

Cross-spectral analysis of two late Berriasian rhythmic limestone-marl successions in SE Spain and SE France favours orbital control

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Abstract

The cyclicities in rhythmic limestone-marl alternations of two late Berriasian (hemi-) pelagic successions are correlated. The first succession has a thickness of 42.8 m, and is situated in the northernmost Subbetic realm near Caravaca (SE Spain). It comprises the *Calpionellopsis simplex* subzone (D1). The second succession, with a thickness of 40.5 m, is located about 950 km to the northeast in the Fosse vocontienne near La Faurie (SE France). It starts 2 to 5 m above the base of subzone D1 and ends near its top.

The carbonate contents of 740 samples of both successions were used to establish a visual correlation. A more refined correlation was established by cross-spectral analysis of the carbonate/clay ratios. Although the two sedimentation realms differ geographically and geologically, the power spectra show a remarkable resemblance at the eccentricity and precession frequencies, which is numerically confirmed by significant coherence at the 80% confidence level. The cyclicities of both, the Caravaca and the La Faurie succession, are, at least in part, orbitally controlled.

Introduction

In this paper we correlate the cyclicities in carbonate content of two late Berriasian calcilutite-marl successions. The first is situated near Caravaca in SE Spain, the second is a comparable succession, located about 950 km to the northeast, near La Faurie in SE France (Fig. 1).

The Caravaca succession studied by Ten Kate & Sprenger (1989) and Sprenger & Ten Kate (1993) starts at the base of the *Calpionellopsis simplex* subzone (D1) and ends at the top of the *Calpionellopsis oblonga* subzone (D2). The La Faurie succession covers roughly 90% of calpionellid subzone D1. Micropaleontologically, both successions have the calpionellid subzone D1 in common. Therefore, in the following a detailed correlation of subzone D1 is proposed. Both successions consist of an alterna-

tion of calcilutites, marly calcilutites and marls. The thickness of subzone D1 in both successions is about the same: 40 m, and both were logged and sampled in detail. The correlation of the rhythmicity is based on the calcium carbonate content of 740 samples of the La Faurie succession and 712 samples of the Caravaca succession. The first correlation is further refined by cross-spectral analysis.

An overview of the Milankovitch theory and the search for Pleistocene and pre-Pleistocene rhythmicities, that are interpreted as orbitally controlled, is given in De Boer (1991), Berger et al. (1984) and Fischer & Bottjer (1991).

Regional setting and field geology

The Caravaca succession is part of the Miravetes

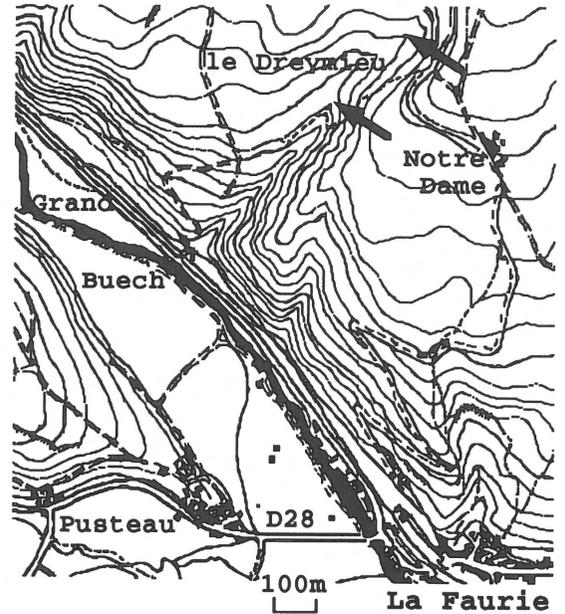
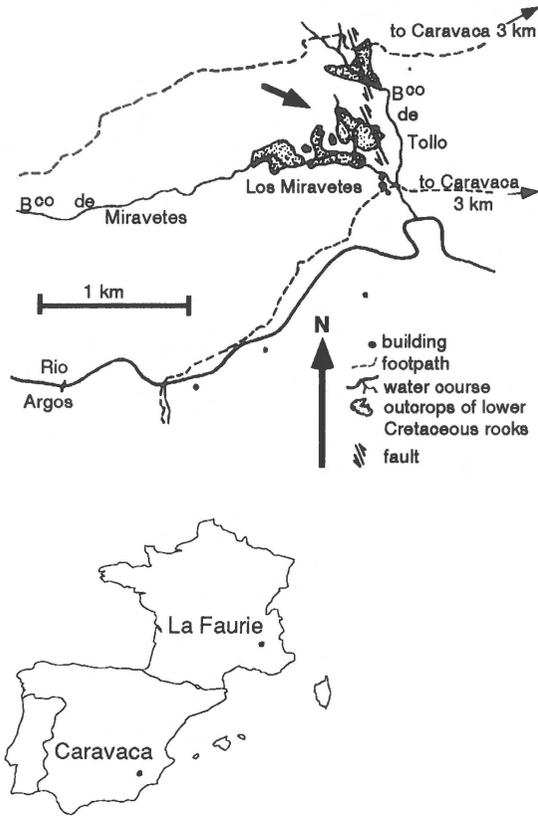


Fig. 1. Location of the sampled late Berriasian successions at Caravaca (SE Spain) and La Faurie (SE France).

Formation (Van Veen 1969, Hoedemaeker 1982). It is located in the Subbetic realm of the Betic Cordilleras in the Province of Murcia, SE Spain. It crops out in the Barranco de Miravetes, approximately 3 km west of Caravaca (Fig. 1). The surveyed succession has a total thickness of 42.8 m, and comprises calpionellid subzone D1 of the upper Berriasian (T. Geel, pers. comm.).

The La Faurie succession in southeast France is located in the northern part of the Vocontian Trough and crops out in the Dreymlau valley, 1 km NNW of La Faurie (Fig. 1) (Le Hégarat 1971, 1980). The surveyed and sampled part of the La Faurie succession has a thickness of 40.5 m. The base of subzone D1, characterized by the first appearance datum of *Calpionellopsis simplex*, was not encountered in the sampled interval. On the other hand, a sample taken at 1.8 m stratigraphically below the base of this interval is assigned to subzone D1 and another sample at 5 m below the base to zone C (T. Geel, pers. comm.). So, the base of D1 probably ap-

pears in the succession 1.8 to 5 m below the base of the interval surveyed. The boundary between subzone D1 and D2 corresponds to the level above which *Calpionellopsis oblonga* predominates over *Calpionellopsis simplex* and is located at the top of the sampled interval or somewhat higher, at most a metre higher (T. Geel, pers. comm.).

The Caravaca succession consists of a monotonous rhythmic alternation of light grey to yellow-brown calcilutites, olive to dark grey marly calcilutites, and soft, dark to bluish grey marls (Fig. 2a). A minor amount of fine silt is present. The yellow-brown calcilutites, rich in coccoliths, are indurated, show a conchoidal fracture and resist weathering. The grey marly calcilutites are less indurated, and have a nodular appearance caused by weathering. The soft and dark marls weather into flaky fragments.

Tectonic complications, hiatuses and mass-flow phenomena, such as turbidites or slumps, are absent. The degree of bioturbation in the succession is

hard to assess: only locally *Cancellophycus* was observed. On the other hand, the absence of distinct laminations in all lithotypes indicates bioturbation. The layer boundaries are often gradational on a 1 to 2 cm scale. Micropaleontologic and lithologic evidence points to a quiet and relatively deep open marine environment on the lower shelf (200 to 500 m) (Van Veen 1969, Hoedemaeker 1982).

The La Faurie succession shows a similar limestone-marl alternation, although in the upper half various stretches occur with a high silt content (Fig. 2b). In addition, the distinction in couplets and triplets of the La Faurie succession is more pronounced than in Caravaca. This is ascribed to higher differences in carbonate content between neighbouring layers and to more distinct layer boundaries. *Cancellophycus* is frequently observed, especially in the calcilutite or calcisiltite layers. Occasionally, some worm tracks or burrows are found. Small-scale stylolites with a depth up to 4 mm occur occasionally. Most likely, the sediments were deposited in a quiet, open marine environment, influenced by terrigenous influx (Le Hégarat 1971, 1980).

In the field the bedding rhythmicity is characterized by the regular appearance of indurated layers of calcilutite, which are separated by one or more layers of marl. We define a multiplet as 'a restricted number of layers, that starts with an indurated limestone layer and ends at the next higher indurated limestone layer'. The number of layers within a multiplet varies between one and seven in Caravaca, and between one and five in La Faurie. The average thickness of the 198 layers in the Caravaca succession is 22 cm. We distinguished 67 multiplets with average and modal thicknesses of 64 cm and 36 cm respectively. In the La Faurie succession the average thickness of 233 layers is 17 cm, and 99 multiplets were distinguished that have an average thickness of 41 cm and a modal thickness of 36 cm (Figs 3a, b).

Methods

Sampling procedure

In Caravaca a total of 198 layers were distinguished

and individually sampled. A total of 740 samples were collected. Each sample has a vertical extent of 2.5 cm and on average the sampling midpoints are 6 cm apart. In La Faurie 712 samples were collected from 233 layers. The samples are on average 5.5 cm apart and have a vertical extent of 2.5 cm.

Determination of carbonate and insoluble residue

The carbonate percentage of each sample of the Caravaca succession was determined with a carbonate bomb using 1 g of powdered sample and 5 ml of concentrated hydrochloric acid. The insoluble residue was separately determined by dissolution of 1 g of powdered sediment in dilute hydrochloric acid. The calculated error is $\pm 1\%$ (for methods see Ten Kate & Sprenger 1989).

The calcium carbonate content of the samples of the La Faurie succession was determined coulometrically and calibrated with a standard solution of sodium carbonate. Reproducibility is within 2.5% of the measured values. The insoluble residue content was simply calculated here as $(100 - \text{CaCO}_3)\%$.

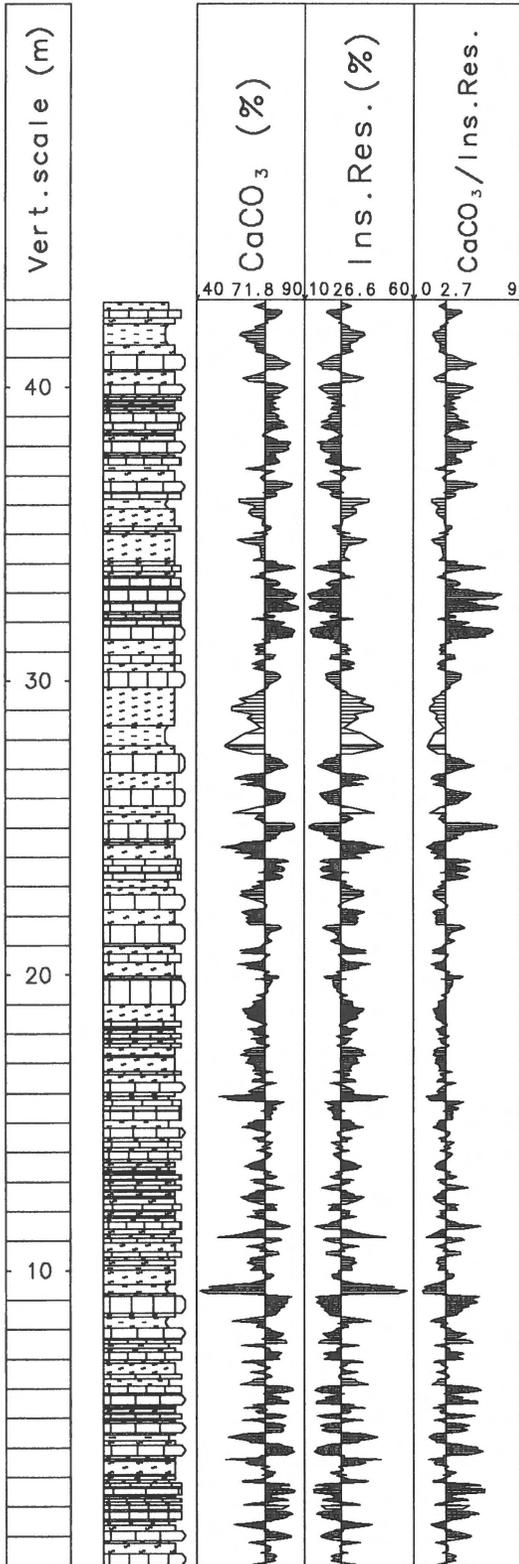
In Figs 2a and b, the carbonate and insoluble residue values of all samples are shown by horizontal lines. The ratio between carbonate and insoluble residue content is used as a proxy variable, that reflects the combined effect of carbonate productivity and terrigenous dilution. The preference to use the ratio of calcium carbonate and insoluble residue instead of the calcium carbonate data, and the question of productivity, dilution and dissolution cycles, are considered in Ten Kate & Sprenger (1989).

Spectral analysis

All univariate spectra were calculated with the Blackman-Tukey method (Blackman & Tukey 1958, Jenkins & Watts 1968). In the time domain, two time series are compared by the cross-covariance function; in the frequency domain, the Fourier-transform of that function is used to create the cross-amplitude spectrum.

The mutual relationship between the powers of two univariate spectra, is brought out by a squared

Caravaca succession



LEGEND



Calcilutite



Calcisiltite



Marly limestone or calcareous marl



Silty marl



Soft marl



Clay

Fossils

ammonites

radiolaria

Pygope

Structures

stylolites

finely laminated

fining upwards

Cancellophycus

bioturbation

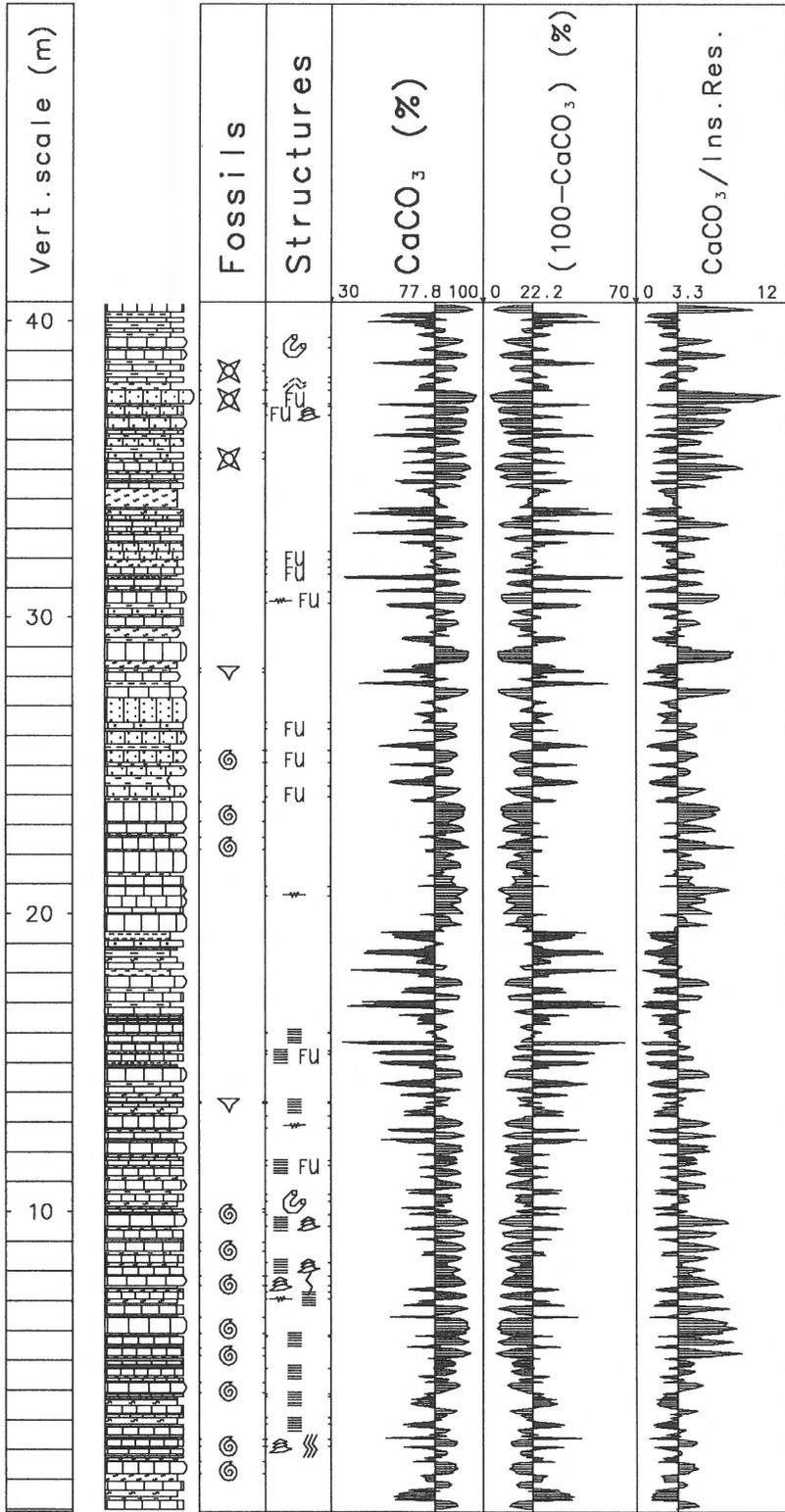
bioturbation, strong

burrows

trails

Fig. 2. Overview of the lithologies and carbonate contents of (a) the Caravaca and (b) the La Faurie successions. The Caravaca succession comprises the entire late Berriasian calpionellid subzone D1, whereas 90% of subzone D1 was surveyed in La Faurie (T. Geel, pers. comm.). (c) Legend for Figs 2a, b.

La Faurie succession



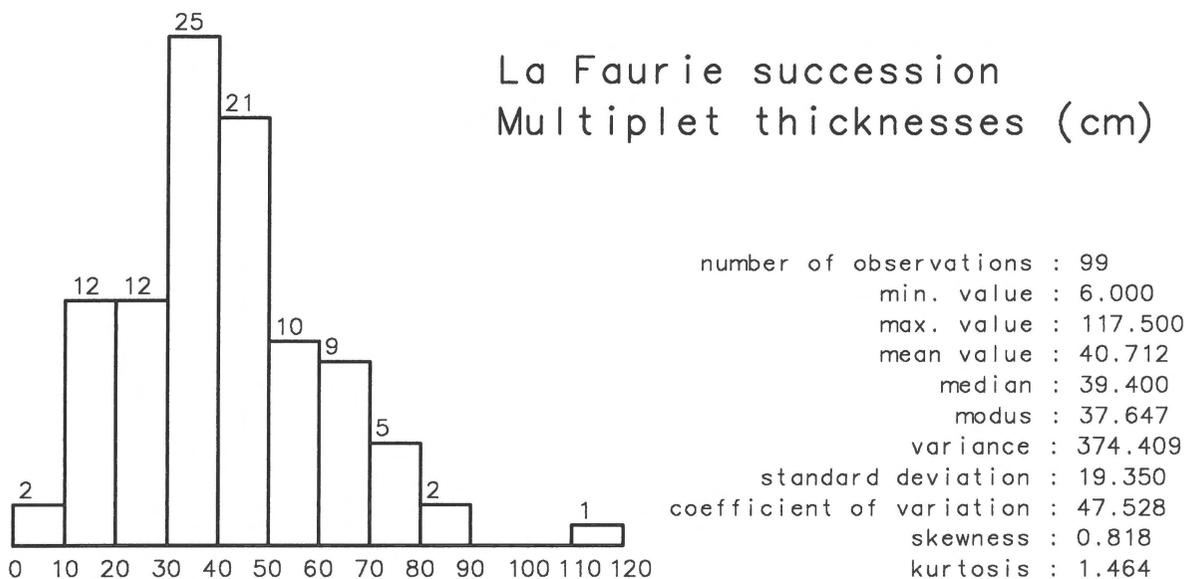
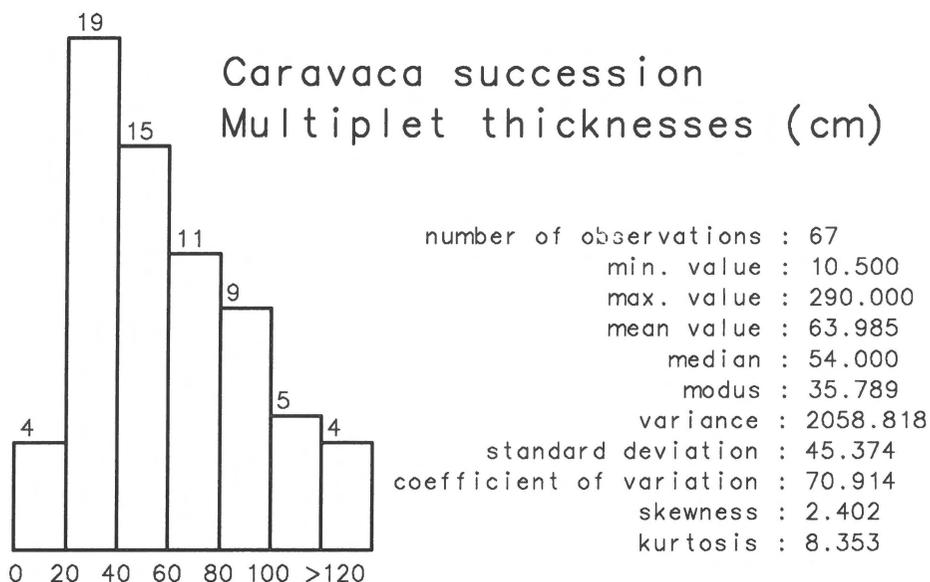


Fig. 3. Histograms of thicknesses (cm) of multiplets in (a) the Caravaca and (b) the La Faurie succession.

coherency spectrum. The value of the squared coherency at a certain frequency varies between 0, i.e. no relationship, and 1, i.e. a direct or inverse, perfect correlation. The concepts 'coherence' and 'squared coherency' are synonymous.

At each frequency of a gain spectrum is indicated how much power is gained when the power of the cross spectrum, that of Caravaca and La Faurie, is

divided by the corresponding power of the univariate spectrum of the first series, that of Caravaca. The spectrum indicates what is gained when a second time series (La Faurie) is taken into account. When the gain is equal to 1, both series contribute an equal amount of power to the cross spectrum. The estimate of the gain at a particular frequency is

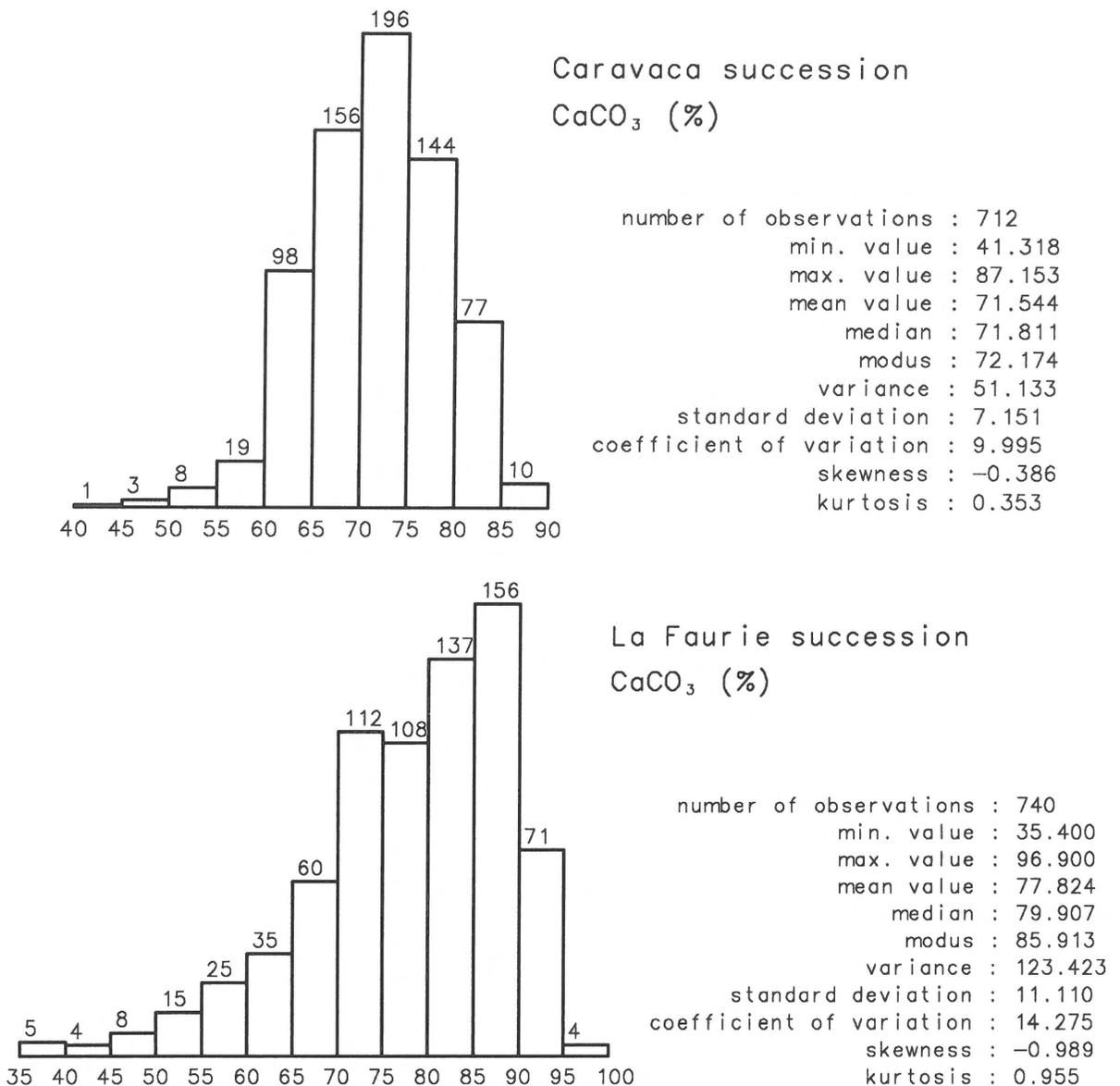


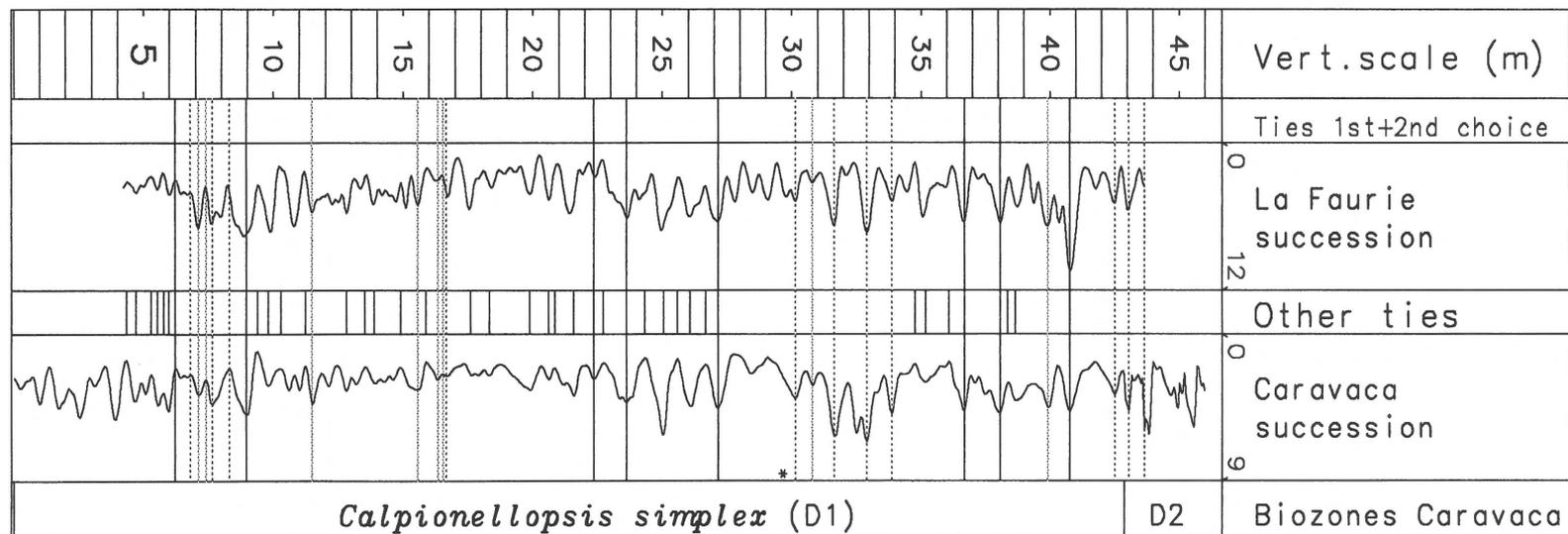
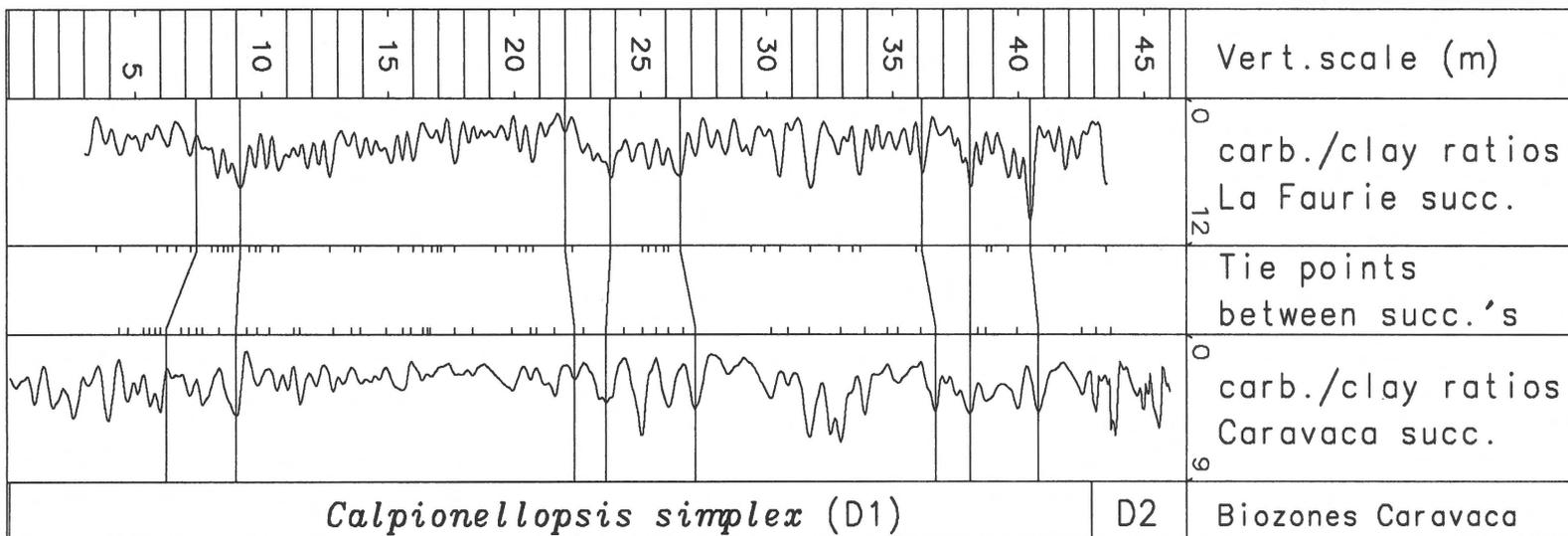
Fig. 4. Histograms of the carbonate content (%) of samples of (a) the Caravaca succession and (b) the La Faurie succession.

only reliable when the corresponding coherence is significant at a certain level of confidence.

Stationarity of the input series is required by all spectral methods (Jenkins & Watts 1968). This signifies, that for example neither mean nor variance may change along the succession. This is called 'stationarity in the wide sense'.

Applied algorithms

Summary statistics (Figs 3, 4) and spectra (Figs 7-10) are calculated with the aid of the stratigraphypaleontology program library SPLIB, designed and supported by the Division of Sedimentary Geology at the Vrije Universiteit. The programs of SPLIB run on an IBM ES/9000 mainframe under operating system VM/XA CMS. The graphical software system (STRATCOLUMN), incorporated in SPLIB,



was used to construct the drawings of both successions (Figs 2, 5, 6) (Sprenger & Ten Kate 1990). Potential users may access SPLIB, provided they have connection to an international TCP/IP network and hold a computer budget at the Academic Computer Centre Amsterdam (SARA).

Results and discussion

Correlation

At first sight the rhythmicity of the carbonate content in both successions seems hardly comparable (Figs 2a, b). The distribution of carbonate content is shown in the histograms of Figs 4a, b. From both histograms it is clear that the mean carbonate content at La Faurie (77.8%) is higher than that of Caravaca (71.5%). Also the range of carbonate content is greater in La Faurie (35 to 97%) than in Caravaca (41 to 88%). The mean thickness of 99 multiplsets in La Faurie, 41 cm, is considerably less than the mean of 67 multiplsets of Caravaca, 64 cm (Fig. 3). The number of multiplsets in La Faurie is higher. The modal thickness of multiplsets at both localities is equal, 36 cm. The total thickness of both sections is also comparable: 42.9 m in Caravaca and 40.5 m in La Faurie.

To alleviate the differences mentioned and to promote a visual correlation, both series were smoothed in the following way. First, an equally spaced data set was created by fitting cubic spline functions through the data points. These functions were sampled at 6 cm intervals, which is equal to the mean sample distance. The interpolated data series were smoothed by a three-point weighted moving average with weights (1/4, 1/2, 1/4) and (1/2, 1/2) for the end members. The smoothing was repeated four times and is especially effective on a vertical

scale up to 50 cm, roughly equal to the average multiplset thickness (Ten Kate & Sprenger 1992). Figure 5 shows the smoothed curves of both successions.

The stratigraphic correlation of both successions is based on the datum planes defining calpionellid subzone D1, as described in the paragraph on field geology. At first, a choice of eight tie lines was carefully made by visual comparison of the plotted data. In Fig. 5 these are shown by continuous lines. Additional tie lines were added by twice repeating the same procedure. In this way a total of 59 tie lines were established between both successions (Fig. 5). A strong change in inclination of tie lines was avoided during their selection.

Ten Kate & Sprenger (1989) and Sprenger & Ten Kate (1993) argued that in the Caravaca succession thickness is proportional to time. Joining the 59 corresponding tie points of both successions results in a pattern of tie lines, which show opposing inclinations. To remedy this, the distances between successive tie points in the La Faurie succession are differentially stretched or shrunk by linear interpolation until all tie lines are horizontal (Fig. 6).

After relocation of the original data points of the La Faurie succession, again cubic spline functions are fitted to generate an equally spaced series at intervals of 6 cm. Again as described earlier, the series were smoothed by applying the moving average procedure four times to ease the visual correlation. The results of this correlation are shown in Fig. 6. The tie lines of first choice are solid, those of second choice are stippled, and those of third choice are again solid, but restricted to the column 'other ties'. In the interval, marked by a star, the number of samples is very low and the cubic spline function results in two local minima instead of the usual wiggly line. The weakness of this interval was constantly avoided during the establishment of the correlation schemes.

←

Fig. 5. Plots of carbonate/insoluble residue ratios of La Faurie (left) and Caravaca (right) successions. Both series were smoothed four times by a weighted three-point moving average. In the middle column 59 tie points of the visual correlation between the successions are indicated. Eight lines, drawn in full, connect tie points of the first choice.

Fig. 6. Final results of visual correlation between carbonate/insoluble residue ratios of the La Faurie and Caravaca successions. Both curves were smoothed four times by a three-point weighted moving average. The tie lines of first and second choice, solid and stippled respectively, are drawn horizontally through all columns. The third choice are the solid lines restricted to the column 'other ties'. (See text for further explanation).

Database

As a rule spectral methods require equally spaced data sets. These data were generated by fitting cubic splines through the original data points of the Caravaca succession and through the relocated data points of the La Faurie succession. The interpolation interval was fixed at 6 cm, which is approximately equal to the mean sample distance. During interpolation, respectively 715 and 658 points were calculated in the Caravaca and La Faurie successions.

The series were tested on stationarity in the wide sense, and a slight non-linear trend was found. Most likely, this trend is caused by the eccentricity cycle of 413 ka, with a cycle length of 30 m (Sprenger & Ten Kate, 1993). In view of the shortness of the succession (40.5 m) this eccentricity cycle cannot be resolved and starts to function as a trend. To remove the non-linear trend and to meet the stationarity criterion, a weighted three-point moving average was repeated 2500 times and was subtracted from the original series (Ten Kate & Sprenger 1992).

Orbital periodicities in the lower Cretaceous

Shortening of the Earth-Moon distance and of the length of the day back into time induces a shortening of the obliquity and precession periods (Berger et al. 1989a, b). For the lower Cretaceous, at 130 Ma BP, this results in a shortening of the precession cycles from 19.0 and 23.7 to 18.4 and 22.8 ka respectively (these figures result from interpolation between values at 72 and 270 Ma BP, as given in Berger et al. 1989a, b). The obliquity periods at 41 and 54 ka shorten to 38.2 and 49.2 ka. Berger et al. (1989a, b) assume the eccentricity cycles at 413, 123, 100 and 95 ka to be stable throughout geologic time.

Spectral analysis

The Caravaca succession contains the calpionellid subzones D1 and D2 in their entirety (Ten Kate & Sprenger 1989). The cyclicities in the observed carbonate values match the quasi-periodicities of the

Milankovitch model quite well (Sprenger & Ten Kate, 1993). On the other hand, when special emphasis is placed on the central 56 m of the succession and when 11 m at the top and base are left out of consideration, then the rate of accumulation seems constant and is estimated to fall between 67 and 71 mm/ka (Sprenger & Ten Kate, 1993). To compare both successions we were forced to take the D1 subzone, which both have in common, but the basal 11 m of D1 at Caravaca have a lower rate of sedimentation that may distort the spectrum to some extent. Rigorous elimination of the base destroys valuable information and nibbles at the resolution of the low frequency-range part of the spectrum. So, from two evils the best is chosen.

Before the visual correlation was performed, a Blackman-Tukey spectrum was made, based on the original sample locations of the La Faurie succession (Fig. 7). A Tukey-Hanning window was used to smooth the spectrum and its calculated bandwidth is indicated (Jenkins & Watts 1968). Along the horizontal axis the frequency in cycles per sampling distance (Δ) is indicated. Underneath the frequencies, the corresponding cycle lengths (in cm) are plotted for convenience. Along the vertical axis the powers are indicated. Numbers above peaks are equal to cycle length (in cm). The graph shows a great number of peaks, that, at least in part, are due to variations in accumulation rate. Subspectra of overlapping segments of the succession also support this conclusion. Going from one subspectrum to the next, it is remarkable that as a rule frequencies with a sizable power are relocated to lower or higher frequencies. This points to non-linearity that is due to variations in accumulation rate. The visual correlation of both successions hints in the same direction (Fig. 5). The spectrum of the La Faurie succession, stippled in Fig. 8, was made after visual correlation. In comparison to Fig. 7, the powers of Fig. 8 are still high, but more reduced in number.

A univariate Blackman-Tukey spectrum of subzone D1 of the Caravaca succession is also shown in Fig. 8. Powers in the frequency range of 0.2 to 0.5 fluctuate around a minimum level. They are attributed to random noise and for that reason not shown in the figure.

The same spectrum is repeated in Fig. 9a, but now

La Faurie succession, before correlation

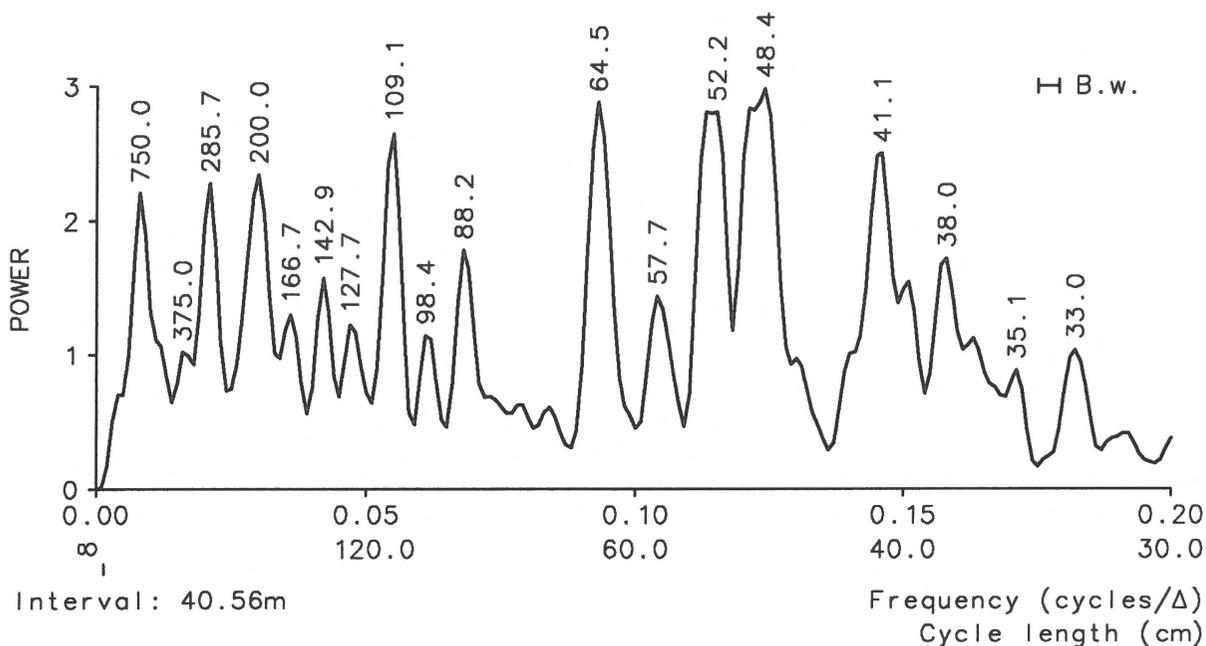


Fig. 7. The Blackman-Tukey spectrum of the La Faurie succession before correlation. It has many peaks that are probably caused by varying rates of sedimentation. The spectrum based on the same data, after correlation, is given in Fig. 8.

a conversion to time has been applied. A constant rate of carbonate accumulation of 67 mm/ka has been assumed (Sprenger & Ten Kate, 1993). The relevant orbital frequency bands are also indicated. The end result is not as good as in Sprenger & Ten Kate (1993). We ascribe this to the shortness of the succession, and the influence of the lowermost 11 m, that were incorporated. Nevertheless, the eccentricity and precession peaks are distinctly present, whereas peaks corresponding to obliquity are united in one peak.

The spectrum of La Faurie shown in Fig. 8, is repeated in Fig. 9b after conversion into time and with the pertinent orbital frequency bands indicated.

Comparing the spectra of subzone D1 in both successions (Figs 8, 9) reveals a number of similarities and differences. The total power of the La Faurie succession is larger, because the variation in carbonate content of the individual layers is greater. This is also clear when the carbonate curves of both

successions are compared (Figs 2a, b). Powers of a Blackman-Tukey spectrum are a direct measure of variance and therefore the power is much higher (Fig. 4). It is highly remarkable that, after carrying out the visual correlation procedure, the powers in the eccentricity and precession bands show a difference in cycle length of only 0 to 3 cm, although both realms of sedimentation are quite different and 950 km apart.

It is also worth noting, that in the La Faurie succession the obliquity peak has much more power than in Caravaca (Fig. 9). This is plausible when the early Cretaceous paleolatitude of both successions is taken into account. Following the reconstruction of Savostin et al. (1986) the paleolatitudes of Caravaca and La Faurie are respectively 15 to 20° N and 25 to 28° N. Therefore, a more pronounced influence of obliquity is expected.

Finally, the striking differences in power in Fig. 8 at 98.4 cm (Caravaca) and 96.8 cm (La Faurie) and

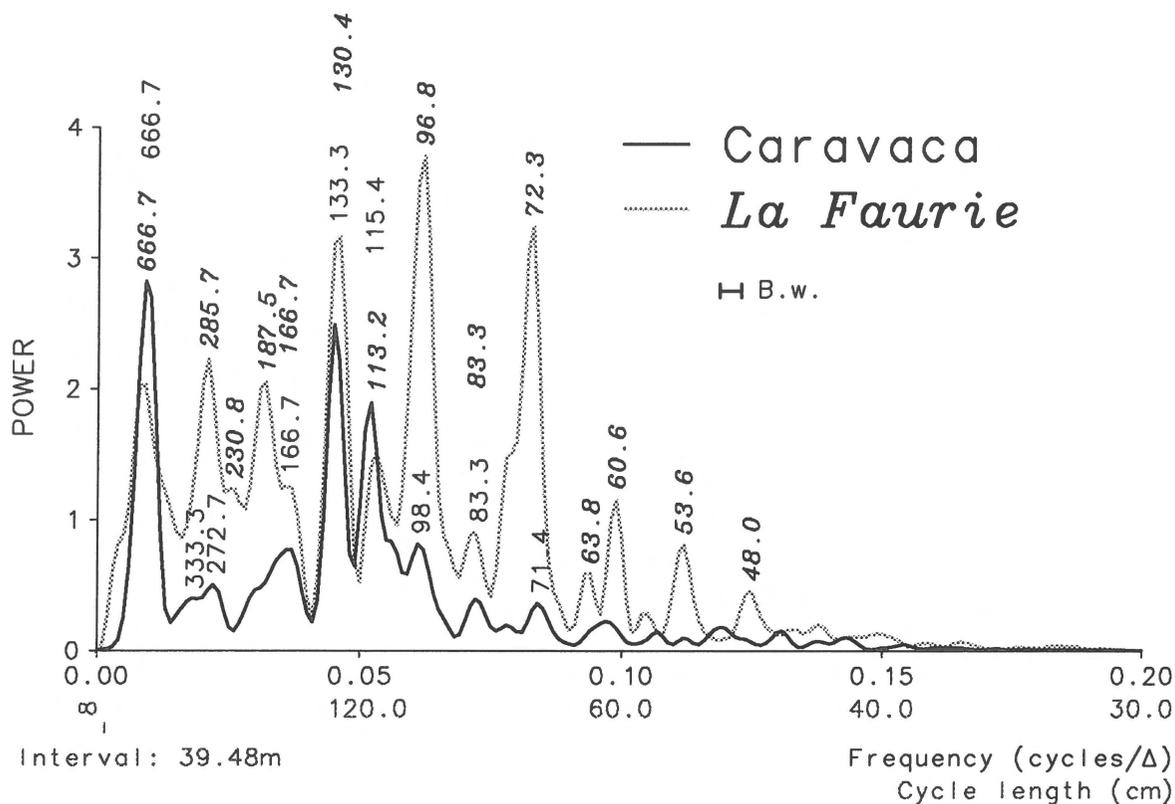


Fig. 8. Blackman-Tukey spectra of the equally spaced carbonate/insoluble residue series of Caravaca (solid) and La Faurie (stippled). They are based on the shared part of both successions (39.5 m) and smoothed by a Tukey window, with a bandwidth (B.w.) as shown. Frequencies are plotted along the horizontal axis, powers along the vertical axis. Cycle lengths (in cm) are indicated along the horizontal axis and on top of the peaks. Frequencies from 0.2 to 0.5 are not reproduced, because power fluctuates around a minimum level.

at 71.4 cm (Caravaca) and 72.3 cm (La Faurie) must be explained. The first pair is located in the orbital frequency band and is interpreted as deterioration of the precession peaks at 130 and at 113 cm. The explanation of the second pair is much harder, because it falls beyond the orbital frequency band. The first pair is probably caused by variations in sedimentation rate on a decimetre-scale. Ten Kate & Sprenger (1989) and Sprenger & Ten Kate (1993) concluded that the variation in the rate of accumulation in the Caravaca succession was small. The power of both pairs is low. In La Faurie on the other hand, both powers are high, but the variation in accumulation rate was appreciable, as discussed earlier.

The visual correlation between both successions is numerically expressed by coherence analysis. The cross-amplitude spectrum of both successions shows that powers on eccentricity and precession

are high (Fig. 10). The spectrum of squared coherency demonstrates that the eccentricity (e_1) and the precession cycles (p_1, p_2) are coherent at the 80% confidence level (Fig. 10). As far as the gain spectrum is concerned, there is a definite gain of power in the obliquity cycles (o_1 and o_2) of La Faurie with respect to Caravaca (Fig. 10). From these facts we conclude, that most likely orbital forcing played a role in the carbonate accumulation at La Faurie. Orbital forcing of the succession at Caravaca was convincingly demonstrated in Sprenger & Ten Kate (1993).

Summary

Arguments are presented, that the rhythmicity in the carbonate content of late Berriasian limestone-marl successions in the northern Subbetics (SE

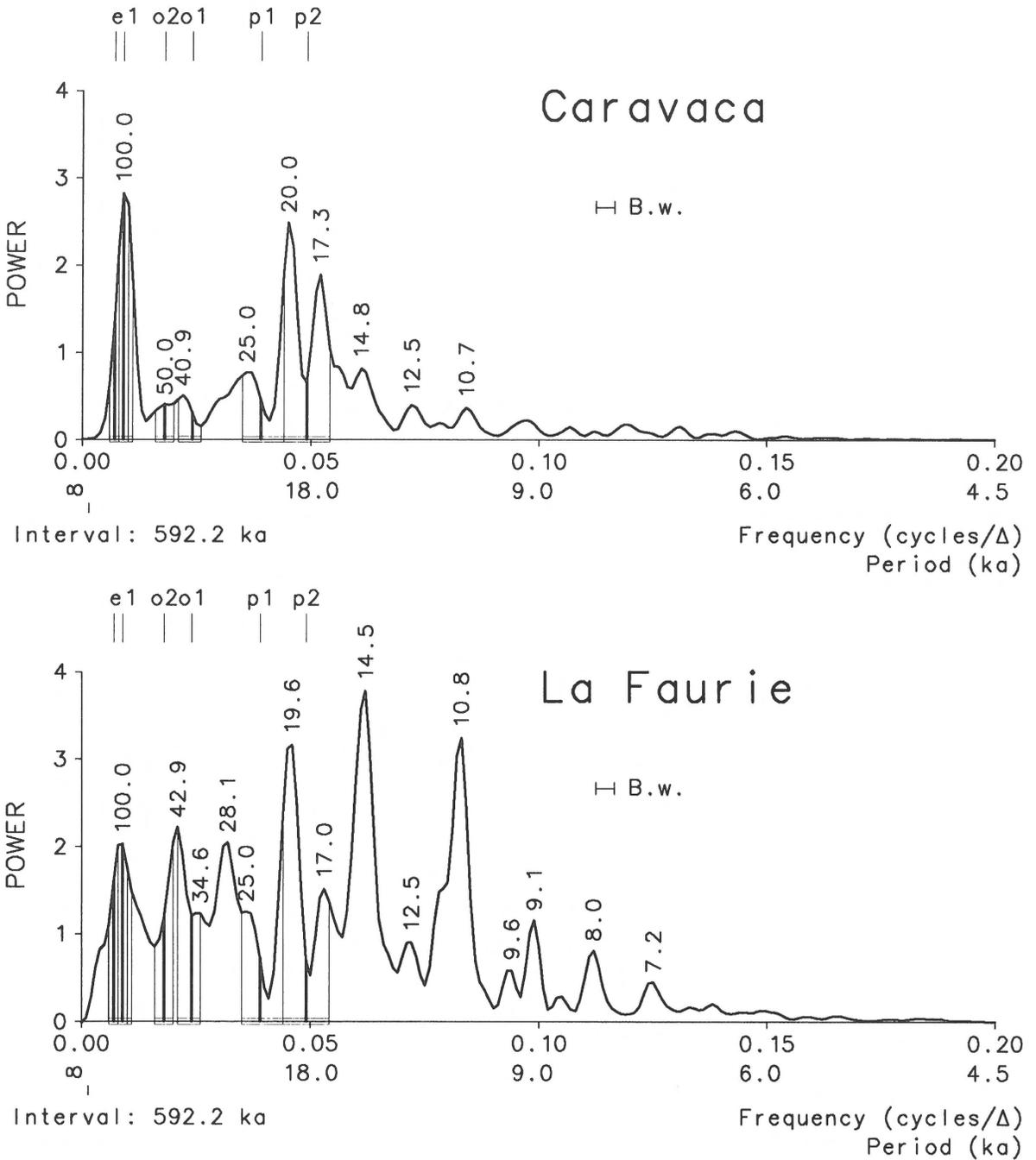


Fig. 9. The same spectra as in Fig. 8, but now translated into time (in ka). The Berriasian frequency bands of eccentricity (e1: 100, 95, and 123 ka), obliquity (o1: 38.2 ka; o2: 49.2 ka) and precession (p1: 22.8 ka; p2: 18.4 ka) are shown with a width of $\pm 10\%$ of their values (Berger et al. 1989a, b). The horizontal scale used to picture the spectrum, causes the eccentricity cycles of 95 and 100 ka to practically coincide. In both spectra a constant rate of sedimentation of 67 mm/ka is assumed, as explained in Sprenger & Ten Kate (in press).

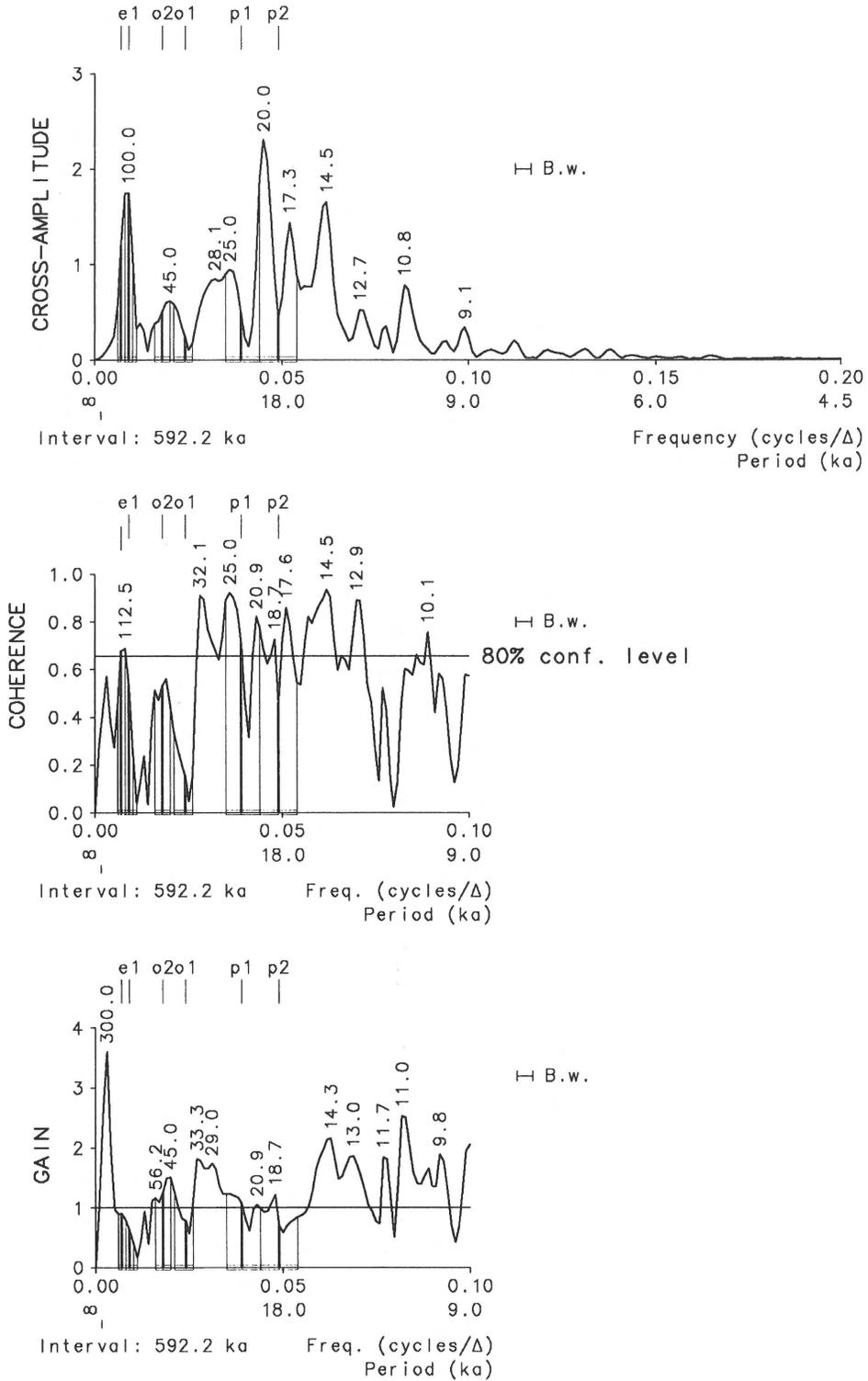


Fig. 10. Compilation of results of cross-spectral analysis of the Berriasian successions of Caravaca and La Faurie. As in Fig. 9, the positions of the Berriasian orbital frequency bands are shown at the top of each spectrum. Frequencies and cycle durations (in ka) are plotted on the horizontal axis. Along the vertical axes the cross-amplitude, squared coherency and gain are plotted. In the coherence spectrum the 80% confidence level is indicated.

Spain) and Fosse vocontienne (SE France) is orbitally controlled.

By visual comparison 59 tie lines were selected to correlate both successions. Although the two sedimentation realms differ geographically and geologically, the power spectra show a remarkable resemblance at the eccentricity and precession frequencies. This is numerically confirmed by significant coherence at the 80% confidence level.

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