DEPOSITIONAL AND GEOCHEMICAL CYCLICITY IN THE CRETACEOUS FINE-GRAINED STRATA OF COLOMBIA. A MODEL FOR ORGANIC MATTER CONTENT

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Spectral analyses of depositional and geochemical time series were conducted on three stratigraphic sections of the Cretaceous Villeta Group, Colombia. Results show statistically-valid cyclicity in distal parasequence stacking patterns and in geochemical variations. Cycles are in the low to high frequency spectra (500 ky - 20 ky). Timing of cyclicity suggests climatic controls on deposition, probably caused by Milankovitch orbital oscillations. Stratigraphic intervals enriched in total organic matter or organic matter indicators such as barium coincide with condensed intervals that are generally associated with observable high-frequency cyclicity. Very thin stratigraphic cycles (< 0,4 m) contain moderate amounts of organic matter because condensation allows organisms to recycle organic carbon. Condensation also allows time for gradual oxidation of organic matter. Thin to moderately thick (0,6-5,0 m) cycles show the highest quantity of organic matter. Sedimentation rates are high enough to inhibit biological destruction and low enough not to dilute organic carbon within the sediments. Thick cycles are characterized by low organic matter because sedimentation rate dilutes organic material. organic matter content not only depends on sedimentation rate but also on paleoproductivity and on grain size and shape. The model presented shows how cycle thickness trends may be used as a very simple approach to predict the amount of total organic carbon.

Análisis espectrales de tiempo-frecuencia fueron aplicados a series deposicionales y geoquímicas en tres secciones del Grupo Villeta del Cretácico de Colombia. Los análisis muestran ciclicidad estadísticamente valida en patrones de apilamiento de parasecuencias en regiones distales de la cuenca y en variabilidad geoquímicas. Esta ciclicidad varía de baja a alta frecuencia (500 ka-20 ka); los resultados sugieren un control orbital tipo Miankovitch. Intervalos estratigráficos enriquecidos en carbón orgánico coinciden con secciones condensadas en las que se observa una ciclicidad estratigráfica de alta frecuencia. Ciclos estratigráficos finos (menores de 0,40 m) contienen cantidades moderadas de materia orgánica, a consecuencia de condensación que permite que organismos reciclen el carbón orgánico y al mismo tiempo permite la oxidación gradual de la materia orgánica. Ciclos estratigráficos finos a medios (0,6 m-5,0 m) muestran la mayor calidad y cantidad de materia orgánica. En estos casos la tasa de sedimentación es suficientemente alta para inhibir la descomposición de la materia orgánica por organismos y suficientemente baja como para no diluir la materia orgánica en la masa de sedimento. Ciclos estratigráficos gruesos (> 5 m) generalmente contienen bajas cantidades de materia orgánica porque altas tasas de sedimentación la diluyen en su masa. El contenido de materia orgánica depende de la sedimentación, de la paleoproductividad oceánica y del tamaño y forma del grano sedimentario. Se muestra cómo el espesor de los ciclos estratigráficos de alta frecuencia puede ser utilizado como una herramienta muy simple para predecir la cantidad de materia orgánica.

Keywords: *Depositional and geochemical ciclicity, statigraphy, cretaceous Villeta group*

INTRODUCTION

The Cretaceous Villeta Group and equivalent units of Colombia offer an excellent opportunity for the study of depositional and chemical cycles. Cycle analyses can be conducted on stratigraphic thickness variations and geochemical signals such as oscillations of organic carbon and major elements. In this paper, bedding features and chemical changes were evaluated for cyclicity with statistical techniques. Depositional and chemical oscillations were analyzed using time series Maximum Entropy Spectral Analyses (MESA; Goldhammer *et al.,* 1990 and references therein). Results show that the Villeta and equivalent units record depositional and geochemical cyclicity that has significant peaks at ~20 ky, ~31 ky, ~ 40 ky, ~100 ky, and ~500 ky. The purpose of this paper is to illustrate new geochemical analyses for the Cretaceous of Colombia and emphasize the importance of cyclicity in the record. In addition, a hypothesis for the relationship between cycle thickness and the content of organic matter is proposed.

Background.

The first work related to the study of depositional cyclicity of the Cretaceous of Colombia was by Bürgl (1961), who claimed that the Cretaceous system showed a 6 million-year depositional cyclicity represented by stage boundaries. Macellari (1988) suggested 5 low-frequency transgressive-regressive depositional cycles. Most recently, Föllmi *et al*. (1992) described higher-frequency depositional rhythmicity in the Cretaceous of Colombia. Villamil (in press) conducted studies on the sequence stratigraphic cyclicity of distal facies of the Villeta Group of Colombia, utilizing Fischer plots. However, to date, spectral analyses have not been used to statistically demonstrate cyclicity for these facies.

It has been hypothesized that cyclicity of the stratigraphic record responds to oscillations of the Earth's climate-ocean system, the well-known Milankovitch cycles (see Einsele and Ricken, 1991 and references therein). The stratigraphic record is influenced by many factors including noise and chaos. Einsele and Ricken (1991) illustrated the point: primary cyclic signals are hidden within depositional background noise, primarily in basinal facies. Strata are compacted and diagenetically overprinted, making recognition of primary signals difficult in some cases but enhancing them in others. Randomness can be filtered with spectral analyses on a time series. If a stratigraphic record, which is composed of many types of signals, shows statistically-valid depositional cyclicity, then this cyclicity should be observed. However, the fact that a certain stratigraphic section does not show cyclicity does not mean that an oscillating control was not influencing deposition. Several frequencies of depositional and chemical cyclicity were discovered in the Cretaceous record of Colombia through the application of statistical tests to field-derived data and laboratory analyses of equally-spaced samples. To calculate the magnitude of these cycles, a new composite macro- and micro-biostratigraphy was used (Villamil, 1994) and was graphically-correlated to the radiometric ages established for the sections in the United States Western Interior by Obradovich (1993) and the calculated time scale of Kauffman *et al.* (1993).

Stratigraphy and location of sections.

The Villeta Group and equivalents are composed primarily of fine-grained facies such as calcareous shales and hemipelagic limestones. The depositional history of the Villeta was highly dynamic and influenced by a combination of climatic, sedimentologic, sea level and tectonic factors (Villamil, 1994). Strata from the Hiló Formation to the chert-dominated Olini Group will be discussed. The Hiló Formation consists of rhythmically bedded shales, cherty shales, and highly calcareous shales and scattered hemipelagic limestones. An overlainly Cenomanian unnamed unit, composed primarily of claystones, calcareous shales, bioclastic limestones and calcareous sandstones. This unit represents an overall regression. The La Frontera Formation has similar facies to the Hiló Formation but has a higher calcareous pelagic component. The Olini Group (latest Coniacian-Campanian) consists of relatively shallow-water (~20m-~150m) cherts interbedded with shales and some hemipelagic limestones; this unit was also studied for cyclicity.

Stratigraphic sections were measured in the Cretaceous outcrop belt of Central Colombia (Figure 1). Distalmost facies were measured in the Upper Magdalena Valley near the towns of Yaguará and Chaparral. The Yaguará section (2° 53' 30,81"N, 5°

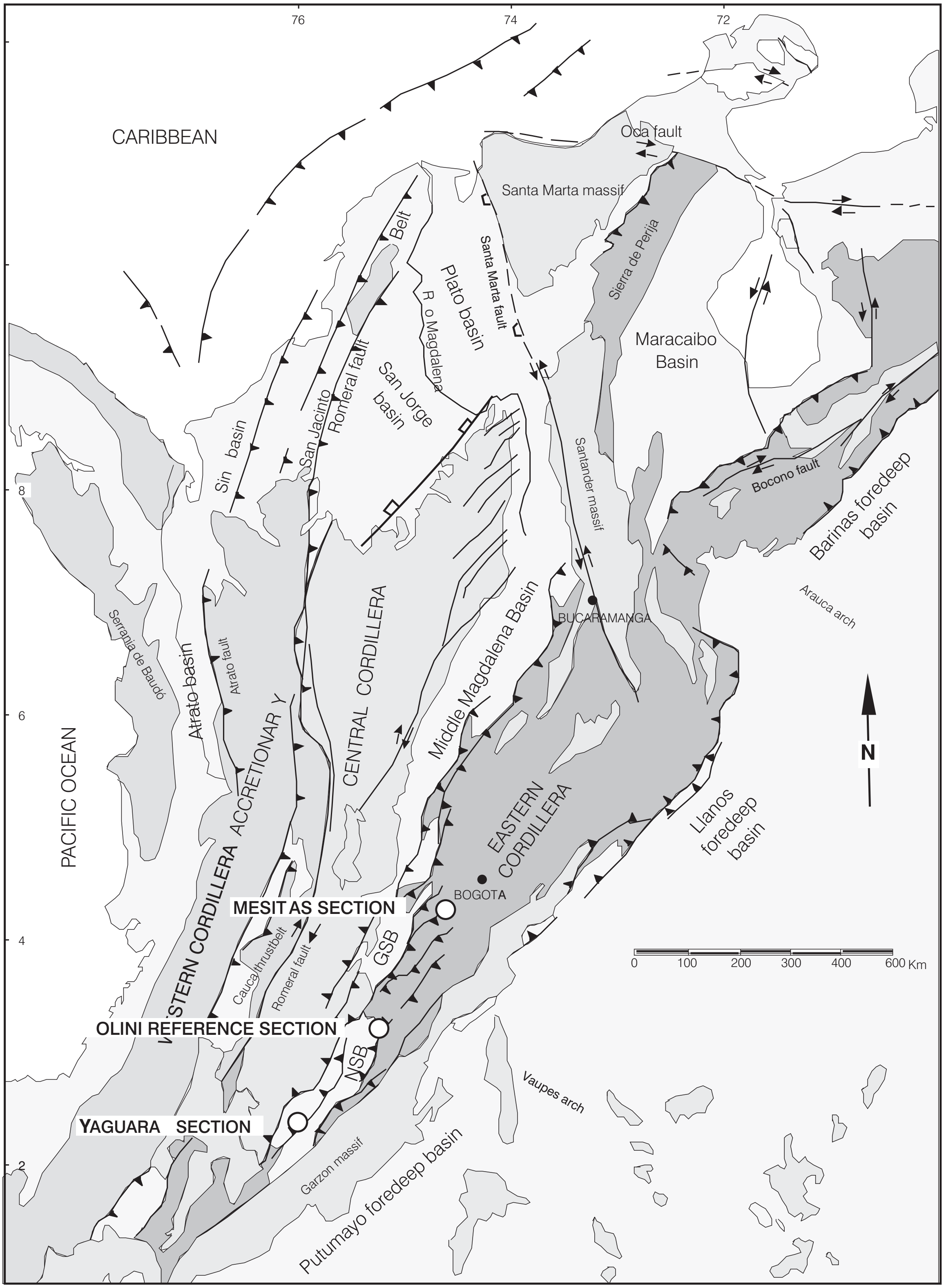


Figure 1. Map of Colombia with the location of stratigraphic sections discussed in text, map modified from Schamel's (1991).

40' 32,43"W) was measured in the Yaguará River near the confluence with the Iquira River. The Olini reference section (3° 40' 32,43"N, 75° 32' 25,95"W) was measured in Olini Creek, half way between Chaparral and Coyaima (Department of Tolima) (Figure 1). The Mesitas del Colegio section was measured on the western flank of the Eastern Cordillera (4° 32' 25,95"N, 74° 26' 45,41"W) at km 28 on the road leading from Bogotá to Mesitas del Colegio along an unnamed creek.

Geologic setting and discussion.

The Upper Magdalena Valley and Eastern Cordillera of Colombia were part of a single large basin during the Albian to Santonian. The paleolatitudinal position of NW South America favored vigorous upwelling onto the upper water column; high paleo productivity characterized Cretaceous times of northern South America. Stratigraphic evidence for high productivity includes: (a) The presence of siliceous-rich rocks such as cherts and siliceous shales, considered as evidence of high paleoproductivity (Berger, 1974, 1976). Phosphates are also considered as evidence for intense upwelling (e.g., Föllmi, 1991). (b) Rich radiolarian assemblages, found in the Late Albian-Early Ceno-manian of the Upper Magdalena Valley by Arango (1995) and Villamil and Arango (in press). (c) Abundant barium, cadmium, phosphorous, and organic carbon values of up to 16% that also supports vigorous upwelling and oceanic paleoproductivity in the Colombian Cretaceous margin (Villamil, 1994 for details).

Stratigraphic units analyzed for chemical and depositional cyclicity were mostly deposited in distal offshore environments (~200-300 m water depth). The distal setting records subtle as well as marked changes in deposition but it poses severe problems for interpretations of sedimentation rates and the development of stratigraphic cycles. The distal offshore setting is, in general, lithostratigraphically condensed; however, in terms of time, it records much more than nearshore settings. Even when no clastic sediment reaches this portion of the basin, the pelagic rain of organisms has the potential to register time of non-deposition of clastics. The development of depositional sequences and parasequences, however, may be limited by low sediment supply and submarine erosion.

It is not coincidental that stratigraphic intervals associated with high magnitude peak transgressions, e.g., second-order maximum flooding surfaces, are characterized by high-frequency hemipelagic (carbonate/silica)-clastic cycles because these are the times of maximum sediment starvation and of diminished autocyclic noise in the record. Examples of maximum flooding high frequency cyclically-bedded units are the Hiló and the La Frontera Formations. The fact that these maximum flooding intervals are characterized by rhythmic hemipelagic bedding supports the idea of a climatic control in paleoproductivity but does not rule out control in clastic deposition because climatic changes control the density and salinity of the water, threby affecting sea level. The idea of considering a dual control on cyclicity, with changes in sedimentation rate and paleoproductivity, may work better than considering a single controlling factor. The model proposed by Eicher and Diner (1989, 1991) explains a dual control in the development of cycles. This model, although centered on paleoproductivity cycles, also shows a climatic effect on relative sea level (Eicher and Diner, 1989). Eicher and Diner (1989, 1991) associated warm-dry cycles with high productivity and a slight rise in sea level. An increase in paleoproductivity would enhance deposition of calcareous organisms and the rise in sea level would trap sediments shoreward, producing a positive feedback in the development of hemipelagic limestone cycles.

Changes in sedimentation rate, and oscillations in oceanic chemistry and productivity control patterns and quantities of element concentration. High concentrations of elements such as barium, phosphorous and others have been proposed to be related to oceanic productivity and therefore can be statistically-analyzed to depict cyclicity. The work of Dymond *et al.* (1992), Turekian and Tausch (1964), and Bolter *et al.* (1964) have shown the importance of Barium measurements in determining the amount of paleoproductivity in a stratigraphic interval. Barium measurements may be better than TOC analyses in outcrop studies because Ba is less sensitive to weathering processes. Although fluctuations in paleoproductivity cause changes in barium and phosphorous in the stratigraphic record, changes in sedimentation rate also dramatically affect element concentrations.

PITFALLS OF CYCLE ANALYSIS

The biggest obstacle for evaluating cyclicity in a time-dependent basis with the Cretaceous stratigraphic record is the relatively poor time control at a continuous scale. Average rock accumulation rate, as a calibration for a time scale, has been used by multiplying the average rate by the stratigraphic thickness. This procedure poses many critical problems because sedimentation rate is assumed to be constant and transferred to «time», and this requires constant sedimentation rate.

The models of Pratt (1985) and Barron *et al*. (1985) explain the occurrence of shales as fine clastic input during wet portions of a climatic cycle, assuming relatively constant rain of hemipelagic organisms, i.e., constant calcareous input and variable clastic sedimentation rate. Productivity cycles (Eicher and Diner, 1989, 1991) create lithological differences as a function of climatic changes that affect paleoproductivity. Higher productivity enhances abundance of calcareous organisms, and sedimentation rate of limestones therefore overwhelms clastic input. An additional factor that influences the assumption of constant rock accumulation rates is that differences in grain size and shape also affect rock accumulation rates. Compaction differences between coarse, spherical grains and fine, flat particles are marked. An evaluation of relative compaction and sedimentation rate should be conducted before applying spectral analyses to time series in «real» time domain.

METHODOLOGY

Data for analyzing depositional and chemical cyclicity were obtained in the field in a careful manner. Stratigraphic sections were measured at different scales of resolution. Sections were measured with a Jacob staff, and individual beds at the cm-scale resolution with a ruler. Stratigraphic intervals of interest for cycle analyses such as condensed sections and stage boundaries were measured at the mm-scale. Samples for geochemistry were collected every 0,5 m throughout the sections studied, and in the intervals of special interest they were collected every 0,05 m. Stratigraphic data were analyzed in terms of depositional cycles in the following manner. A fundamental cycle, which is a distal fine-grained facies equivalent of a nearshore parasequence was proposed. The base of the cycle starts at the base of a hemipelagic limestone bed, the top of the cycle is the base of the next hemipelagic limestone.

Geochemical analyses were conducted on discrete outcrop intervals. Therefore, stable geochemical markers have to be selected for the study of cyclicity. Barium is not easily weathered or altered and may record paleoproductivity in an accurate manner. Evidence for this comes from the present oceans (Bolter *et al*., 1964 and Schmitz, 1987) and from the deep sea record (Turekian and Tausch, 1964) among others. Three hundred samples were selected and analyzed with ICP. The entire Villeta Group of the Upper Magdalena Valley was analyzed at a larger scale to compare to the Cenomanian-Turonian (C-T) boundary interval throughout the same region.

Statistical methods to evaluate cyclicity.

Spectral analyses used are based on algorithms of simplified Fourier series. Data were plotted as values versus stratigraphic thickness or cycle number. Spectral analysis replicates the shape of the data plot using different frequencies of sine wave curves and outputs the relative frequency of the dominant waves. Fourier analysis decomposes a time series into a fundamental wave and additional harmonics. The transform is of the general mathematical form:

$$f(t) = X1 + X2\sin(t) + X3\cos(t) + X4\sin(2t) + X5\cos(2t) + \ldots$$

Maximum Entropy Spectral Analysis (MESA) with the fast algorithm developed by Dunn *et al.* (1986) was applied to all data.

RESULTS

Low-frequency cycles.

The Cretaceous of Colombia is composed of several second-order (*sensu* Haq *et al.*, 1987) sequences with an average frequency of 6 Ma. This cyclicity was originally recognized and discussed by Bürgl (1961). The spacing of second-order maximum flooding intervals is expressed in the geological record as isotopic facies generally associated with concretions and black shales. A cyclicity of approximately 500 ky in the Cretaceous of Colombia is apparent when

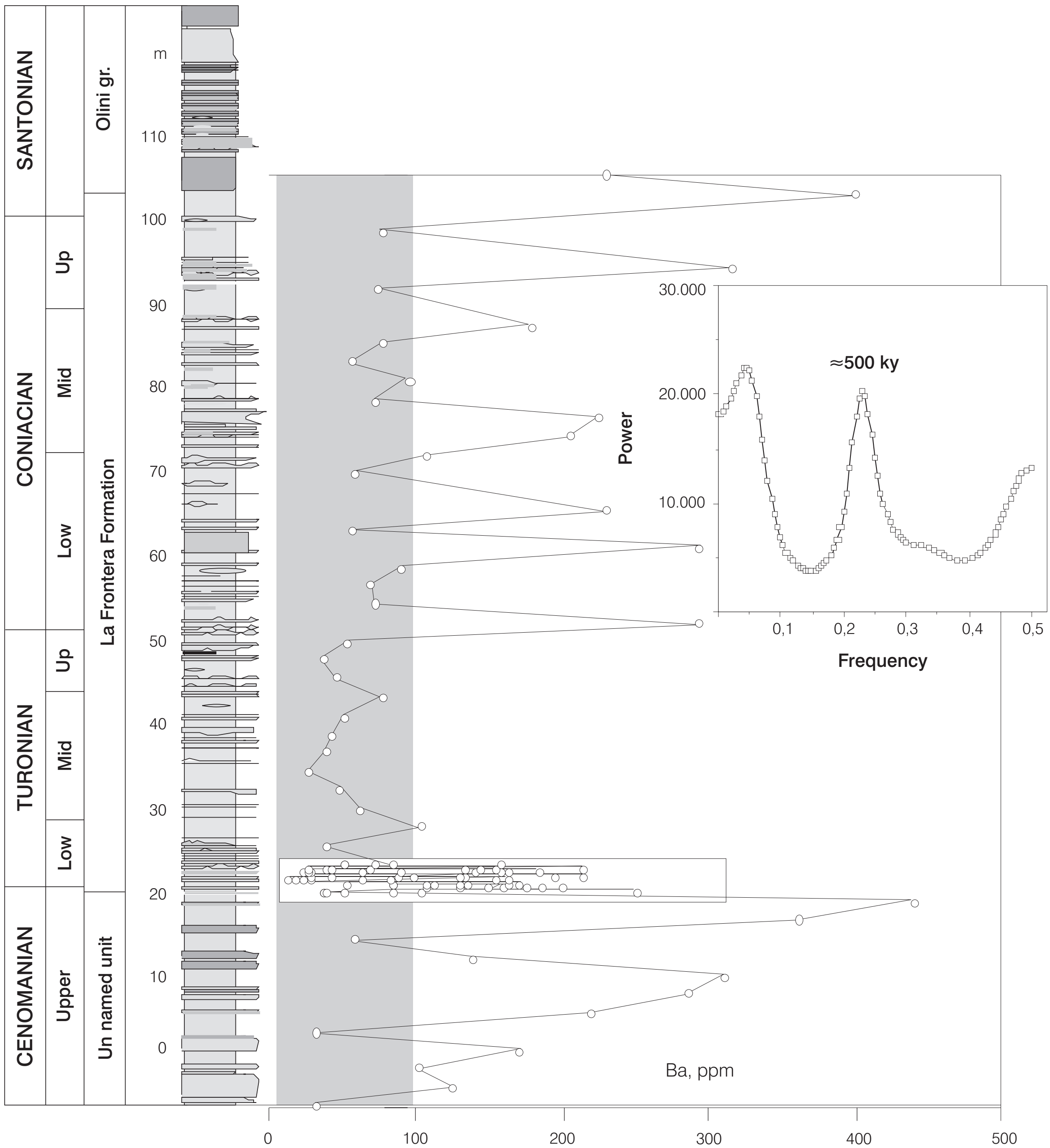


Figure 2. Barium data and spectral analysis of a barium time series of the Yaguará section in the Uper Magdalena Valley of Colombia. Shaded area represents values below average and white area values above average. The power / frequency inset are the results of the spectral analysis utilizing Maximum Entropy Spectral Analysis.The central peak represents -500 ky cyclicity

running a maximum entropy spectral analysis on equally-spaced geochemical data, particularly barium and phosphorous (Figures 2 and 3, respectively). These ~500 ky cycles may have been the result of relatively long-term variations in productivity, the result of high-frequency, high-order maximum flooding or condensed sections or a combination of both. Figures 2 and 3 show concentrations of Ba and P of samples collected and analyzed every meter in the Yaguará section. The insert on both figures, as in all the following ones, is the result of spectral analyses on the time series. Frequency is in the x-axis and power, the correlation value of

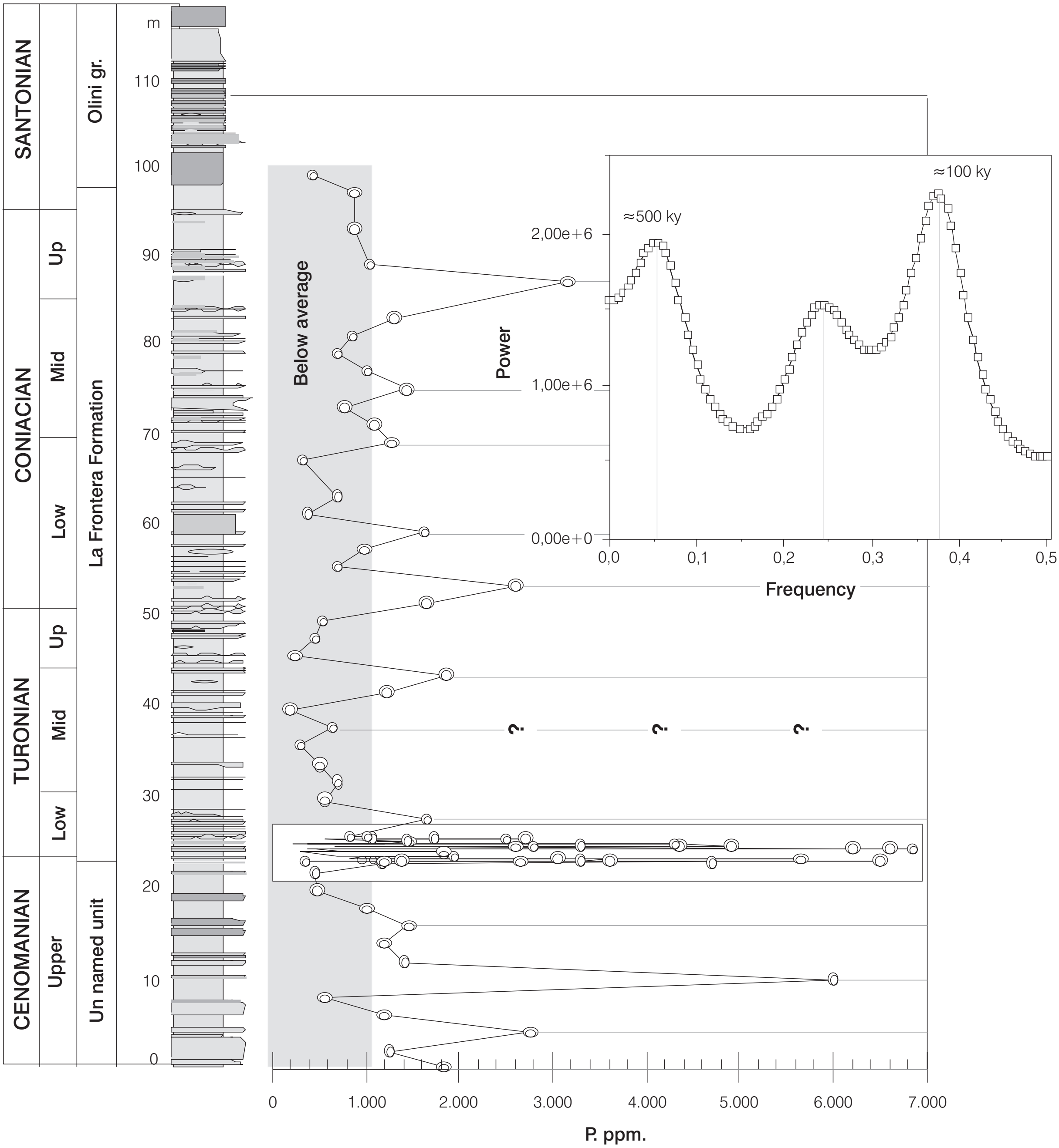


Figure 3. Geochemical data and spectral analysis of phosphorous time series of the Yaguará section in the Upper Magdalena Valley of Colombia. Shaded area represents values below average and white area values above average. The power / frequency inset are the results of the spectral analysis utilizing Maximum entropy Spectral Analysis. Peaks of the inset represent - 500 ky and - 100 ky cyclicity.

frequencie is in the y-axis. ~500 ky oscillations in concentration are detected in all sections measured as variations in different elements. The origin of these cycles is uncertain but ~500 ky cycles may be sufficiently close to the 400 ky Milankovitch ellipticity cycles.

Vertical variations in Ba content can be interpreted in terms of paleoproductivity because it has strong biogenic associations (Chow and Goldberg, 1960 and Dymond *et al.*, 1992). Bishop (1988) showed that barium is taken up and transported by sinking biogenic particles in the ocean. Spectral analysis, in the inset of Figure 2, shows two peaks at high and low frequencies, probably reflecting combined cycles. ~500 ky cyclicity can also be detected in Ba of the Olini reference section (Figure 4). The most pronounced peak in Figure 4 is at ~500 ky and represents the same type of cycles discussed above. Cycle analysis for the entire Olini section produces low power results because data from various systems tracts and facies are mixed. However, even with limited reliability, time-series analyses still are sensitive to the ~500 ky signal.

High-frequency cycles.

Depiction of 100 ky cycles has to be evaluated with closely-spaced samples. Figure 5 shows thickness trends of the Olini reference section. The stratigraphic section was divided into systems tracts. Running time series on different systems tracts diminishes the potential error caused by differences in sedimentation rate and measuring across unconformities. Figure 5 shows the Olini reference section and the data base composed of cycle thickness vs. cycle number (bottom inset). Four time series results are shown, one for all the data and three for different segments of the stratigraphic section. The top left diagram shows analyses for all cycles. The result is quite noisy suggesting blending and interference of signals, probably by differences in sedimentation rate. There are two peaks, however, near frequencies 0,3-0,4; the peak to the left is quite strong and rises above noise level suggesting that it represents some sort of statistically-valid peak in cyclicity. The value of this peak is approximately 100 ky. The other three graphs are results of spectral analyses on individual systems tracts. The upper right graph (A) is the resulting spectral analysis of the lower Villeta Group of the Upper Magdalena Valley. This portion of the Villeta was measured from the top of the Caballos Formation (lower Albian) to the latest portion of the highstand tract (Albian-Cenomanian boundary), and it represents a short transgressive systems tract, a maximum flooding interval, and a condensed highstand. Time series analysis shows a peak at ~100 ky, reflecting bed repetition in the lower Villeta Group. Stratigraphic equivalents to this portion of the Villeta in other regions of Colombia also show a strong imprint of relatively high-frequency cyclicity.

The middle left graph of Figure 5 (late HST B) represents time series results from the Albian-Cenomanian boundary to the base of the La Frontera Formation. Results show a strong peak at ~100 ky; this cycle is reflected stratigraphically as parasequence repetitions and as bundling of shale beds. This interval represents gradual progradation from the Cenomanian-Albian boundary interval to the latest Cenomanian. The third spectral analysis was conducted on the La Frontera highstand (Figure 5, HST C). The La Frontera highstand shows two peaks in depositional cyclicity. The right peak represents ~100 ky, reflected stratigraphically as relatively thick limestones with minor bundles inside.

The Yaguará stratigraphic section also shows marked 100 ky depositional cyclicity (Figure 6). This section was divided into discrete intervals to avoid comparing differences in sedimentation rates. The lower time series analysis represents the stratal repetitions of the condensed section interval. This analysis shows three peaks; the highest one is at ~100 ky, followed by ~40 and <20 ky peaks. The time series in the middle of Figure 6 shows cycle analysis for the entire La Frontera Formation and part of the underlying unnamed unit. The remaining time-series plot does not show cyclicity in any frequency. This may reflect mixing sediments representing very low and relatively high sedimentation rates. The graph at the top of Figure 6 shows the second-order early highstand La Frontera Formation. This plot shows a peak at ~100 and a smaller-scale peak at ~40 ky.

The Mesitas del Colegio stratigraphic section (Figure 7) is located in a more proximal region of the basin. Figure 7 shows the stratigraphic section to the left, the data of cycle thickness versus cycle number on the bottom, and the time series conducted on this data set. Time series analysis shows a peak at ~100 ky and a smaller one at a higher frequency. The statistical validity of these cycles cannot be precisely evaluated; however, peaks suggest that a control with a frequency on the order of 100 ky affected sedimentation patterns.

Geochemical analyses depict ~100 ky cyclicity but not as strongly as ~500 ky cyclicity. Figures 3 and 4 show higher frequency cycles that are close to 100 ky. Phosphorous content in the Yaguará section (Figure 3) shows a strong ~100 ky signal attributed to highfrequency changes in sedimentation rates, paleo-

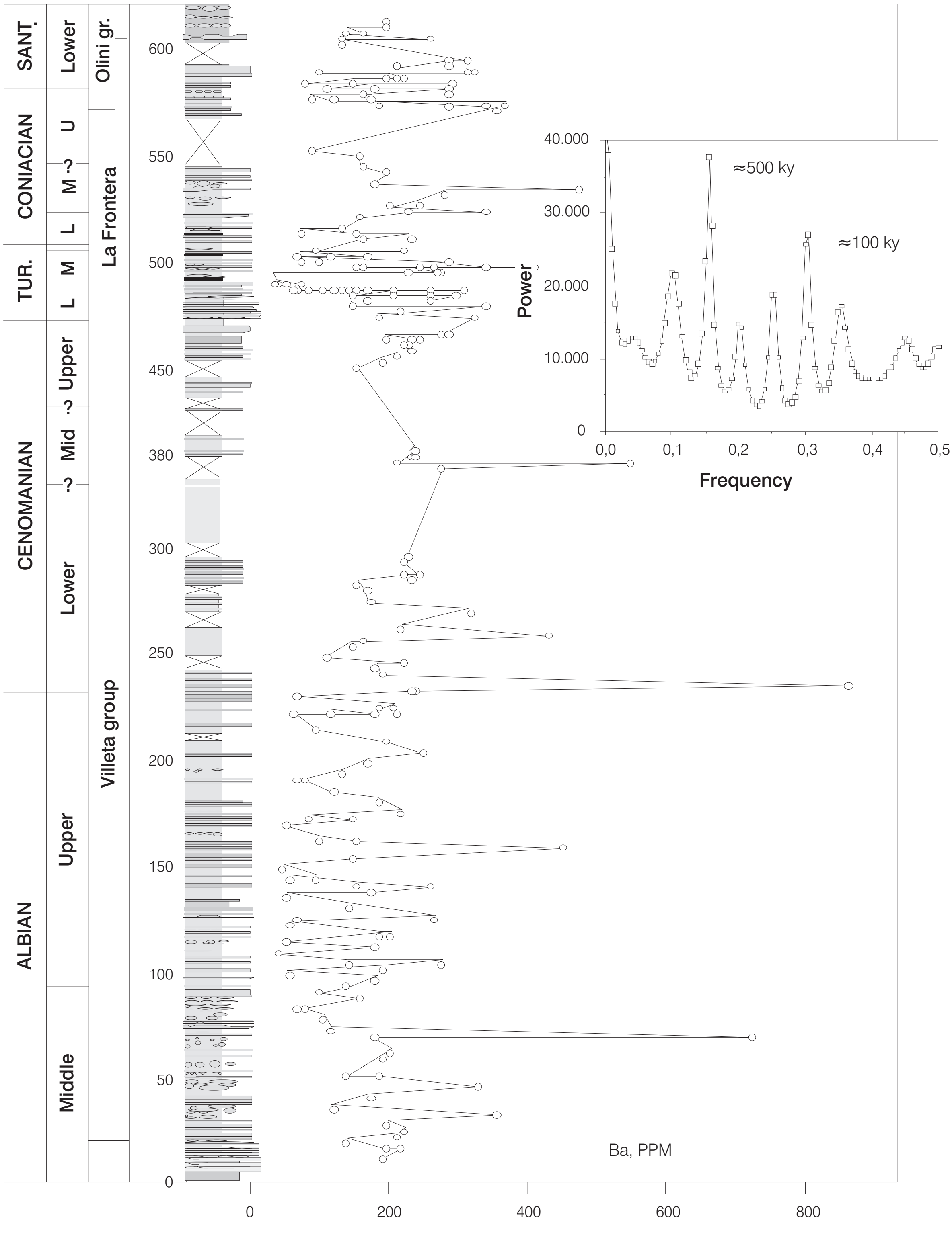


Figure 4. Geochemical data and spectral analysis of the Olini reference section barium time series (see Figure 1 for location). Several peaks in cyclicity can be observed in this 600 meter-thick section; the strongest peak is represented in the spectral analysis --inset-- by the highest peak, 500 ky in duration. Additional peak to the right represent higher relative frequencies 100.

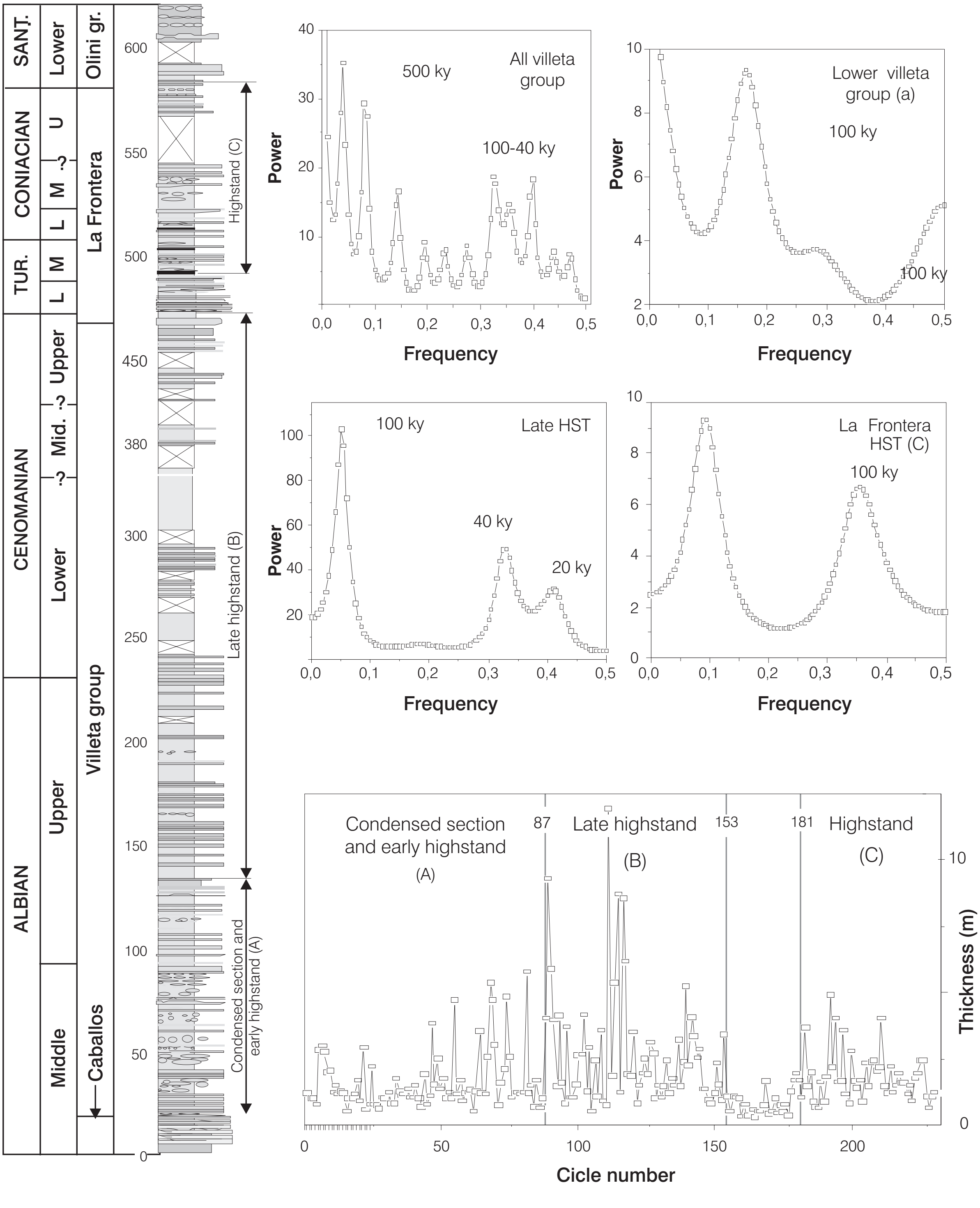


Figure 5. Different spectral analyses stratigraphic segments of the Oliní reference section. The inset on the bottom of the figure represents the thickness of cycles plotted versus the cycle number. Data has been separated in systems tracts for spectral computations. The upper left spectral analyses represents all measured beds, the upper right inset is the spectral analysis for only the lower portions of the Villeta Group (A) --the Hiló Formation--. The central left spectral analysis was conducted on the late highstand portion of the Villeta, upper Albian to uppermost Cenomanian. The central right inset represents the spectral analisys for the condensed section and early highstand HST (C).

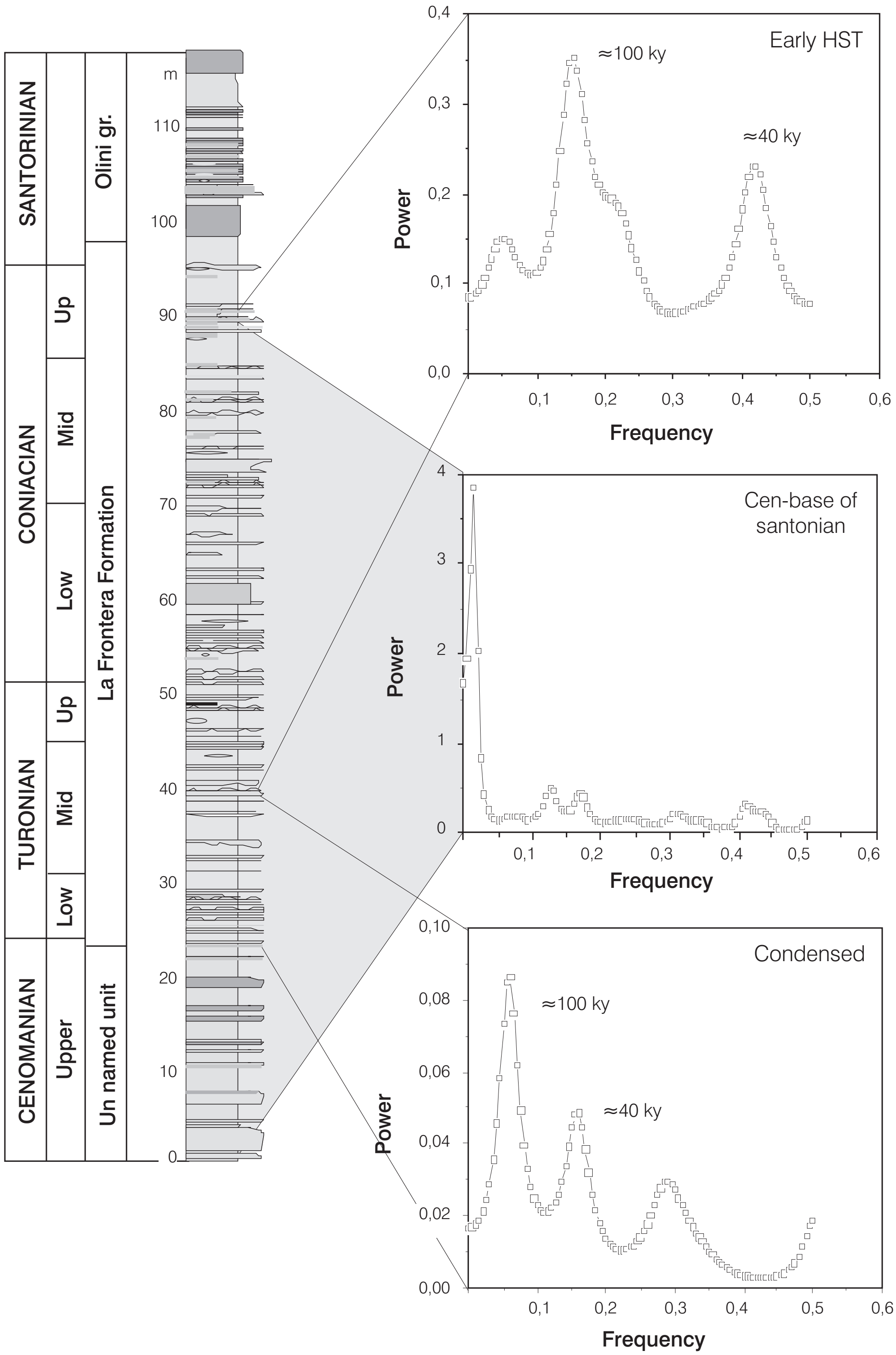


Figure 6. Spectral analyses for different systems tracts of the Yaguará section.
The stratigraphic section was divided into three segments to avoid marked differences in sedimentation rate, insets are correlated to stratigraphic segments

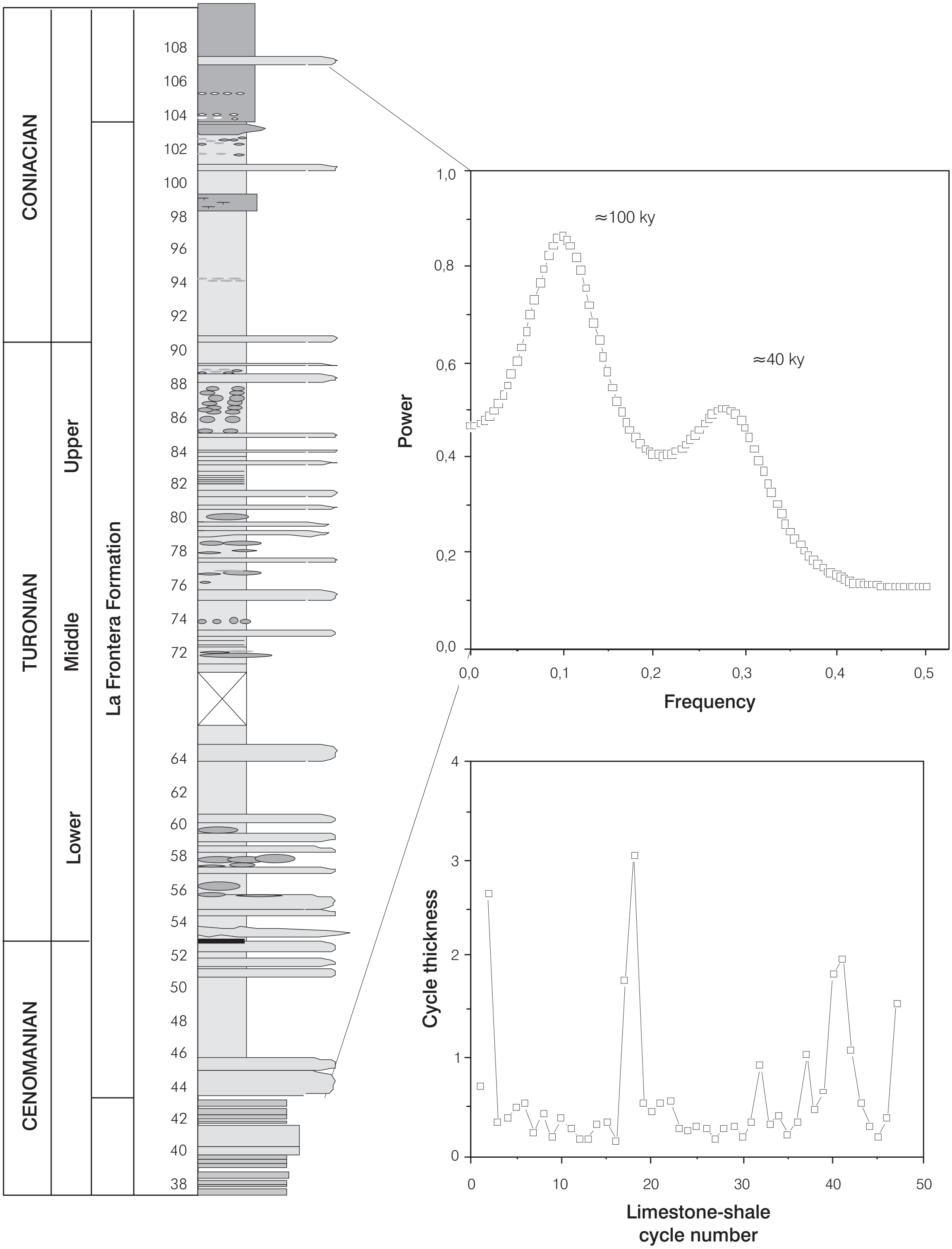


Figure 7. Spectral analysis on parasequence thickness trends of the Mesitas del Colegio stratigraphic section, Eastern Cordillera.

productivity oscillations, or both. Stratigraphically, ~100 ky cyclicity in phosphorous peaks reflects landward shifts of facies belts; e.g., phosphatic-rich intervals are associated with transgressive pulses or distal parasequence boundaries. These phosphatic lags reflect sediment starvation and condensation (e.g., Föllmi *et al.,* 1991) and have been used extensively to depict condensed sections. Geochemical peaks in phosphorous content coincide with the occurrence of phosphatic lags. Evidence for sedimentary concen-tration of phosphatic lags comes from the shape and size of phosphatic pebbles and sedimentary structures. These pebbles vary in size from large (up to 0,03 m) to very small (< 0,001 m). Additional geochemical indicators to inger 100 ky cyclicity used in the present work are phosphorous and barium (Figures 2-4).

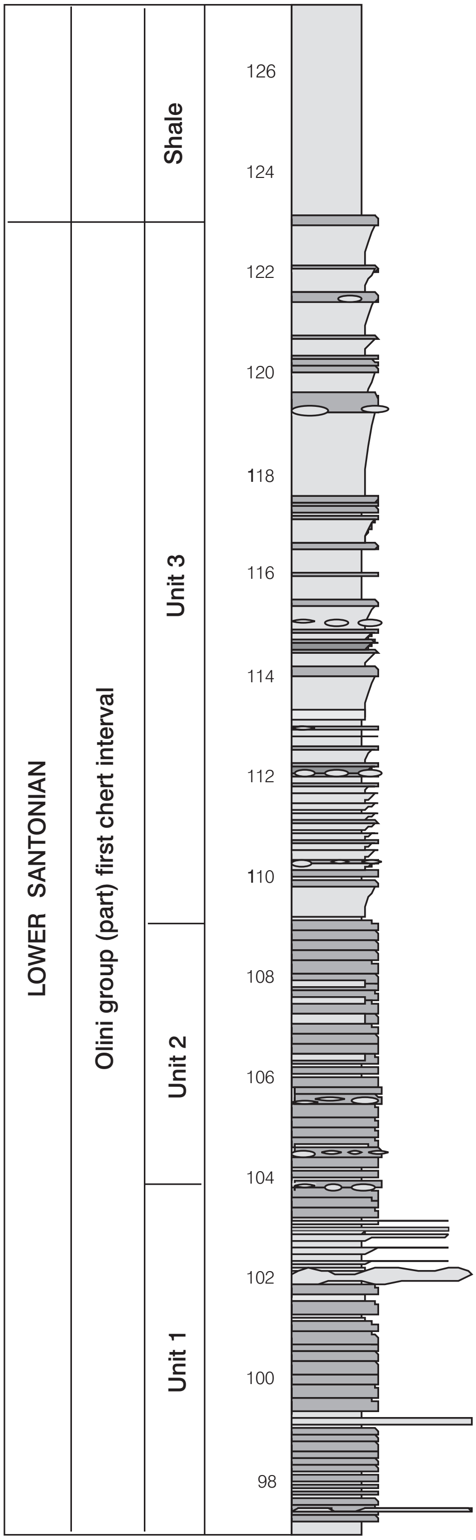
40 ky cyclicity can be interpreted from vertical variations in the stratigraphic thickness of distal parasequences (Figure 5, late HST B). 40 ky cyclicity of condensed intervals such as the lower portion of the Hiló and the base of the La Frontera Formations are easily observed in the field. ~40 ky cyclicity has a strong signal in cherts and siliceous shales of the Olini Group and the La Luna Formation (Figure 8). The Olini Group is composed primarily of black cherts interbedded with siliceous shales deposited under vigorous upwelling conditions. The Olini Group was measured in the Yaguará River in the southern portion of the Upper Magdalena Valley. Dating the Olini Group has been difficult because of very rare occurrence of ammonites. The amount of chert (biogenic) input apparently was controlled by climatic cyclicity. Strata of the Lower Chert of the Olini Group are cyclically-bedded and bundled into larger cycles. Figure 8 shows spectral analyses of the Lower and Upper Chert intervals of the Olini Group measured in the Upper Magdalena Valley.

Geochemically, ~40 ky cyclicity can be detected by spectral analyses of calcium, barium, phosphorous and other element time series. Figure 9 shows results of spectral analyses conducted on elemental concentrations on closely-spaced samples (0,5 m). Spectral analyses on time series of geochemical information every 0,5 m were only conducted for the base of the La Frontera Formation. In many instances, analyses of high-frequency cyclicity of the Cretaceous of Colombia yield 31 ky peaks in the spectral analyses; these 31 ky peaks may be the result of blending 40 and 20 ky cycles (Figure 9). 20 ky cyclicity can be observed with spectral analyses on 0,5 m time series (Figure 9 a, b). Figure 8 shows a restricted and high-powered peak at or near 20 ky. There are at least two possibilities for explaining why the Olini strongly records 20 ky cycles. The first possibility is that slight variations in paleoproductivity or sediment supply, when upwelling is very strong, affect the stratigraphic record dramatically compared to similar variations in a less vigorous upwelling regime. The second possibility is that chert deposition is more sensitive to variations in sediment supply and paleoproductivity than other lithologies.

INFLUENCE OF CYCLICITY IN THE CONTENT OF ORGANIC MATTER.

The percentage of organic carbon or organic matter stored in a rock depends on: production of organic carbon, transport to the bottom and storage in sediments, and preservation of organic carbon in the sediment and rock. Studies with emphasis on paleoproductivity control on organic carbon deposition have been conducted by Hallam (1967) and Eicher and Diner (1991). Other studies suggest that organic carbon variations within stratigraphic cycles have a diagenetic origin (Ricken, 1986). Studies that attribute changes in organic carbon within stratigraphic cycles as a result of a combination of effects, i.e., variations in sediment supply, paleoproductivity and diagenesis, have been conducted by Arthur and Dean (1991). Oceanic paleoproductivity, differential sedimentation, and the type of sediment, determine the total content and quality of organic carbon stored in a rock.

Oceanic paleoproductivity controls the amount of organic matter that reaches the sea bottom. Northwest South America was located during most of the Cretaceous in a position that favored high productivity and organic matter rain (Villamil, 1995) that reached a maximum during the Santonian with chert-dominated fine-grained, sediment-depleted settings. Santonian-Maastrichtian fine-grained strata are generally highly siliceous shales or pure cherts (e.g., the Olini Group, Plaeners Fm.). The latest Cretaceous Guadalupe Group is composed of medium-to coarse-grained sandstones interbedded with cherts. While sandstones were being deposited in one region of the basin, shallow-water cherts were being deposited in the areas of low sediment supply.



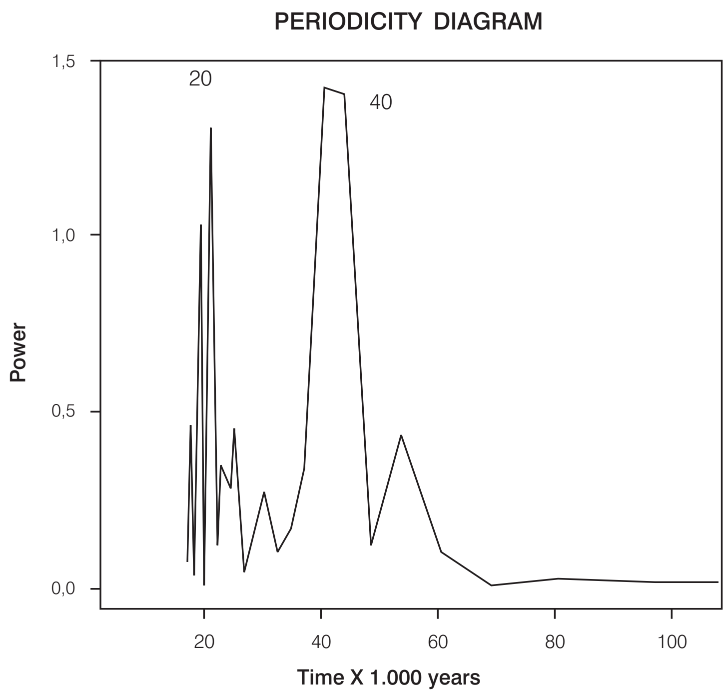


Figure 8. Spectral analyses of two different intervals of the Santonian-Early Campanian Olini Group in the Upper Magdalena Valley. Note strong peaks at 20 and 40 ky.

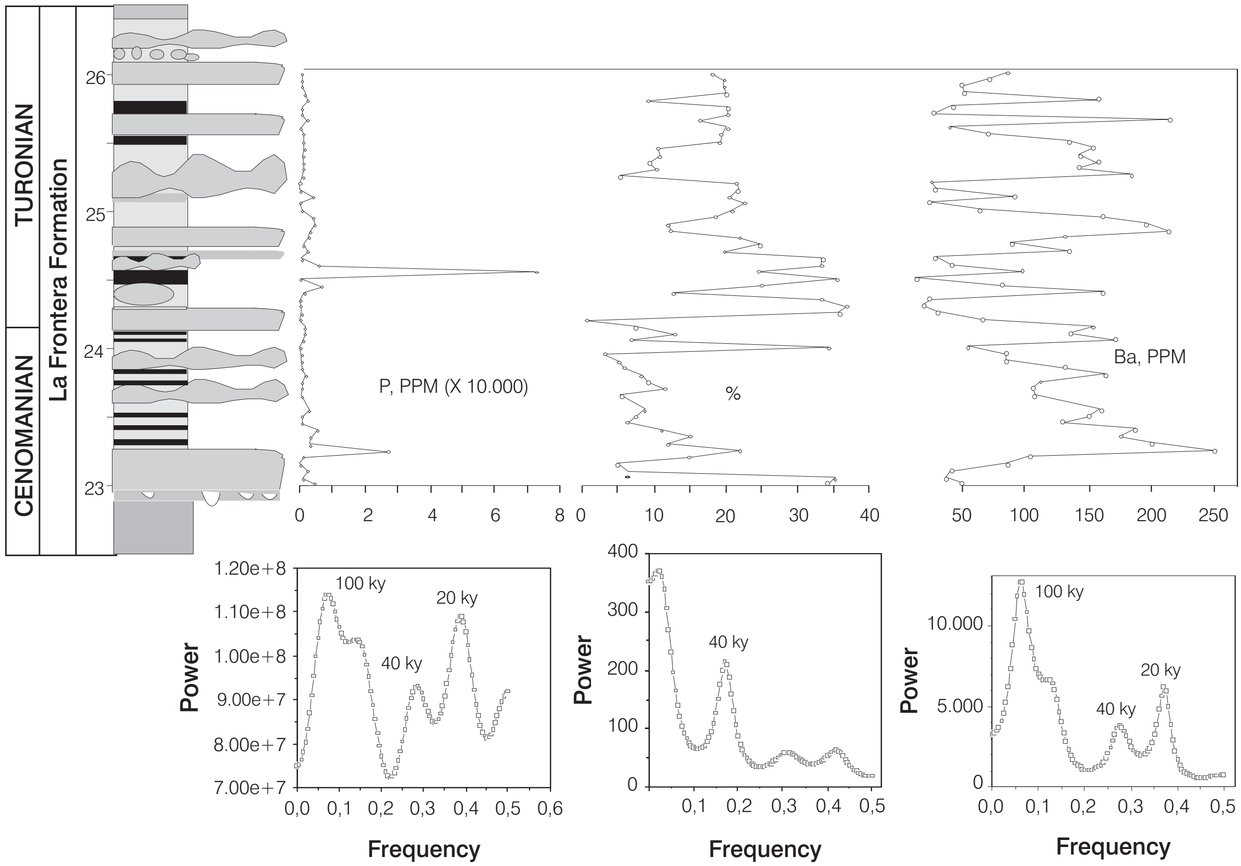


Figure 9. Geochemical data and high-frequency (100, 40, and 20 ky) cyclicity in a phosphorous (a), barium (b) and calcium (c) time series of the La Frontera Formation measured near the town of Yaguará, Upper Magdalena Valley. Strongest peaks in results represent ~20 ky Milankovitch cycles.

Sedimentation rate and the type of sediment that reaches the bottom control the storage of organic matter (Figure 10). Johnson (1982) showed that organic matter in sediments is quite low with very slow rates of deposition because microbes have time to attack and decompose organic matter. As sedimentation rate increases, the content of organic matter increases because time for microbe destruction of organic matter diminishes. This direct relationship holds true until fast sedimentation rate dilutes organic matter (Figure 10). If sedimentation rate determines the thickness of stratigraphic cycles and sedimentation rate controls the amount of organic carbon, then there should be a relationship between cycle thickness, type of cycle and TOC content. In addition to this relationship, oceanic productivity also determines the type of sediment (biogenic) that reaches the bottom, i.e., as productivity increases, populations adapted to higher nutrient contents will replace previous populations.

The combination of these relationships would hypothetically locate the highest organic matter content in distal toes of parasequences where sedimentation rate allows sufficient organic matter to be trapped in the sedimentary matrix (Figure 11). Figure 11 shows an extrapolation of this relationship within a sequence stratigraphic model. Thicker cycles with higher sedimentation rate contain more organic material because a higher sedimentation rate favors trapping and preservation of organic matter. Cycles that are too thick, however, are depleted in TOC because organic matter is diluted within the sediment.

STRATIGRAPHIC RESPONSE TO ORBITAL CYCLES, SUMMARY AND ANALYSIS

Periodic changes of climate due to astronomically controled variations of the distribution of solar radiation over the Earth influence the stratigraphic record

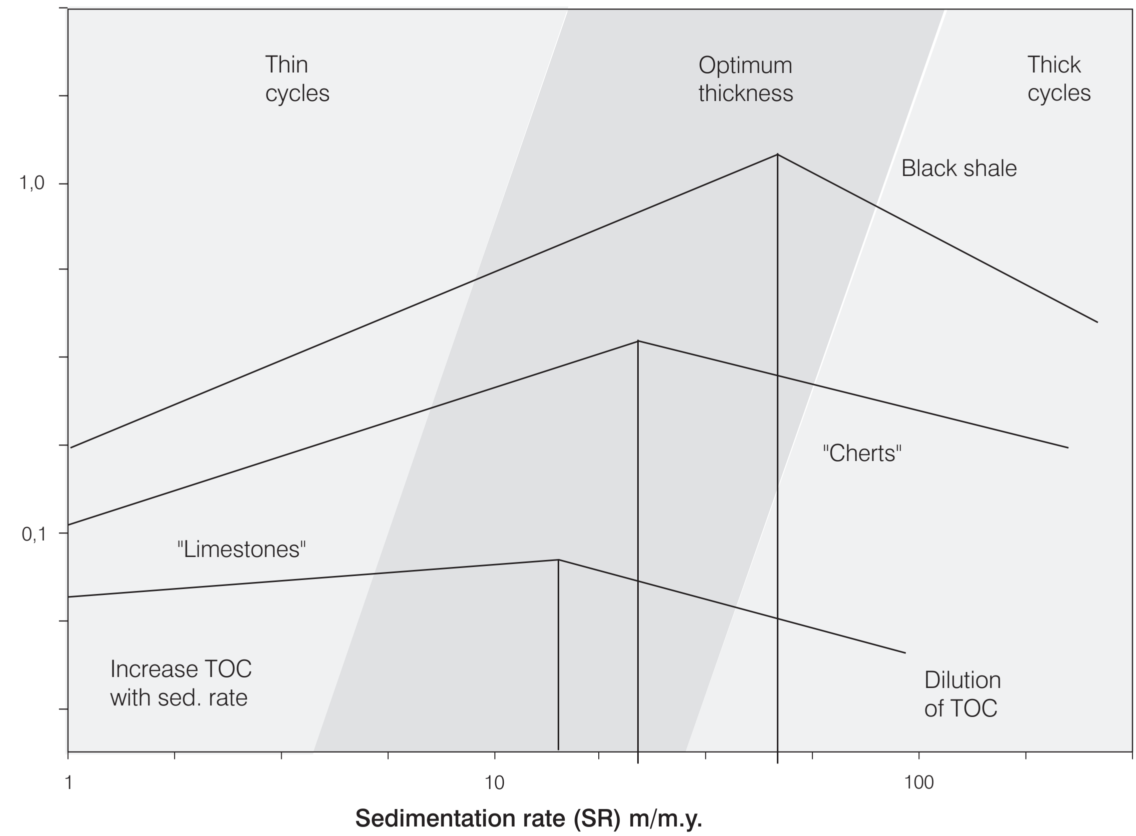


Figure 10. Relationship between sedimentation rate and organic matter content in different types of lithologies and cycle thickness (modified from Johnson, 1982).

through variations of climatic and oceanic circulation systems. This influence controls the distribution of carbonate and organic matter within the rock (De Boer, 1990). Changes in insolation: at low latitudes, the influence of the precession cycle is dominant and causes latitudinal shifts of the caloric Equator (De Boer, 1991). High levels of insolation may produce the following effects: **a)** Increased oceanic and continental evaporation leading to shorter residence time of water masses on land reservoirs and on the surface, and production of relatively dense saline waters in the ocean (Pratt, 1985 and Barron *et al*., 1985). Shorter residence time of water over the continents and in the ground water reservoir may result in changes of precipitation and continental runoff and in a decrease of net water transport to oceanic basins. The stratigraphic response is a decrease in sedimentation rate and a decrease in the distance of sediment transport. **b)** A rise in temperature also causes a double effect on the volume of water masses. On one side, water masses will increase in volume because of the thermal expansion (Eicher and Diner, 1991). On another side, however, water mixing is favored by an increase in circulation, and density may vary with mixing. The stratigraphic response of an increase in water volume would be an increase in accommodation space in the nearshore setting and trapping of sediment shoreward. Thermal expansion produces a positive effect that adds up to a decrease in residence time; both factors combined trap sediments shoreward by creation of accommodation space and decrease the net rate of sediment transport. Therefore the warm-dry portion of the cycle would produce a parasequence boundary in nearshore settings and a portion of the cycle that is low in sediment supply in distal regions.

In addition, differences in insolation may have produced changes in the velocity of water circulation because of different degrees of energy in the ocean-atmosphere system. Increase in water circulation rates resulted in higher paleoproductivity. An increase of accommodation space with lowered sediment supply coupled with an increase in paleoproductivity favors deposition of calcareous- or siliceous-rich hemicycles

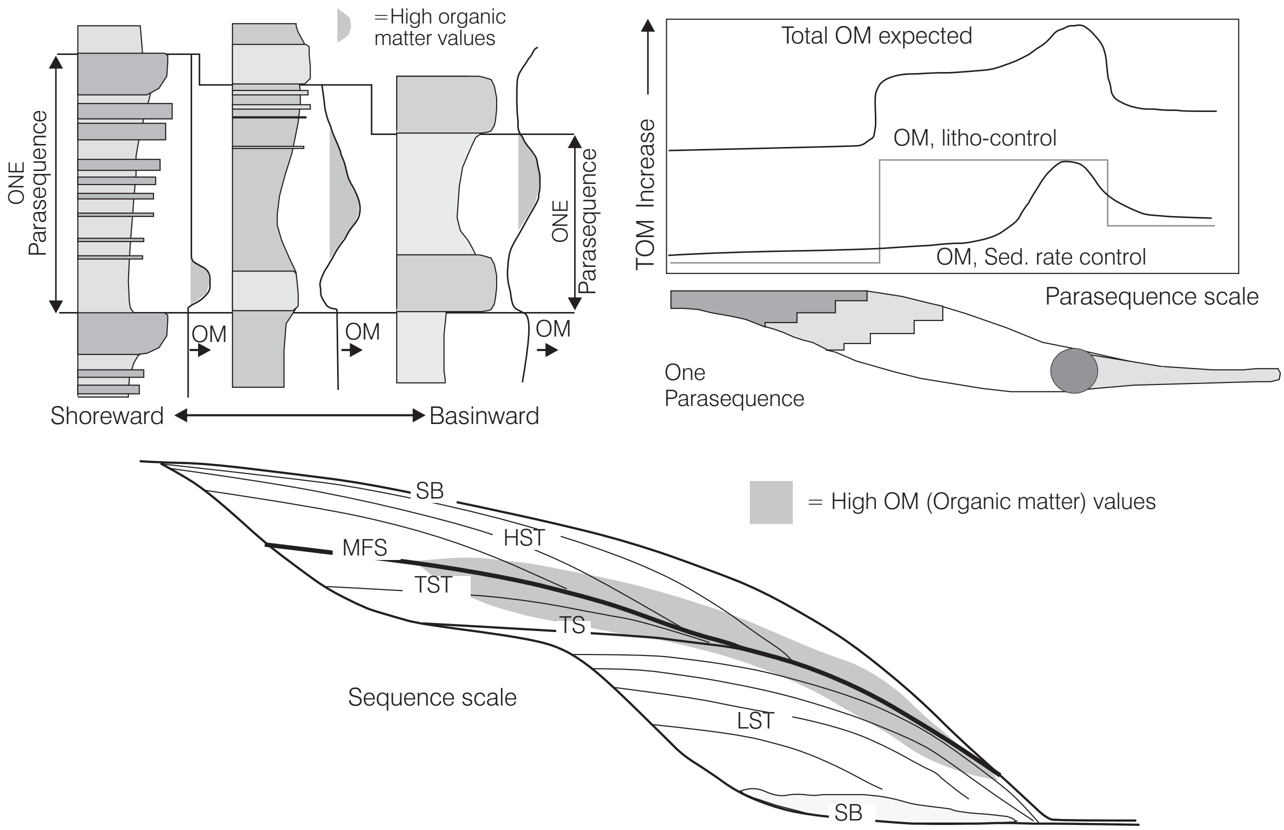


Figure 11. Model that shows the hypothetical distribution of organic matter within one depositional cycle or parasequence. The circle in the parasequence shows the location of highest organic matter content within the parasequence. Simplified model with the location of highest organic matter sites at the sequence scale. Note how organic-rich levels are diachronous their accumulation begins earlier in distal regions and terminates later also in distal regions.

rather than clastic-rich hemicycles. A decrease in insolation favors precipitation and runoff and does not favor vigorous oceanic circulation. The stratigraphic effect observed during low insolation periods is clastic-rich hemicycles.

A completely different set of factors that should also be considered when proposing stratigraphic responses to Milankovitch astronomical cycles are changes in gravitational forces due to different positions of the planets. These changes in gravitation directly and markedly affect tides which, in turn, affect net sediment transport and stability of sediment piles. Tidal differences caused by astronomical cycles of the Milankovitch frequencies have not been studied sufficiently but could probably change current views of the stratigraphic response to orbital cycles.

CONCLUSIONS

- Depositional and geochemical cyclicity in low to high frequencies dominated the Cretaceous distal, fine-grained deposits of Colombia and are in agreement with Milankovitch orbital oscillations. Results presented here, however, do not prove Milankovitch cyclicity because analyses were conducted on the stratigraphic thickness domain rather than in the time domain. Spectral analyses of geochemical and stratigraphic time series do not allow a clear test of paleoproductivity or dilution models. Cretaceous chronology does not allow precise calculations of sedimentation rate to determine whether variations in sedimentation or in paleoproductivity produced observed cyclicity.
- Frequencies of approximately 500, 100, and 40 ky were detected with spectral analyses of geochemical and stratigraphic data. Sedimentation rate, sediment type and paleoproductivity determine the quantity and quality of organic matter preserved in a rock. Because climatic cyclicity controls sedimentation rate and paleoproductivity, it also determines

the position of organic-rich facies within a stratigraphic unit. Very thin and amalgamated cycles are characterized by low sediment supply and therefore may contain low amounts of organic matter. Thicker cycles with higher sedimentation rate contain more TOC, but cycles that are too thick are depleted in TOC because organic matter is diluted within the sediment.

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