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Strong evidence of high-frequency (sub-Milankovitch) orbital forcing by amplitude modulation of Milankovitch signals

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Abstract

High-frequency (sub-Milankovitch) signals have occasionally been recognised in the sedimentary record but their interpretation is yet controversial. The transmission of most information involves modulating the original signal. Transmission in the geological sense is the process of changing the astronomical signal into insolation, climate and, finally, the observed sediment. Modulated signals may contain different frequencies from the original, and the former can sometimes be recognised more easily than the original ones. Thus, sedimentary cycles belonging to the high-frequency band could be interpreted as a possible modulation of the astronomical Milankovitch signals. To check this possibility, a detailed spectral analysis was carried out on a selected marl–limestone and limestone Jurassic succession, in which high-frequency signals in the sub-Milankovitch range, with a persistent peak at 13–14 kyr, were recognised. Relationships between frequencies of the registered peaks suggest that the sedimentation pattern is caused by the amplitude modulation (AM) of the Milankovitch forcing. In AM, the amplitude of a carrier frequency is modulated according to the value of a signal. The spectrum of the resulting AM signal is composed of three frequencies, the frequency of the carrier and two side tones, but the carrier and one side tone may be suppressed without destroying the information. The information remains in the other side tone, usually the one with the highest frequency. This version of AM is called single-sideband carrier-suppressed (SSBCS). For Milankovitch forcing, the implication is that the signals are not transmitted as added-up sinusoidal signals, but both the short eccentricity and the obliquity signals affect the sedimentation pattern by AM of the precession signal, which is the carrier frequency. The sub-Milankovitch peaks registered in the succession studied reveal the SSBCS AM of the original Milankovitch signals, with the SSBCS frequencies being highly significant in the estimated power spectra, after applying conservative tests assuming underlying red noise.

Keywords: sub-Milankovitch cycles; amplitude modulation (AM); single-sideband carrier-suppressed (SSBCS)

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1. Introduction

Significant cycles at sub-Milankovitch periodicities have been reported in the literature, although no conclusive hypothesis explains their origin, particularly for the pre-Pleistocene record.

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Several explanations have been proposed, mainly related to the imprint of astronomical forcing: (a) the tail-end of the precession-band forcing with periodicities of 14–28 kyr; (b) the geographical filtering of the seasonal insolation and the influence of palaeolatitude, these peaks being interpreted as real precession harmonics and combination tones due to the passage of the Sun across equatorial sites twice-yearly during precession cycles [1,2]; (c) responses of the non-linear climatic system to external fluctuations in the insolation rate, and thus interpreted as heterodyne tones of primary orbital frequencies [3–11]; and (d) the tidal influence on sedimentary environments in the range of 10^4–10^5 yr [12], as long-term equilibrium tides, or 'hypertides' [13]. Moreover, some interpretations allude to the influence of allocyclic or autocyclic parameters as climatic control, but without great precision [14,15], or as small-scale, high-frequency eustasy and local tectonic movements [16,17]. Recently, frequency modulation (FM) of a precession signal was also proposed [18].

In order to analyse the possible modulation of Milankovitch orbital forcing and its record in pre-Pleistocene sediments as high-frequency signals, we focus our study on a rhythmic succession from the Lower Kimmeridgian (Upper Jurassic, Betic Cordillera, southern Spain), in which high-frequency cyclicity (sub-Milankovitch cycles) has been registered.

2. Geological background

During the Mesozoic, the South Iberian palaeomargin was influenced by the relative movements between Iberia and Africa. The Betic Cordillera, belonging to the South Iberian palaeomargin, represents the northern part of the Tethyan Alpine Belt at its western end. In the Betic Cordillera, the Prebetic Zone corresponds to the epicontinental platform areas. Inside the Prebetic Zone, two palaeogeographic units were differentiated: the External and the Internal Prebetic (Fig. 1), corresponding to comparatively proximal and distal parts of the epicontinental platform, respectively. The deposition area during the Late Jurassic was located around 30°N [19], with a subtropical climate, which may have been seasonally warm and wet [20,21].

In the Lorente Formation, Lower Kimmeridgian deposits are composed mainly of a marl–limestone rhythmite with a well-developed cyclic stratal pattern. The three selected sections (Puerto Lorente, PL; Segura de la Sierra, SS; and Fuente Alamo, FA; Fig. 1) can be considered as representative of the sedimentary pattern recorded in the epicontinental realm during the Platynota Chron (Early Kimmeridgian, Late Jurassic), showing a characteristic thickness stratal pattern of alternating marl–limestone and limestone beds. Lithological variations in the Platynota succession between sections have been interpreted primarily as a consequence of differential palaeogeography and bottom physiography [21,22]. Thus, thinner calcareous marl–limestone rhythmites registered in the PL section were deposited in comparatively proximal and topographically raised areas, while thicker successions enriched in marls, such as those from SS and FA sections, were accumulated in depressed depocentres.

All the standard sub-Mediterranean ammonite chronozones for the Early Kimmeridgian and the three classical subzones for the Platynota Zone were identified [21] (Fig. 1). This confirms the completeness of the succession analysed and the absence of biostratigraphically recognisable hiatuses, this being particularly important for high-resolution cyclostratigraphic research. Ichnological analysis [23] has revealed that only minor discontinuities occasionally exist, and the record of preserved mixed layers confirms the completeness of the succession even at the intra-biostratigraphic resolution. Taphonomy enables us to rule out reworking phenomena; neither high-density concentrations of fossils (shell lags) nor taphonomic condensation were detected.

Previous sedimentologic research on this rhythmic succession, based on field observations and a detailed mathematical analysis, make possible the interpretation of Milankovitch forcing at different scales [20,21,24], as well as the multifactorial control on the stratal pattern [22]. The influence of climate forcing at the scale of Milankovitch orbital variations was interpreted mainly at the range

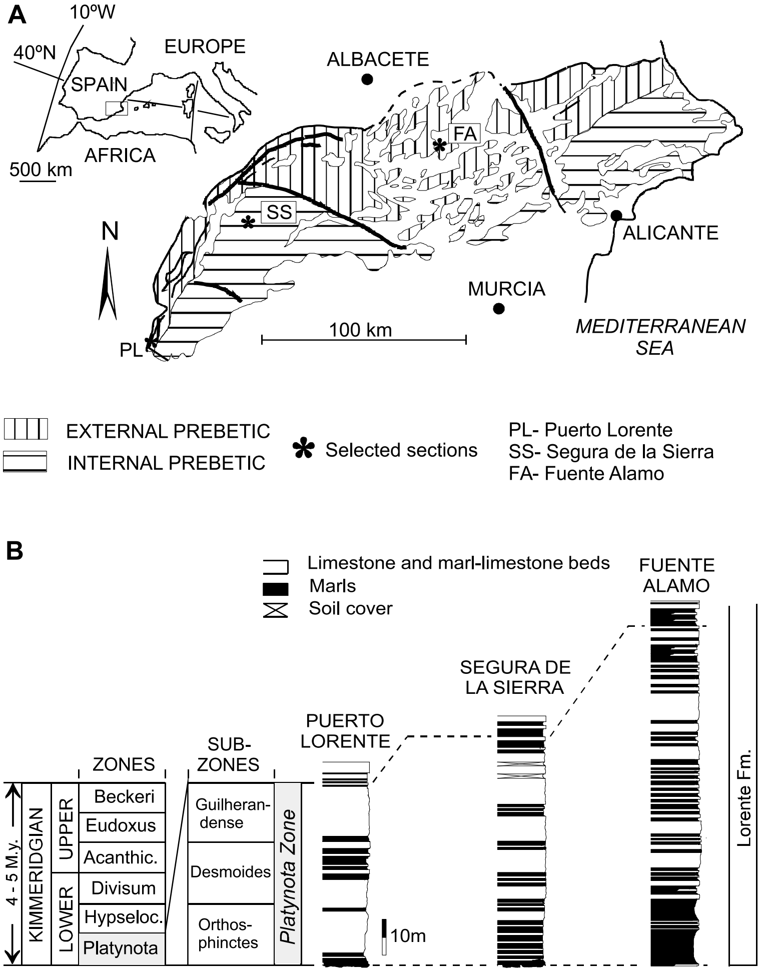


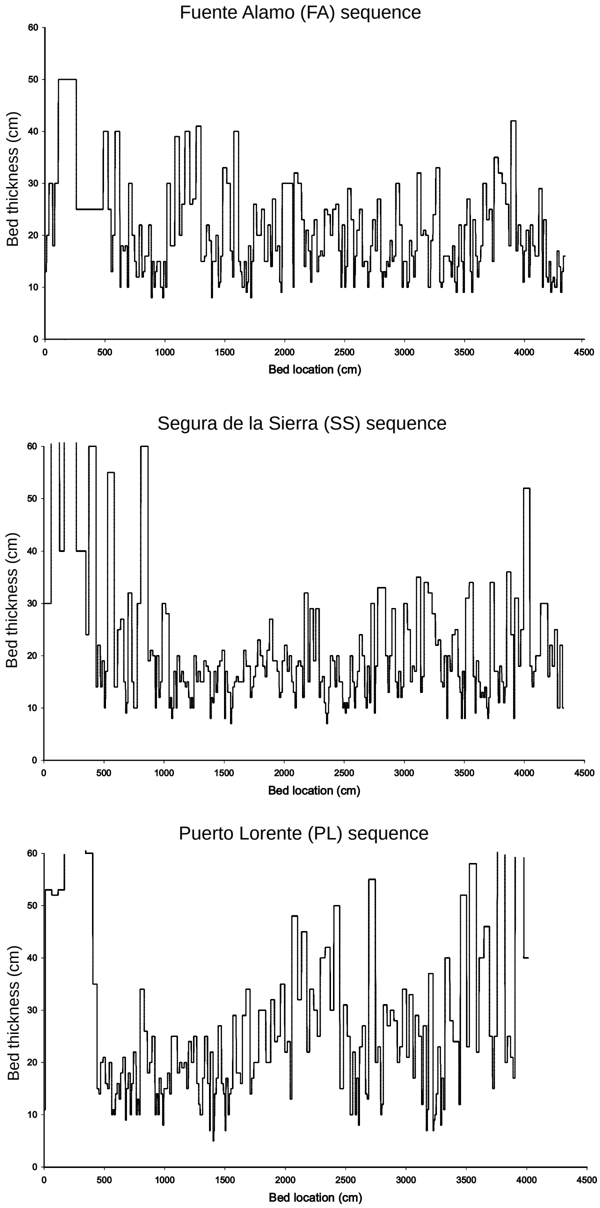
Fig. 1. (A) Location and geological sketch of the three selected sections in the Betic Cordillera, southern Spain. (B) Estimated duration and standard sub-Mediterranean ammonite zones and subzones (only for Platynota Zone) for the Kimmeridgian *Sensu gallico* [30] and lithological columns of the three selected sections.

of the precession and short-range eccentricity cycles. However, together with the Milankovitch cycles traditionally recognised in the sedimentary record, statistically significant sub-Milankovitch peaks (those ranging from 5 to 15 kyr) were registered at the high-frequency band.

3. Methodology

Cyclostratigraphic analysis was conducted on bed-thickness data of the Platynota Zone (Lower Kimmeridgian, Upper Jurassic) succession, by applying an exhaustive mathematical procedure, using the original CYSTRATI programme and a library of computer programmes [25,26]. Previous studies on the Platynota rhythmic succession were processed at a control interval of 17 and 15 cm (between mode and mean of thickness data). This approach renders general information on the cyclicity in the power spectrum, from low to high frequencies [20,21,24], being especially informative for the analysis of Milankovitch cycles, but less appropriate when the analysis is focussed on high-frequency cycles.

To evaluate the significance of those peaks reg-



Fuente Alamo (FA) sequence

Segura de la Sierra (SS) sequence

Puerto Lorente (PL) sequence

Fig. 2. Zero-mean sequences with constant sampling interval for the three selected thickness sections.

istered in the high-frequency band, each sequence was sampled at a constant rate of 1 cm, following the methodology of Schwarzacher [27], and implemented using the computer programme CYSTRATI [25]. The total number of samples at a constant sampling ratio is 4340, 4327 and 4013 for the three sections FA, SS and PL, respectively.

The following step involves the subtraction of the experimental mean in order to have zero-mean sequences (Fig. 2). These zero-mean sequences with a constant sampling interval are then appropriate for applying different spectral estimators, as suggested by Berger et al. [8], to take advantage of each spectral estimator and minimise their drawbacks. As often occurs in statistics, there is no estimator consistently superior to the others, particularly when using real data (case study vs. simulated data). Thus, it is difficult to assess the validity of the hypothesis assumed in formulating each estimator, especially when working with relatively short series. The spectral estimators selected were: (a) unsmoothed periodogram, (b) Blackman–Tuckey estimator with Parzen window and $M = 500$ terms, and (c) maximum entropy estimator with $M = 1000$, 500 and 350 terms. The frequency range of interest was between 0.002 and 0.02, corresponding to periods of 500–50 cm. Frequencies lower than 0.002 cycles per sampling interval (cpi) are affected by the underlying red noise and trends, while those higher than 0.02 cpi fall outside the sub-Milankovitch band.

The periodicity of the peaks registered was also calibrated. The estimated duration for the Kimmeridgian *Sensu gallico* varies between 2.6 and 6 Myr, with 4 and 5 Myr being the most frequent values proposed [28,29]. Thus, given that the traditional Kimmeridgian *Sensu gallico* is divided into six biochronozones [30], a duration of 667 and 833 kyr (mean of 750 kyr) for the Platynota Chron was assumed.

4. Results

4.1. Statistical analysis

Basic statistics for three thickness sequences show the following (Table 1):

1. Total thickness of the Platynota succession is clearly different between sections (53 m in PL, 62 m in SS, and 91 m in FA), while the thickness succession without marls shows similar values, especially between SS and FA sections (both around 43 m thick).
2. Number of beds (231 beds), mean (19 cm), mode (15 cm) and average bed thickness (17 cm) are similar between SS and FA sections, and clearly different from PL section (175 beds, 23 cm, 10 cm, and 20 cm, respectively).

According to the statistical bed-thickness data, SS and FA appear to be very similar, and quite different from the PL section. As commented above, the differences recorded in facies and stratal patterns between sections can be related to variations in palaeogeography (distance from shore), and bottom physiography.

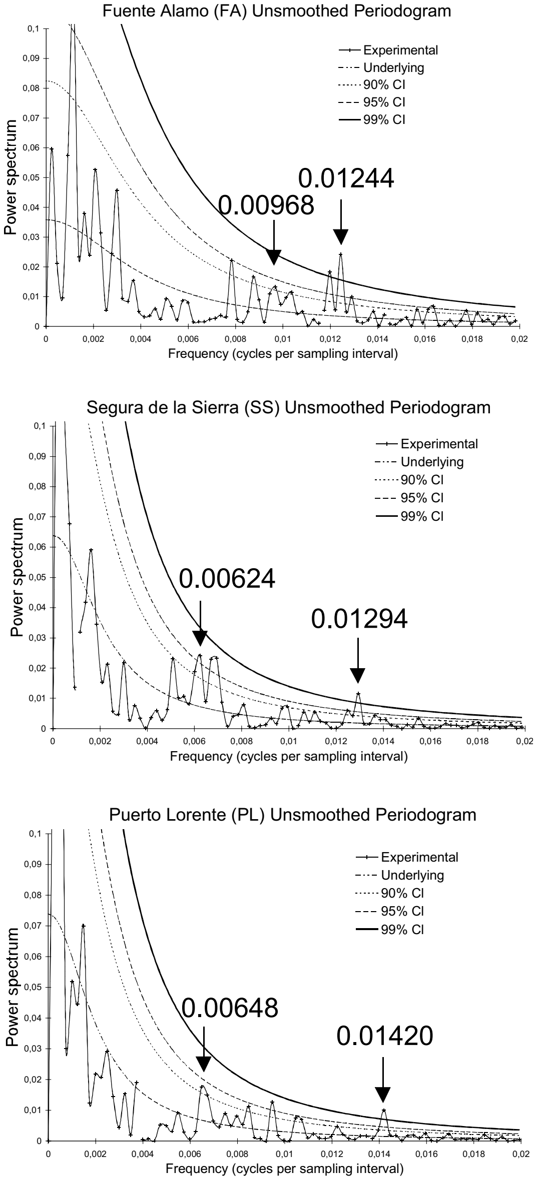
4.2. Spectral treatment

The studied succession is not very long (around 750 kyr for the Platynota Chron), increasing the uncertainty of the spectral estimates, but the data are less likely to be affected by a strong trend. No trend removal was performed, so that the correlation structure of the original data remains unaltered.

The spectral analyses performed (unsmoothed periodogram (UP), Blackman–Tuckey (BT), and maximum entropy (ME)) on the three selected thickness series show some distinct features. The unsmoothed periodogram gives good resolution of the peaks (Fig. 3), but due to the high variance of the estimator, other approaches were used to identify the most significant peaks. The conservative estimator, Blackman–Tuckey with Tuckey window, and $M = 500$ terms for the correlogram which is smaller than $N/8$, with N being the series' number of data, shows two maxima in each of the power spectra (Fig. 4). Finally, to corroborate the data gathered, the maximum entropy estimator has been applied using $M = 1000$, 500 and 350 terms. This allowed us to check the resistance of the peaks, to determine which peaks disappear, and to shift their position or leave them at the

Table 1
Basic statistics of the three studied sequences

Section	Total thickness (m)	Thickness without marls (m)	Number of beds	Mean (cm)	Mode (cm)	Average (cm)
Fuente Alamo	91	43	231	19	15	17
Segura de la Sierra	62	43	231	19	15	17
Puerto Lorente	53	40	175	23	10	20


Fuente Alamo (FA) Unsmoothed Periodogram

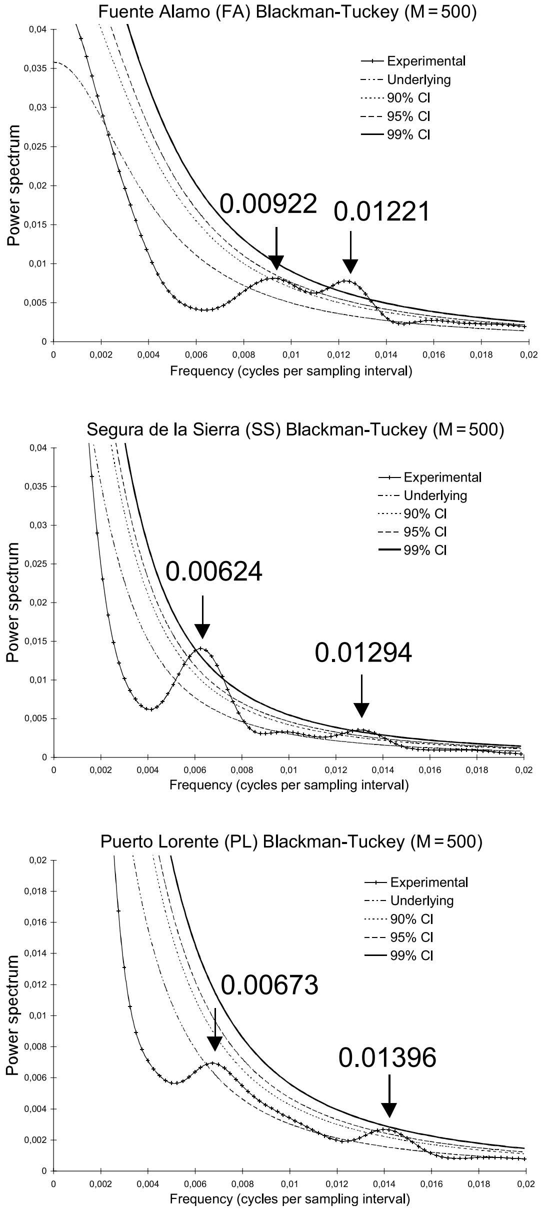
Segura de la Sierra (SS) Unsmoothed Periodogram

Puerto Lorente (PL) Unsmoothed Periodogram

Fig. 3. Unsmoothed periodograms for the three selected thickness sections. Arrows over the most significant peaks, showing the registered frequency values.

same frequency location (Fig. 5). The most statistically significant peaks have been calibrated (Table 2):

1. In the FA section, the most relevant peak or maximum has a frequency of 0.01244 (80.4 cm; 14.1 kyr) in UP and ME, and of 0.01221 (81.9 cm; 14.3 kyr) in BT. A second group of maxima is located in the range of frequencies around 0.00968 (103.3 cm; 18.1 kyr) in UP, and 0.00922 (108.5 cm; 19.0 kyr) in BT.
2. In the SS section, the most relevant maximum has a frequency of 0.01294 (77.3 cm; 13.5 kyr) in UP and BT, and of 0.01320 (75.8 cm; 13.3


Fuente Alamo (FA) Blackman-Tuckey (M = 500)

Segura de la Sierra (SS) Blackman-Tuckey (M = 500)

Puerto Lorente (PL) Blackman-Tuckey (M = 500)

Fig. 4. Blackman–Tuckey with Tuckey window and $M = 500$ for the three selected thickness sections. Arrows over the most significant maxima, showing the registered frequency values.

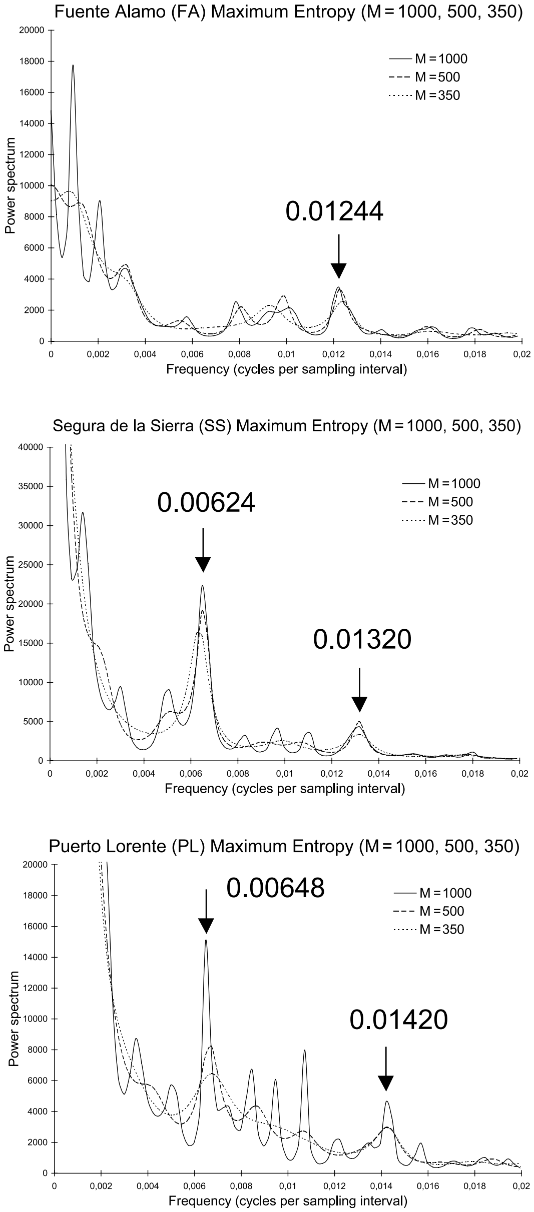


Fig. 5. Maximum entropy estimator with $M = 1000$, 500 and 350, for the three selected thickness sections. Arrows over the most significant peaks, showing the registered frequency values.

kyr) in ME. Other relevant maxima are registered at a frequency around 0.00624 (160.3 cm; 28.05 kyr) in the three spectral analyses performed.

3. In the PL section, the most significant peak corresponds to a frequency of 0.01420 (70.4 cm; 13.0 kyr) in UP and ME, and of 0.01396 (71.7 cm; 13.3 kyr) in BT. A second relevant peak is registered at 0.00648 (154.3 cm; 28.5 kyr) in UP and ME, and at 0.00673 (148.6 cm; 27.5 kyr) in BT.

The integrated analysis of the data, by applying the different spectral estimators in the three selected sections (Table 2), led us to conclude that: (a) the most significant peak registered in the three sections, in the entire power spectrum (even in the smoothest ones), and with an amplitude consistently surpassing the 99% confidence level, had a periodicity of between 13 and 14 kyr; (b) a resistant peak, statistically significant throughout the power spectrum performed in the SS and PL sections, was registered at a periodicity between 27.5 and 28.5 kyr; and (c) a 18–19 kyr peak was statistically significant only in the FA section.

4.3. AM

The difficulty in characterising high-frequency cycles, especially in the pre-Pleistocene record, makes a more detailed analysis necessary before confirming its record and proposing any interpretation. In contrast to the idea of Hinnov and Park [18] of FM of a hypothetical constant carrier by Milankovitch signals, and its restriction when mixed precession–obliquity signals occur, we analyse the possible modulation of the signals registered in the succession studied, but through variations in the amplitude of the original signal components.

The phenomenon of AM in wireless transmission consists of signal modulation in which the amplitude of a 'carrier' wave, with frequency f_c, is changed due to mixing in a non-linear way with the modulating 'signal', with frequency f_s, where in general $f_c > f_s$. If the signal is also sinusoidal, the spectrum of the AM signal is composed of three frequencies, the frequency of the carrier and two side tones equal to the sum and the difference of carrier and signal frequencies: $f_s - f_c$, f_c and $f_s + f_c$, i.e. a central frequency and two symmetrical side lobes. Often the carrier and one side tone may be suppressed without destroying the information because this information is present in the remaining side tone (usually the one with the highest frequency, which is the addition of signal and carrier frequencies). This version of AM is called single-sideband carrier-suppressed (SSBCS) AM, and provides power and bandwidth economy. The processes of modulation and transmission in electrical engineering have nothing to do with cyclostratigraphy – only in the final result does the analogy apply.

According to the above, we calculate the spectrum of the theoretical frequencies for SSBCS AM of the most usual Milankovitch orbital signals. The most important wavelengths of the Milankovitch cycles are 100 kyr for the short-range eccentricity cycle, 41 kyr for the obliquity cycle, and 21 kyr for the precession cycle, and their frequencies are:

$$f_e = \frac{1}{100} = 0.01,\ f_o = \frac{1}{41} = 0.02439,$$

$$f_p = \frac{1}{21} = 0.04761$$

for short-range eccentricity (e), obliquity (o) and precession (p) cycles, respectively. The theoretical amplitude-modulated waves for the high-frequency side lobe (f_s+f_c), would be:

$$f_e + f_o = 0.03439 \quad \text{and} \quad \frac{1}{f_e + f_o} = 29.1 \text{ kyr}$$

$$f_e + f_p = 0.05761 \quad \text{and} \quad \frac{1}{f_e + f_p} = 17.35 \text{ kyr}$$

$$f_o + f_p = 0.0720 \quad \text{and} \quad \frac{1}{f_o + f_p} = 13.88 \text{ kyr}$$

The frequencies (0.03439, 0.05761, and 0.0720), and thus periods (29.1, 17.35, and 13.88 kyr, respectively), of the theoretical amplitude-modulated waves derived from the SSBCS AM of the most usual orbital signals show similar values to those of the most significant peaks (27.5–28.5, 18–19, and 13–14 kyr), registered in the thickness succession studied here.

5. Interpretation

As was commented previously, peaks with similar periodicities to statistically significant ones located in the high-frequency band of the power spectra performed (at periodicities of 27.5–28.5, 18–19, and 13–14 kyr, the latter being especially relevant), have been reported in the literature, although their interpretation has not been conclusive.

After analyzing the data, we interpret these high-frequency cycles, following Hinnov and Park [18] on the modulation of orbital cycles. The similarity between the theoretical AM frequencies of the most usual orbital Milankovitch signals, and the frequencies of the most significant peaks registered in the studied thickness succession, lead us to consider this possibility. The peaks registered could be physically explained as AM transmission, where eccentricity and obliquity were the signal frequencies, while either obliquity or precession were the carrier ones. Precession was the carrier for eccentricity and obliquity, and obliquity could have been also the carrier for

Table 2
Statistically significant peaks in the three selected sequences, for each spectral estimator applied

Sequence	Unsmoothed periodogram			Blackman–Tuckey (M = 500)			Maximal entropy (M = 1000, 500, 350)		
	Frequency	Period (cm)	Period (kyr)	Frequency	Period (cm)	Period (kyr)	Frequency	Period (cm)	Period (kyr)
Fuente Alamo	0.00968	103.3	18.1	0.00922	108.5	19.0			
	0.01244	80.4	14.1	0.01221	81.9	14.3	0.01244	80.4	14.1
Segura de la Sierra	0.00624	160.3	28.05	0.00624	160.3	28.05	0.00624	160.3	28.1
	0.01294	77.3	13.5	0.01294	77.3	13.5	0.01320	75.8	13.3
Puerto Lorente	0.00648	154.3	28.5	0.00673	148.6	27.5	0.00648	154.3	28.5
	0.01420	70.4	13.0	0.01396	71.7	13.3	0.01420	70.4	13.0

eccentricity. In this AM transmission, only the f_s+f_c frequency (s, signal, c, carrier) was recorded as the SSBCS version. This is the high-frequency component, which, in turn, is the one with the highest chance of being detected in these sequences because of the range of thicknesses observed.

Even though the calculated frequency values, and thus periods (27.5–28.5, 18–19 k, and 13–14 kyr) do not coincide exactly with the theoretical data (29.1, 17.35, and 13.88 kyr) from amplitude-modulated Milankovitch signals, the similarity is nevertheless strong. In this sense, it is necessary to take into account the quasi-periodic nature of the carriers and minor deviations due to such factors as the shortening of the main astronomical periods (Milankovitch cycles) during the pre-Quaternary [31,32], the temporal calibration of the time interval studied (Platynota Chron), and the influence of local factors on the sedimentary record.

The proposed interpretation opens a new approach to cyclostratigraphic analysis, through the recognition of amplitude-modulated frequencies of the original orbital forcing cycles, independent of the linear record of these primary cycles. The linear response of a sedimentary basin to the Milankovitch climatic forcing may not have been well registered, and the orbital imprint in the stratigraphic pattern may be difficult to recognise. In this case, AM analysis constitutes a new tool to demonstrate orbital forcing on the sedimentary environment, by reflecting non-linear signals of the orbital insolation forcing. In this sense, this paper will help to provide a better understanding of sedimentation patterns and cycle formation in stratigraphy, particularly in pre-Pleistocene sediments, where the linear evidence of orbital climatic forcing can be comparatively poor. This interpretation reinforces the analogy between analysing a stratigraphic system and wireless transmission, as pointed out by Schwarzacher [27].

6. Conclusions

Spectral analyses of a rhythmic marl–limestone and limestone thickness succession from the Platynota Chron (Early Kimmeridgian, Late Jurassic), show statistically significant cycles at the high-frequency band, at periodicities of 27.5–28.5, 18–19, and 13–14 kyr, the latter being especially relevant. These frequencies agree with combination tones of the short-eccentricity, obliquity and precession Milankovitch cycles, and, particularly, the combination tones of obliquity and precession have been detected. Thus, an external controlling forcing for the sedimentary pattern at the range of sub-Milankovitch periodicities could be inferred.

The analysis of these frequencies allows an interpretation of the origin of these registered high-frequency cycles as reflecting the AM of a carrier signal. Short-eccentricity and obliquity signals affected the sedimentation pattern by AM of the precession signal, which was the carrier frequency. Only the high side lobe (sum of carrier and signal frequencies) was detected, as happens in SSBCS AM. The theoretical frequencies of the SSBCS AM of the most important Milankovitch signals (short-range eccentricity, obliquity, and precession), at 29.1, 17.35, and 13.88 kyr, are very similar to those of the most significant cycles registered in our case study, strengthening the possibility of a relationship. Of especial relevance in the case study is the high-frequency cycle (sub-Milankovitch) at 13–14 kyr that corresponds to AM of the original Milankovitch cyclicities, where the obliquity is the 'signal' frequency (f_s) and the precession the 'carrier' one (f_c).

Our results show an important new way for interpreting high-frequency cycles, and for evaluating the relationship between orbital forcing and the sedimentary response, especially in pre-Pleistocene sediments.

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