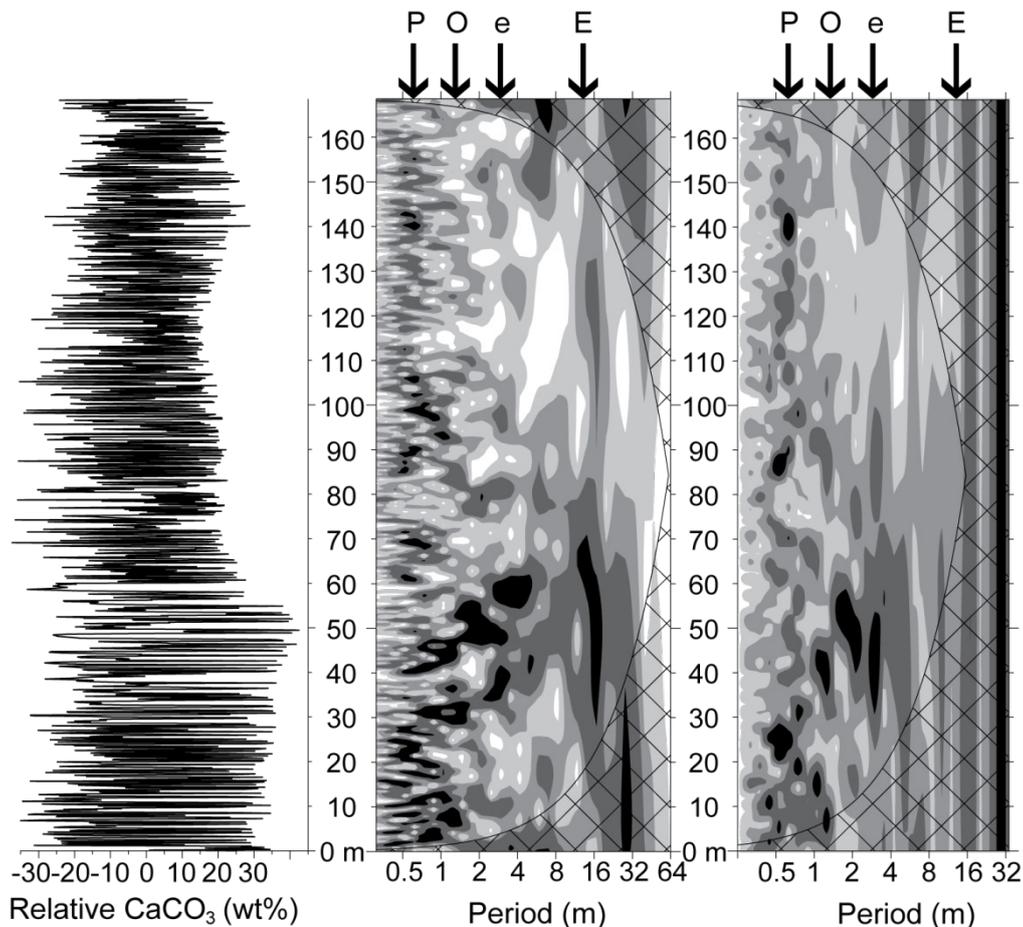


Figure 7: Two wavelet analyses are represented using the method of Torrence and Compo (1998) and correlated to the relative CaCO_3 of the detrended dataset. The wavelet analysis on the right has been done using a 6 Morlet frequency and on the left using a 24 Morlet frequency. The arrows show the periods for Milankovitch cycles identified on the spectral analyses (P for Precession, O for Obliquity, e for 100 kyr-eccentricity and E for 405 kyr-Eccentricity).

Discussion

Sedimentation and cyclicity

No hiatuses were identified at Chaudon-Norante on the basis of field observations, greyscale correlations with the thick and continuous Les Dourbes section. Stratigraphic continuity is also supported on the basis of the correspondence of cycles observed in the two studied sections. The duration of the Early Bajocian can thus be precisely and confidently calculated at Chaudon-Norante by means of cyclostratigraphy. The Chaudon-Norante section, which presents regular marlstone-limestone couplets, has been selected for cyclostratigraphic methodology rather than the GSSP Cabo Mondego in Portugal which presents more nodular limestones and less regularly alternating couplets (Suchéras-Marx *et al.* 2012). The observed sedimentary carbonate cycles can be produced amongst factors by changes in productivity of pelagic carbonate (productivity cycle), of carbonate mud export from shallower areas (export cycle), of siliciclastic input from the hinterland or by diagenetic processes (Einsele and Ricken 1991; Einsele 1996; Pittet and Strasser 1998). Models of diagenetically induced cycles are often based on carbonate dissolution in relation to aragonite transformation (Munnecke *et*

al. 2001; Westphal *et al.* 2004). These models can easily explain the limestone-marlstone alternations but are not able to explain the hierarchical organization of cycles such as the one observed at Chaudon-Norante. Moreover, they fail to explain the long-distance correlation observed between Les Dourbes and Chaudon-Norante. During the Early Bajocian at Cabo Mondego, Portugal, the carbonate pelagic production by calcareous nannofossils increased but represents only 20% of the total carbonate (Suchéras-Marx *et al.* 2012). At Chaudon-Norante, the carbonate pelagic production is equal to lower than in Cabo Mondego (Unpublished PhD thesis Suchéras-Marx 2012). Thus, pelagic productivity cycle cannot explain the genesis of the carbonate cycles observed at Chaudon-Norante. Siliciclastic dilution cycles cannot be ruled out but, based on correlations between the Jura platform and the Digne area (i.e.; Chaudon-Norante and Les Dourbes), some authors argued that the sedimentation in the basin during the Bajocian was essentially controlled by the export of carbonate from the platform (Ferry and Mangold 1995; Thiry-Bastien 2002).

The cycles identified by time series analysis, as far as they have been identified on carbonate content variations, may have recorded either changes in the amount of carbonate produced on the platform itself and then delivered to the basin, or changes in the intensity of carbonate export from the platform to the basin, without necessarily important changes in the shallow-area carbonate production. Carbonate production on platforms is commonly related to climatically-driven environmental conditions or to sea-level variations (Hallock and Schlager 1986; Pittet *et al.* 2000). Also, platform morphology coupled to sea-level variations can play a major role in platform export intensity. Flat-topped platforms can be subaerially exposed during low sea levels, resulting in both a decrease in carbonate production and basinward export (Schlager *et al.* 1994; Pittet *et al.* 2000). In contrast, carbonate ramp systems are less affected by changes in production rates during sea-level fluctuations (Reuning *et al.* 2002), because the shallow locus of carbonate production will move along the ramp profile, following the sea level (Gréselle and Pittet 2010). On the other hand, the export of carbonates from the shallow areas to the basin was more efficient during lowstand in platforms with ramp morphology due to reduction of the distance from the production area to the accumulation area, as shown for the Valanginian of the Vocontian Basin (Gréselle and Pittet 2010). During the Bajocian, carbonate export dynamics from the Jura carbonate ramp to the Subalpine basin were also more efficient during lowstand of sea level as evidenced by important carbonate deposits corresponding to lowstand system-tract in the basin (Ferry and Mangold 1995; Thiry-Bastien 2002). Hence, the carbonate content at Les Dourbes and Chaudon-Norante is likely controlled by sea-level export cycles. Such cycles produced by export of carbonate from platforms have already been documented in different Jurassic stages and carbonate-dominated sections in Europe (Pittet and Strasser 1998; Mattioli and Pittet 2002; Pittet and Mattioli 2002; Olivier *et al.* 2004; Suan *et al.* 2008a; Bádenas *et al.* 2009). Nevertheless, correlations between the Jura platform and the Vocontian basin have been made at the scale of the 3rd order cycle (*sensu* Vail *et al.* 1991) which may be related either to tectonics or to climatically-driven eustatic sea-level changes. The fluctuations in carbonate content recorded in the studied section could be climatically-driven by eustatic cycles but the resolution of the correlations between the Jura platform and the Chaudon-Norante section cannot by itself completely confirm a control by Milankovitch cycles of sea-level fluctuations.

Duration of the Early Bajocian and of the $\delta^{13}\text{C}$ positive excursion

We quantified the duration for the Early Bajocian at about 4.082 Myr based on the bandpass filtering of the different astronomical cycles (Table 1). This result clearly differs from the previous acceptance of a 2 Myr duration proposed by Gradstein *et al.* (2004) who considered an equal duration for all the ammonite subzones of the Bajocian. Cyclostratigraphy has been frequently used and validated for Jurassic (e.g., Claps *et al.* 1995; Hinnov and Park 1999; Weedon and Jenkyns 1999; Kemp *et al.* 2005; Suan *et al.* 2008a) and Cretaceous times (e.g., Giraud *et al.* 1995; Locklair and Sageman 2008; Huang *et al.* 2010) providing more rigorous duration estimations than those previously inferred from ammonite biochronology. Radiometric ages have been proposed in the last ammonite Zone of the Aalenian and the first ammonite Zone of the Late Bajocian based on Canadian deposits (Pálffy *et al.* 2000). Based on those results, the Early Bajocian is a little shorter than 7.6 Myr. Unfortunately, the errors associated with ages proposed for the Middle Jurassic are longer than the proposed duration of the stage, and no confidence linked to this duration is available so far (Pálffy *et al.* 2000; Gradstein *et al.* 2004). The proposed duration for the Early Bajocian as well as its four ammonites zones can be used as reference since Chaudon-Norante ammonite biostratigraphy is well defined and has been used in the definition of Bajocian biochronostratigraphy (Pavia 1983; Rioult *et al.* 1997; Gradstein *et al.* 2004).

Our cyclostratigraphic estimates also allow us to discuss the duration of the positive CIE recorded in Chaudon-Norante as well as in several other European sites. The duration of a C isotope perturbation is a key parameter for the understanding of the driving mechanism(s). The Early Bajocian $\delta^{13}\text{C}$ positive excursion is very well identified and separated in two intervals. The first interval is marked by increasing carbon isotope ratios and lasted $1.357 \text{ Myr} \pm 158 \text{ kyr}$. The second interval corresponds to climax $\delta^{13}\text{C}$ values and lasted $2.724 \text{ Myr} \pm 219 \text{ kyr}$.

Other significant positive C isotope excursions are known in the geological record. The Late Cenomanian carbon isotope positive excursion, associated to the Oceanic Anoxic Event 2 (OAE2; around -94Ma), is one of the most important and studied positive CIE during the Mesozoic. It has been estimated at 197 kyr (increase values ~ 90 kyr and climax ~ 107 kyr, Kuhnt *et al.* 2005), 430 kyr (Voigt *et al.* 2008) or 572-601 kyr (Sageman *et al.* 2006). Even if there is debate about the estimation of the duration of the OAE2, this event was shorter than 1 Myr and thus shorter than the Early Bajocian carbon isotope positive excursion. The OAE2 is contemporary to a rapid warming of surface and shallow waters (Huber *et al.* 1999), a fast rising sea level (Voigt *et al.* 2006) and increase rate of organic carbon burial at the origin of the positive CIE. Despite some similarities between the Late Cenomanian and the Early Bajocian, anoxia in the oceans, the worldwide organic-rich deposits and the duration of the OAE2 event challenge its comparison to the Early Bajocian event. The Weissert Event (Erba *et al.* 2004), a carbon isotope positive excursion occurring during the Valanginian (~ 136 Ma), has been estimated to last ~ 2 Myr (Erba 2004), 2.3 Myr (Sprovieri *et al.* 2006) or 1.5 Myr for the positive CIE until the interval where $\delta^{13}\text{C}$ values start decreasing (Gréselle and Pittet 2010; Gréselle *et al.* 2011). This major positive CIE is interpreted as an increase in primary production (Stoll and Schrag 2000; Erba and Tremolada 2004) in relation with more

humid conditions in enhanced greenhouse conditions possibly triggered by the Paraña-Etendeka volcanic province activity (Erba *et al.* 2004; Weissert and Erba 2004). Thus, the Early Bajocian carbon isotope positive excursion has a duration in the same order of magnitude as the Weissert Event and may have related origins.

The Early Bajocian is also an interval of great changes in marine biota. The most important one is a large diversification of ammonoids with a major turnover corresponding to the disappearance of the Hildoceratoidae and the diversification of the Stephanoceratoidae and the Hammatoceratoidae (Pavia 1983; Cresta 1988; Rioult *et al.* 1997). There is a major change in coccolithophores with the diversification of the genus *Watznaueria*, whose species have dominated the nannofossil assemblage for 80 Myr (Erba 2006). Even though this is beyond the scopes of the present work, the new time scale for the Early Bajocian presented here will help the quantification of evolutionary rates and lead to a better understanding of diversification rate in marine biota.

Climatic conditions in the Early Bajocian

During the Early Bajocian, a temperature increase of Tethys Ocean has been observed based on oyster and belemnites $\delta^{18}\text{O}$ (Dera *et al.* 2011). On the other hand, large glendonites, indicators of cool conditions, were deposited in Siberia during the Bajocian although these occurrences lack precise correlation with European biostratigraphic schemes (Price 1999; Rogov and Zakharov 2010). Hence, if both warming at low latitude and cooling at high latitude are synchronous in time, a progressive increase in latitudinal temperature gradient during the beginning of the Early Bajocian had occurred.

The positive $\delta^{13}\text{C}$ excursion has been linked to an increase in primary production in relation with a diversification and increase of coccoliths abundance under eutrophic conditions (Suchéras-Marx *et al.* 2012). Such a process could have resulted from increasing flux of continentally-derived nutrients (Bartolini *et al.* 1996; O'Dogherty *et al.* 2006) or increasing intensity or frequency in monsoon or storm activity (Price *et al.* 1998) as already proposed for the genesis of Hungarian deposits (Raucsik *et al.* 2001; Raucsik and Varga 2008). The increase in the latitudinal temperature gradient have enhanced the atmospheric mass flux from equator to the poles and, with it the rainfall, explaining the increase in weathering and/or in storm activity (Price *et al.* 1998). Thus, the $\delta^{13}\text{C}$ positive excursion could be the consequence of a significant climate change. The origin of this climate change remains hypothetical but might be linked to an increase in volcanic activity that was documented at the Aalenian/Bajocian boundary (Bartolini and Larson 2001). This scenario is close to the one proposed for the Late Valanginian carbon isotope positive excursion (Weissert Event) (described in Gréselle *et al.* 2011 and Barbarin *et al.* 2012, see references therein), a geological event more documented than the Early Bajocian positive CIE. In addition to the climatic, geochemical and biological similarities between the Early Bajocian and the Late Valanginian, these two geological events also have relatively close durations. Further comparison would lead to a better understanding of the climatic and geologic mechanisms driving these carbon cycles perturbations.

Conclusion

For the first time, a duration for the Early Bajocian (Middle Jurassic) has been estimated by means of a cyclostratigraphy study applied to calcium carbonate content of sediments in Chaudon-Norante, France. According to previous works (Pavia 1983; Ferry and Mangold 1995; Thiry-Bastien 2002) and greyscale-based correlations with the Les Dourbes section, no hiatuses or sedimentary condensed interval has been identified, providing confidence in the duration scheme we propose:

- Early Bajocian lasted ~4.082 Myr.
- Discites zone lasted 0.66 Myr, 0.84 Myr for the *Laeviuscula* zone, 1.37 Myr for the Sauzei (synonym of Propinquans as recorded in other areas) and 1.22 Myr for the Humphriesianum zone.
- The Early Bajocian $\delta^{13}\text{C}$ positive excursion has been separated in two intervals, characterized respectively by increasing values and lasting 1.36 Myr, and high steady-state values for 2.72 Myr.

A drastic climate change is observed during the Early Bajocian that was at the origin of the $\delta^{13}\text{C}$ positive excursion through the initiation of more humid climatic conditions and of an oceanic fertilization.

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