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# QUANTITATIVE BIOSTRATIGRAPHIC MODEL FOR THE TERTIARY OF THE LOWER MAGDALENA BASIN, COLOMBIAN CARIBBEAN

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The reinterpretation of biostratigraphic information by new models and quantitative correlation techniques substantially improves its resolution and its correlative potential, thus minimizing oil exploration risks. With this aim, biostratigraphic information, i.e. first (FO) and last (LO) occurrence events of benthonic and planktonic foraminifera was analysed from sixteen wells from the Lower Magdalena Valley (LMV).

The inconsistencies found in the biostratigraphic record, i.e. varying successions of first and last appearances of species from well to well as a result of several factors such incomplete sampling and preservation, true variation in the distribution of fosil taxa, etc., and the great amount of biostratigraphic data makes it practically impossible to accurately constrain basin history from biostratigraphic information by unaided visual inspection. This motivates the treatment of biostratigraphic information with new quantitative approaches, such as constrained optimization (CONOP9 software) and graphic correlation concepts (GraphCor 3,0) and the comparative method approach of Cooper *et al*. (2001).

The succession of biostratigraphic events found through the application of each technique was statistically filtered and compared with Kendall tau coefficients whose values were 0,8. An optimal biostratigraphic succession of LOs was found and calibrated with the Berggren *et al*. (1995) global time scale by a LOESS regression model for the middle Eocene-Pliocene interval, thus revealing three major changes in sediment accumulation rates for the basin during this time interval: (1) middle Eocene to Oligocene, with low accumulation rates, (2) early Miocene to middle Miocene, with high accumulation rates and (3) late Miocene to Pliocene, with lower accumulation rates. The calibrated composite succession enabled the construction of age-well depth plots, which indicate periods of local deposition and accumulation rates, and periods of erosion, no deposition or very low accumulation rates (unconformities). The best plots were used to build a model for the correlation of unconformities, which shows that they are heterochronous, lasted at least 2,5 Ma, and are of limited extent.

Finally, a correlation model was proposed that includes: (1) a time-calibrated succession of biostratigraphic events, and (2) a Haq curve that shows how each geologic period is recorded in each well.

***Keywords:*** *tertiary, quantitative biostratigraphy, graphic correlation, planktonic foraminifera, geology calibration, Cuenca del Valle Inferior del Magdalena.*

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La reinterpretación de la información bioestratigráfica mediante nuevos modelos y técnicas de correlación podría mejorar sustancialmente su resolución y su potencial correlativo y disminuir el riesgo exploratorio. Con este fin, se tomó información de eventos de primeras (FO) y últimas observaciones (LO) de foraminíferos planctónicos y bentónicos en 16 pozos, localizados geográficamente en el Valle Inferior del Magdalena (VIM).

Las inconsistencias halladas en el registro paleontológico (i.e. distintos órdenes de aparición y desaparición de una especie de pozo a pozo) y la gran cantidad de información disponible impiden por simple inspección visual descifrar con alta precisión, la historia bioestratigráfica de una cuenca. Esto motiva el tratamiento de la información bioestratigráfica con nuevas aproximaciones cuantitativas tales como optimización con restricciones (software CONOP9) y correlación gráfica (software GraphCor 3,0) y el desarrollo metodológico de Cooper *et al*. (2001).

La sucesión de eventos bioestratigráficas encontrada mediante la aplicación de cada técnica fue estadísticamente filtrada y comparada con los coeficientes tau de Kendall cuyos valores fueron de 0,8. Se encontró una sucesión biostratigráfica óptima de LOs y se calibró con la escala de tiempo global de Berggren *et al*. (1995) mediante un modelo de regresión LOESS para el intervalo Eoceno medio-Plioceno temprano el cual reveló tres grandes cambios en las tasas de acumulación para la cuenca durante este intervalo: (1) Eoceno medio a Oligoceno, con bajas tasas de acumulación, (2) Mioceno temprano a Mioceno medio, con altas tasas de acumulación y (3) Mioceno tardío a Plioceno, con bajas tasas de acumulación. La sucesión compuesta calibrada permitió construir gráficos edad-profundidad de pozo, que indicaron períodos de depositación local y tasas de acumulación y períodos con muy bajas tasas de acumulación, no depositación o erosión (inconformidades). Los mejores de estos gráficos fueron usados para construir modelos de correlación de inconformidades, los cuales mostraron que estas son heterócronas y con duración de no menos de 2,5 Ma, pero que no afectaron en su totalidad al área de estudio.

Por último, se planteó un modelo de correlación que incluyó: (1) una sucesión de eventos bioestratigráficos calibrada temporalmente, y (2) la curva de Haq que mostró como cada período geológico es registrado en cada pozo.

***Palabras clave:*** *terciario, correlación bioestratigráfica, correlación gráfica, foraminíferos planctónicos, calibración geología, Cuenca del Valle Inferior del Magdalena.*

## INTRODUCTION

Oil exploration in the Colombian Caribbean has been intensified due to the pressing need to increase the countrys's reserves. The application of new concepts for the analysis of geological information has become, therefore, an imperative issue. Furthermore, the knowledge of the Colombian Caribbean offshore geology is still very incomplete.

The study of the fossil content from a quantitative perspective could improve in understand the sedimentary basin history. It could help to built facies maps, depositional rates, recognition of unconformities, rates of evolution and migration of species, evaluation of fossil keys, among others (Edwards, 1991).

The use of biostratigraphic quantitative tools on a great amount of information has been possible with the computer improvement. Different approaches in biostratigraphy quantitative have involved probabilistic, deterministic, multivariate and relational methods and each of them have been automated. RASC, for instance, works by probabilistic and GraphCor and CONOP9 work by deterministic methods. These methods have allowed using intensive statistical and deterministic methods in attempt to resolve biostratigraphic problems.

The results comparison by these methods could help a lot to asses the end results entailing high reliable. Particularly, the valuation of biostratigraphic events like FO and LO is a crucial problem involved in the biostratigraphic schedules. The search of proper methods helping to take the decision about which species have high biostratigraphic value open the road to subsequent statistical analysis and geological interpretation.

Different biostratigraphic schemes have been proposed for the Colombian Caribbean since 1956 (Petters & Sarmiento, 1956; Bürgl, 1961; Duque-Caro, 1968; Stone, 1968; Martínez, 1995; Jaramillo,1999; Rincón *et al*., in prep. Figure 1).

The first section studied at the Lower Magdalena Basin (LMV), is Carmen-Zambrano (Bolivar) whose zonation is based mainly on benthonic foraminifera through the early Oligocene to middle Miocene interval (Petters & Sarmiento, 1956. Figure 1). Bürgl (-in Porta, 1970) extended Petters and Sarmiento's (1956) zonation and compared it with the planktonic zonation of Bolli (1957) from Trinidad. Duque-Caro (1968) does a similar exercise and proposes eight assemblage zones based mainly of planktonic foraminifera spanning the late Cretaceous- to Pliocene interval, whereas Stone (1968) proposes eight planktonic zones for the Oligocene to the middle Miocene. With the application of Bolli's (1957) Caribbean scheme, the Petters and Sarmiento (1956) zonation became younger (Figure 1). Later on, Duque-Caro (1972, 1975) describes the stratigraphy of northern Colombia and recognizes planktonic foraminifera of late Cretaceous to late Miocene age, and two unconformities: pre-middle Miocene and pre-late Miocene (Figure 1). Four provinces are recognized of which two correspond to the Colombian Caribbean; the Northwestern province encompasses the Sinú, Cartagena-Barranquilla and Plato troughs and the San Jorge Basin (Duque-Caro, 1972, 1975). The Northeastern Guajira province includes the Cocinetas, Portete and Chichivacoa Basin. In the San Jorge Basin, eight classic planktonic foraminifera zones and five unconformities: pre-Tertiary, pre-upper Eocene, Oligocene-Miocene, pre-upper Miocene and pre-Pliocene are recognized (Bürgl 1961, 1965; Duque-Caro 1968, 1972; Stone 1968; Porta 1970).

The first quantitative biostratigraphic study for the Colombian Caribbean is due to Martínez, Muñoz, and Vélez (1994) who reviewed and analyzed planktonic foraminiferal information from 23 wells of the Sinú and San Jorge sub-basins. Martínez *et al*. (1994) applied the Graphic Correlation method, manually, thus proposing reworking of fauna in one well and three unconformities: middle middle Miocene-late middle Miocene, late Miocene-early Pliocene and possibly late Oligocene-early early Miocene. Later attempts include: (1) the application of probabilistic techniques on planktonic foraminifera from 18 wells that resulted in a "scaled optimum sequence" and seven biostratigraphic zones from the late (?) Oligocene to the Pliocene (Martínez, 1995) and, (2) the graphic correlation method, that resulted in a "composite sequence" (Jaramillo, 1999). Both approaches provided comparable results in the succession of biostratigraphic events (Jaramillo, 1999).

Recent unpublished Ecopetrol documents report biozonation schemes based on benthonic foraminifera.

Duque-Caro (1994, 2000, 2000a, 2002. Figure 1), defines between 10 and 12 benthonic foraminifera zones for the LMV Basin following the Petters and Sarmiento (1956) and Duque-Caro (1968, 1975) biostratigraphic schemes. For the Guajira area, 10 Oligocene to Pliocene zones, based on benthonic foraminifera and seismics, and seve unconformities are defined (Duque-Caro and Reyes, 1999). Similarly eight tectono-stratigraphic successions based on planktonic zones and well constrained hiatus are proposed (Rubio & Ramírez, 1999). More recently, a biozonation scheme containing 11 planktonic foraminifera zones from Oligocene to Pleistocene age is proposed (Rincon *et al*., in prep. Figure 1).

The stratigraphic position of a species depends on numerous factors making the stratigraphic record highly imperfect. Therefore, an increase of events and wells could dramatically increase the contradiction in the observed succession of species. Factors include sampling design, migration, differential rates of taxon evolution in different places of the world, incomplete preservation, true variation in the distribution the fossils taxa and mixing of sediments among others (Gradstein, Agterberg, Brower., & Schwarzacher, 1985; Cooper *et al*., 2001).

Since the problem becomes multivariate and multidimensional, the possibilities of a successful qualitative correlation with the raw observed data

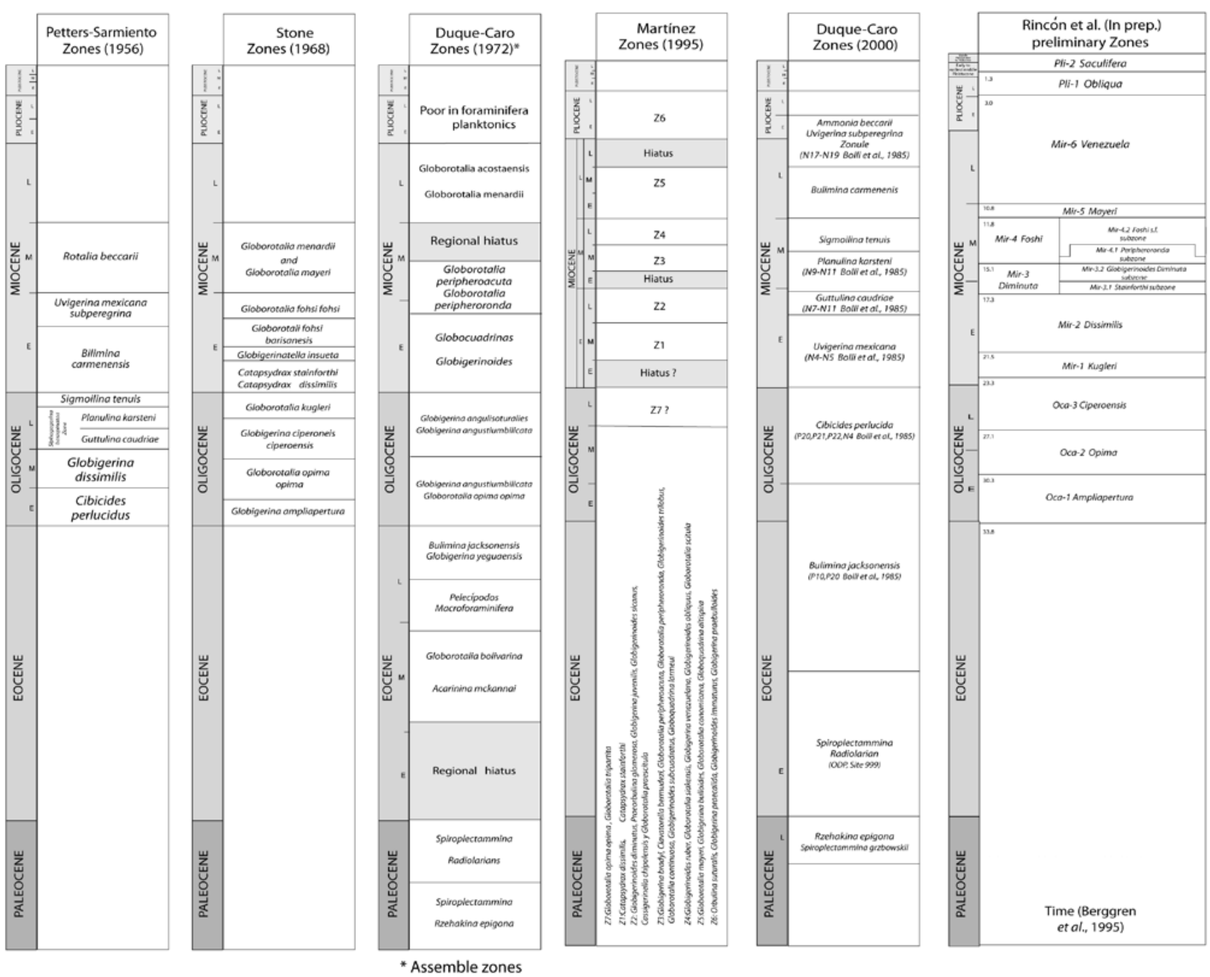


Figure 1. Some micropaleontology zonations proposed for the Lower Magdalena Valley (LMV) Basin

decreases substantially. Geological simplifications are frequently required at the moment of correlation due to the unwieldy amount of data and the impossibility of making sense of this data, by traditional biostratigraphic approaches. A lot of species do not keep the same succession of appearances or disappearances from well to well. Therefore, most of them should be disregarded in the correlation process (Cooper *et al*., 2001). A model that tries to resolve this multivariate and multidimensional problem would considerably increase the bio-chronostratigraphy resolution of the basin by providing the succession of biostratigraphic events for each span of geologic time.

For the Colombian Caribbean, a local bio-chronostratigraphic scheme rather than a global one is needed. A scheme in accord to information and biostratigraphic problems of the LMV. This biostratigraphic scheme should be: (1) a predictive tool, thus reducing uncertainty in oil exploration in a basin mostly covered by Quaternary deposits, and (2) contain a precise assessment of each one of the species. For the Colombian Caribbean, biostratigraphic problems that could be solved by quantitative biostratigraphy have not been addressed.

In this paper we apply and compare quantitative correlation methods on 16 wells from the LVM with fora-

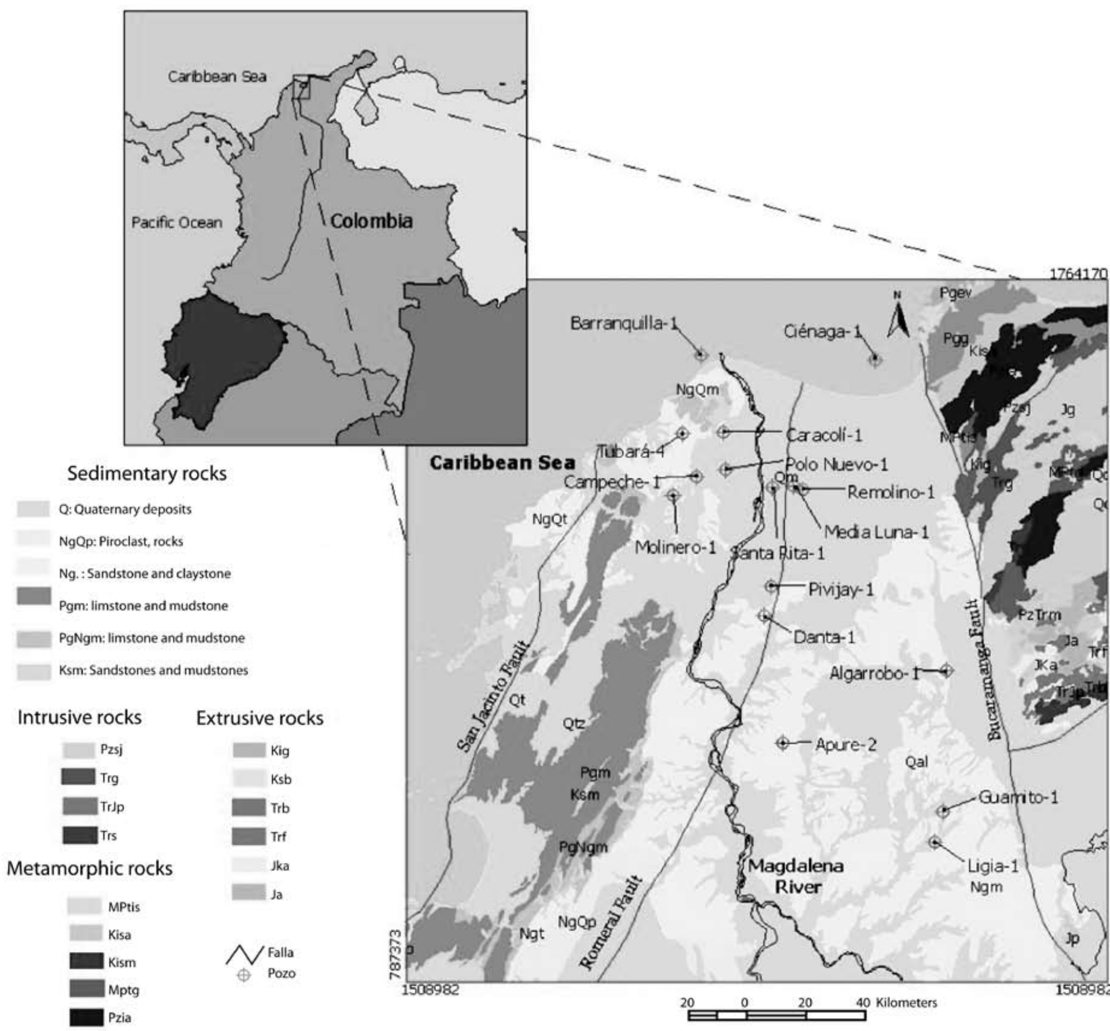


Figure 2. Lower Magdalena Valley: geological context and location of wells (Ingeominas, 1997)

miniferal biostratigraphic information which is assessed previously in order to identify biostratigraphic markers with high quality. Two biostratigraphic tool are applied; CONOP9 and GraphCor 3,0 softwares. CONOP9 software is based on the constrained optimization concepts (Kemple, Sadler & Strauss, 1995; Sadler, 2003), whereas GraphCor 3,0 software is based on graphic correlation principles (Shaw, 1964; Hood, 2001). Comparative studies between both methods have shown similar results. This is the case, for example, for the Riley Formation Texas (Kemple *et al*., 1995), and the Taranaki Basin, New Zealand (Cooper *et al*., 2001).

With this integrated approach, we intend to develop a high-resolution, highly-predictive planktonic foraminiferal biostratigraphic model that would decrease

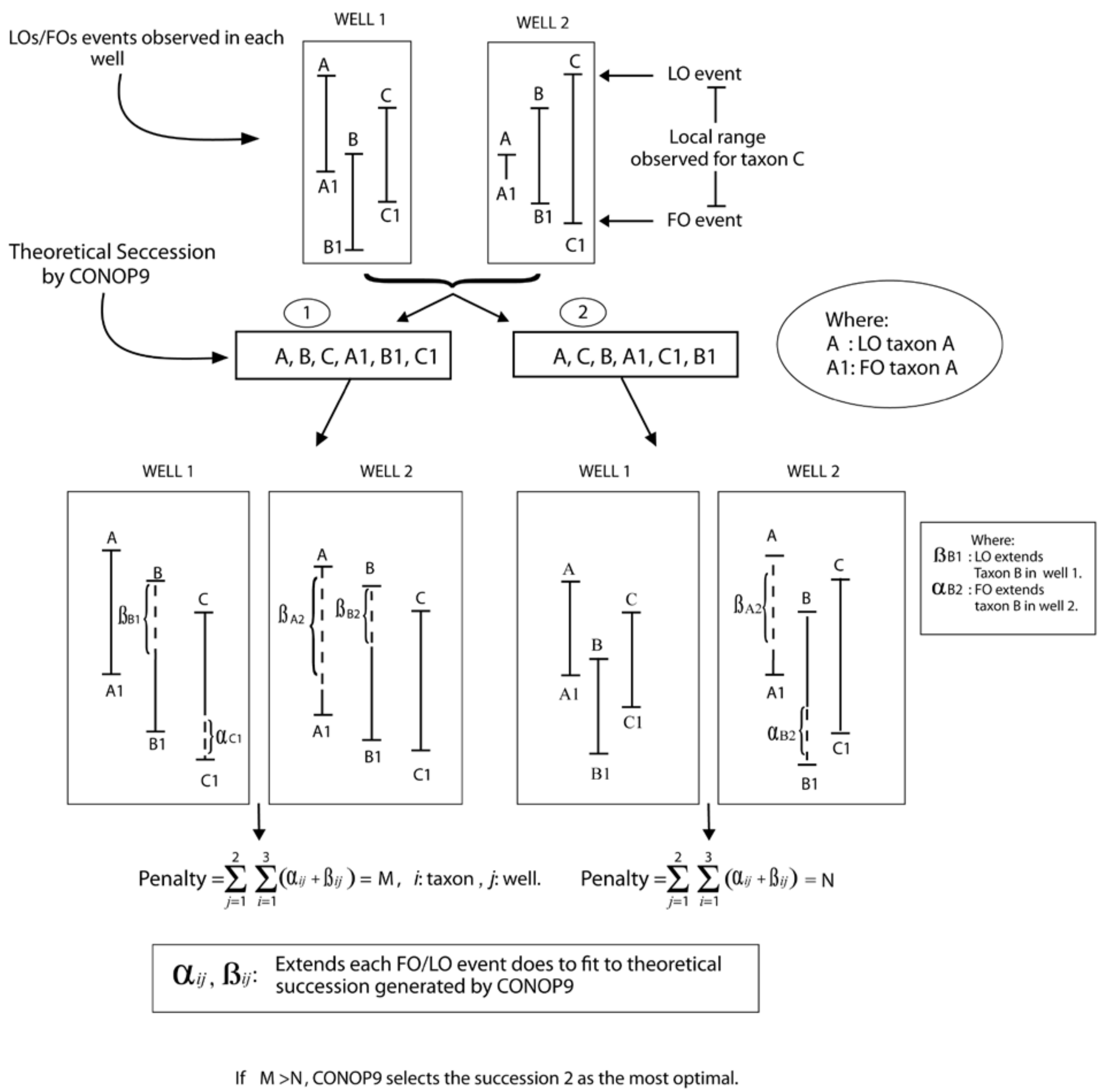


Figure 3. Schematic diagram showing how CONOP9 works for first occurrence (FO) and last occurrence (LO) events. CONOP9 generates random successions and compares them with observed data in each well. CONOP9 selects, after many tests, the succession that produces the lowest total extension of the events in the wells

exploration risks. In addition, we intent to built a time-calibrated biostratigraphic correlation model that incorporate the maximum number of biostratigraphic events, particularly those of high biostratigraphic value. This model assists, in a precisely reproducible way, to accurately define the geological history of the basin.

## METHODS

The first (FO) and last (LO) occurrence events of planktonic and benthonic foraminifera of the wells Barranquilla-1, Ciénaga-1, Tubará-4, Caracolí-1, Polo Nuevo-1, Santa Rita-1, Remolino-1 y Pivijay-1, Campeche-1, Molinero-1, Media Luna-1, Danta-1, Algarrobo-1, Apure-2, Guamito-1 and Ligia-1 were compiled (Figure 2). The original biostratigraphy of these wells is due to Duque-Caro (1994, 2000a, 2001a, 2001b, 2002).

CONOP9 works by constrained optimization to find one or more feasible optimal global solutions for the sequence of FO and LO events (Kemple et al., 1995).

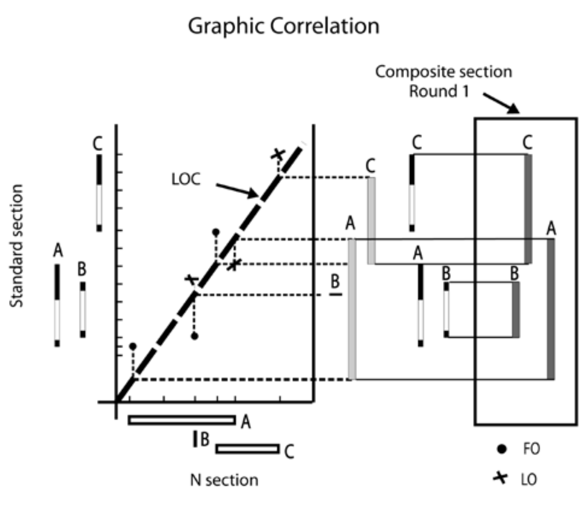


Figure 4. Building process of a Composite Sequence of events by Graphic Correlation. The first step combines a reference section (axis Y) with a comparison section (axis X) through line of correlation (LOC). From this combination a more complete composite sequence of events is built on axis Y. The new result is combined with another comparison section. After all sections have been added, the results due to one section are removed and a second round of correlation is undertaken. These rounds are repeated until the LOC stabilizes. FO: first observation data. LO: Last observation data

This is achieved comparing all the observed events in each well with a randomly generated succession model. From is initial guess, the optimal model is generated by trial and error using series of random mutations, The optimal solutions can be field data with the minimum net adjustment of the locally observed FOs and LOs (Figure 3). For a given model sequence of events, the distance between local-observed and model range end events is measured. The total sum of these distances (total penalty, cost or misfit) is tallied and used to evaluate the fitness of each mutation in the trial and error process (Figure 3).

The mathematical formulation shows the parameter involved in the constrained optimization process (Kemple *et al*., 1995, modified for wells) (*Equation 1*, Figure 3):

$$\text{minimize } T = \sum_i \sum_j \left[ |\alpha_{ij} - a_{ij}| + |b_{ij} - \beta_{ij}| \right] \quad \forall \text{ taxon } i \text{ and well } j \tag{1}$$

Constrained to:

$$\alpha_{ij} - a_{ij} \geq 0,\ b_{ij} - \beta_{ij} \geq 0,\ \alpha_{ij} - \beta_{ij} \geq 0$$

Where $\alpha_{ij}$ and $\beta_{ij}$ are parameters founded for each mutation, and $a_{ij}$ and $b_{ij}$ are the FO and LO, respectively, of taxon $i$ in the well $j$. For each mutation, $\alpha_{ij}$ and $\beta_{ij}$ are founded and $T$ calculated. The optimal solution is that one who made $T$ minimum. It means the model sequence optimal produced the extents ranges are minimal and this is the best solution. The *Equation 1* becomes more complex if other considerations are taken into account. For instance, if LO event has more biostratigraphic value than FO event. The constrained restricts the process and avoids results without sense. More details could be see in Kemple *et al*. (1995).

In the Graphic Correlation method (Shaw, 1964), a composite section of events is built on a X-Y graph where FO and LO events from successive wells are compared. At the beginning, the best and most complete stratigraphic section is selected as a standard that will be compared with another section by means of a line of correlation (LOC). This partial composite section is combined with successive sections and submitted to a number of different rounds of combinations until biostratigraphic ranges are not more extended, i.e. when they reach their maximum extent and the LOC is stable (Edwards, 1984. Figure 4). The choice of the best stratigraphic section (or well) depends on the interval of sampling, the abundance and the quality of the biostratigraphic record and the span of geological time (Carney & Pierce, 1995).

The "Manual" method is a subjective method. It consists on a visual analysis of the sequence of fossil events within a well and across wells in order to establish a sequence of events of "key fossils" that do not overlap each other across wells. It is the traditional method to establish zonation entailing deletions of species in wrong order regarding to zonal schedules previously established.

Using CONOP9, a best-fit composite succession of events was found, and the merits of the FO and LO events for correlation were assessed. The assessment was based on the magnitude of the standardized misfit ($Z$) for each event and averaged ($Z$) by the number of wells where each event is present (Cooper *et al*., 2001). The range of $Z$ was statistically explored and rating limits defined in order to filter the species with high biostratigraphic value. It was assumed that events with higher penalization added more to the measure of misfit and thus, reflected greater inconsistencies when compared to the theoretical succession. In general, those groups of events whose $Z$ are low were assumed to bear higher biostratigraphic values.

CONOP9 offers several different measures of misfit. Because the "Level" measure favores local successions with a better stratigraphic resolution and higher fossil content (Cooper *et al*., 2001), and assuming that within the study area facies with different sediment accumulation rates occur (Sadler, 2003), the standardization of misfit values for each FO and LO event was done with the Level option using the following Equations:

$$Z_{ik} = \frac{V_{ik} - M_j}{S_j}, \qquad (2)$$

$i$ = 1, 2, 3, …, m species,

$j$= 1, 2, 3,…, n wells,

$k$: LO or FO event

$$\overline{Z} = \sum_{1}^{l} \frac{Z_{ik}}{l}, \; l \leq n \qquad (3)$$

Where $V_{ik}$ is the level penalty value for species "$i$" and event "$k$" FO or LO, $M_j$ is the mean penalty value for well "$j$", $S_j$ is the penalization standard deviation for the well $j$, and $l$ the number of wells where the event was observed.

Simultaneously, an exploratory assessment was made on the quality of each well including variables such as stratigraphic resolution, time range, depth, and microfossil content, in order to define a reference well. A succession of composite events was built upon the reference well by GraphCor 3,0. For each well combination a line of correlation (LOC) was drawn as to fit most FOs and LOs events, specially those from planktonic foraminifera species with better biostratigraphic values as found in a previous test (for details see Cuartas, 2006). Kendalls'tau coefficient was used to compared the successions of events found by CONOP9, by GraphCor 3,0, and by "Manual" graphic correlation, i.e. the "Manual" succession by Rincón *et al*. (in prep).

Time calibration of the CONOP9 optimal succession was done on LO events of planktonic foraminifera whose biostratigraphic values were high. Because planktonic taxa are better suited than benthonic foraminifera for regional biostratigraphic schemes (e.g. Bolli *et al*., 1989), the resulting succession of the best foraminifera planktonic events, i.e. those with the lowest misfit, was compared, mainly, with the Berggren, Kent, Swisher, and Aubry, (1995) chronostratigraphic scheme. The time-calibration of the biostratigraphic succession was performed with a LOESS regression model in the R 2.1.0 software (*R Development Core Team*, 2005). LOESS is a non-parametric local-regression statistical method, therefore, it does not make assumptions on the relationship among the involved variables, i.e. succession and time (Cooper *et al*., 2001). LOESS fits the data through small local fits, resulting in a smoothed curve (Neter, Kutner, Nachtsheim, & Wassweman, 1990). The LOESS model allows prediction of a relative sea-level curve for the LMV that is comparable to the Haq, Hardenbol, and Vail (1987) global standard. We used the Berggren *et al*. (1995) global chronostratigraphic review to time calibrate our curve with the Haq *et al*. (1987) curve, hoping to explore the relation between eustatic fluctuations and the dynamics of the depositional systems of the LMV.

Age-depth plots were made for each well in order to determine sediment accumulation rates and possible unconformities of regional extent (Cooper *et al*., 2001). Additionally, a biostratigraphic correlation model was suggested using the ages predicted by the LOESS model.

## RESULTS

### CONOP9 and GraphCor 3,0 runs

Through the application of constrained optimization (CONOP9) and economy of fit (GraphCor 3,0) concepts we obtained the following results.

### GraphCor 3,0 run

*GraphCor* 3,0 run was done using only species found in three or more wells, excluding those whose FO events occurred at the same level as their LO events, and those with open nomenclature, i.e. sp., spp. and cf. A composite biostratigraphic succession was obtained after the third round of correlation, i.e. when biostratigraphic ranges stabilized. Difficulties were found when drawing some LOCs owing to the great spread of data. Some correlation points group on the top right of the X-Y graph making it difficult to trace the LOC and hindering the stratigraphic arrangement of events. The obtained GraphCor 3,0 biostratigraphic succession was compared with the CONOP9 biostratigraphic succession, though the succession events by GraphCor 3,0 were not assessed as we did with CONOP9.

### CONOP9 run

A CONOP9 biostratigraphic succession was obtained and compared with GraphCor 3,0 and the "Manual" successions (Rincón *et al*. in prep.), and then statistically filtered. *Z* for FO events were divided in three regions according to changes in the spread of data and general changes in the concavity of the density curve (Figure 5). Region one is limited to *Z* between -0,84 and 0,42 and includes ~72,5% of the data, of which ~70% are benthonic foraminifera and the remaining ~30% are planktonic foraminifera. Region two is limited between 0,42

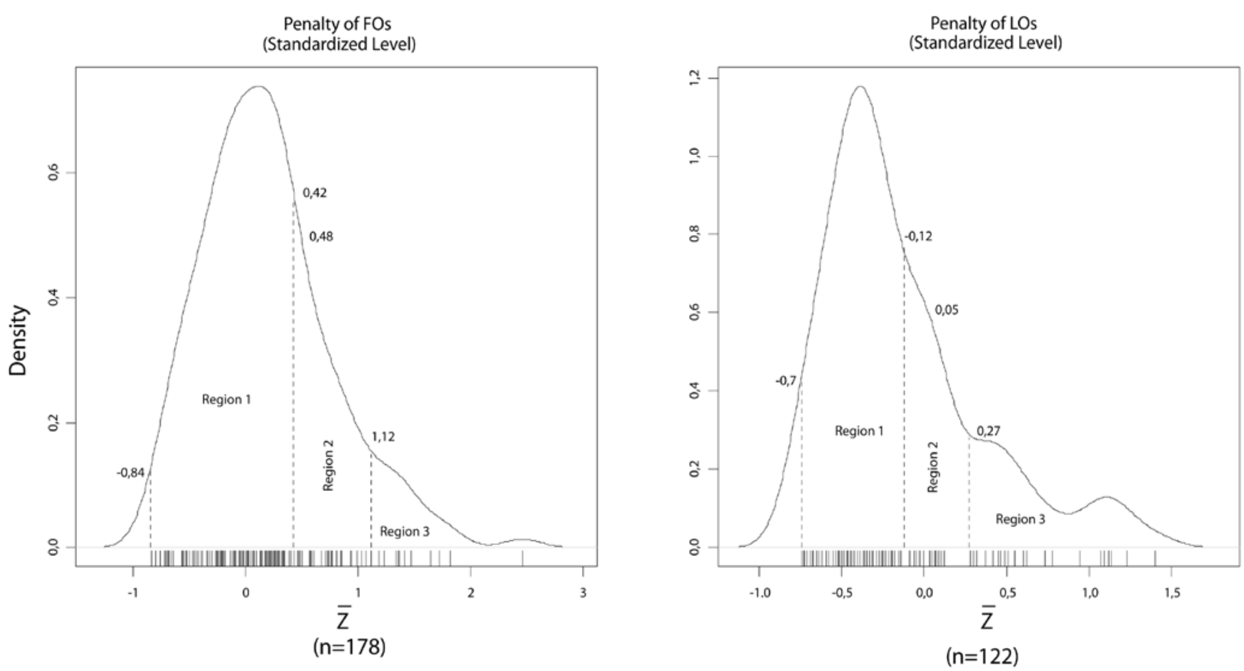


Figure 5. Density graph for "Level" penalty standardized and averaged ($\bar{z}$) for first and last occurrence (LO) events from 16 wells. They were divided in three regions according to changes in the spreading of data and the concavity of the curve. On both, the third quartile (0,48 y 0,05) appears as the most suitable discriminatory measure. The density plots left and right are smoothed versions of the respective histograms. The bandwidth used in R software was of 0,16

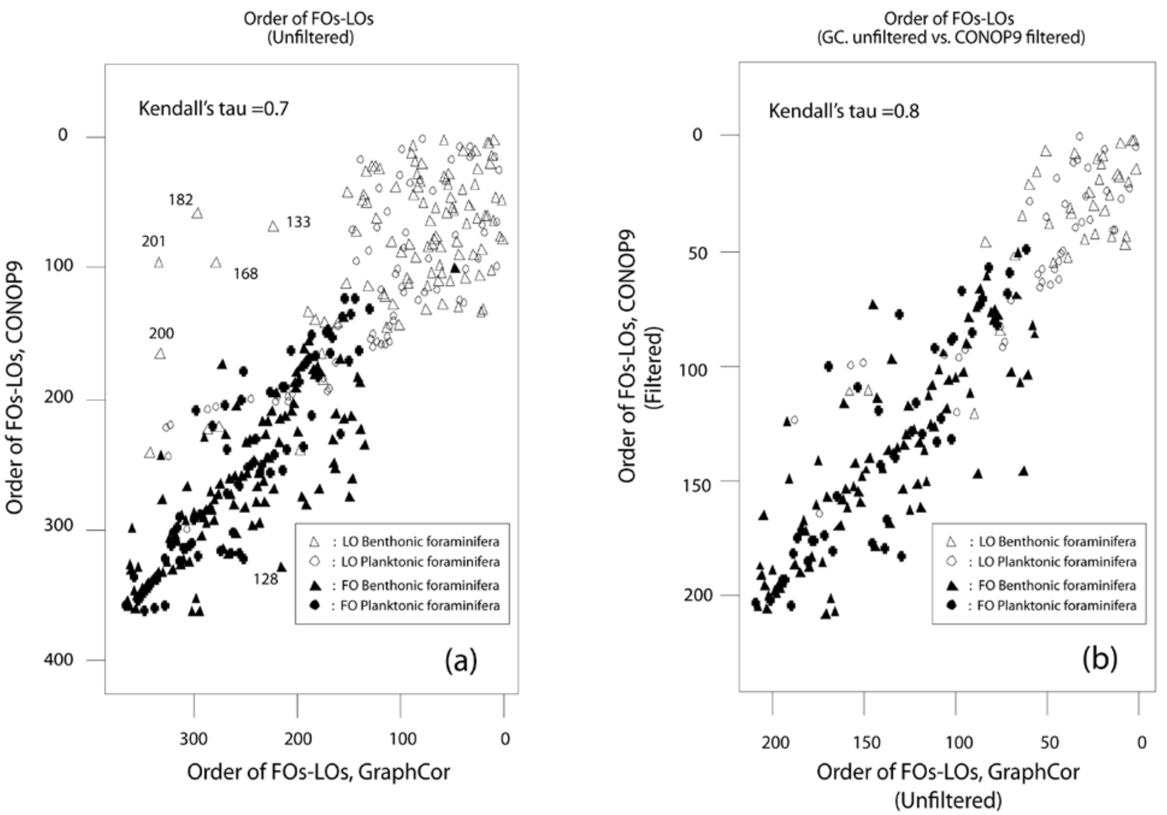


Figure 6. Cross plots between order of first (FO) and last (LO) occurrence biostratigraphic events found by GraphCor 3,0 y CONOP9. (a) Comparison between unfiltered FO and LO biostratigraphic events. (b) Comparison between order of FOs and LOs events of high-value (filtered) and the order of the same events obtained by GraphCor 3,0 sequence unfiltered. Note data spreading on the upper right hand is lower than that on the upper left hand. The number codes on (a) represent species affect the Kendall's tau coefficient

and 1,12, includes ~21% of the data, of which ~68% are benthonic foraminifera and the remaining ~32% are planktonic foraminifera. Finally, region three is limited between 1,12 and 2,46, with the remaining 6,5% of the data that consists of benthonic foraminifera exclusively.

FO events show a greater spread from the third quartile (0,48), located near the upper limit of Region one. Therefore, the third quartile is accepted as the filter limit to those events with a greater biostratigraphic value (Table 1). Events above this limit were excluded because they added higher misfit with the optimal succession.

Similarly, $Z$ values for LO events were divided in three regions (Figure 5). Region one is limited between -0,7 and -0,12 and includes ~ 65% of the data, of which 53% and 47% are benthonic and planktonic foraminifera, respectively. Region two is limited between -0,12 and 0,27, encompasses ~20% of the data, of which 83% and 17% consists of benthonic and planktonic foraminifera, respectively. Region three, between 0,27 and 1,4 consists of the remaining 15% represented by benthonic (~74%) and planktonic (26%) foraminifera.

From the third quartile (0,05), in the density graph for LO events (Figure 5), it becomes evident from which $Z$ values show a higher spreading. This occurs near to upper limit of Region one. From this value, biostratigraphic events were excluded from the optimal succession and from the graphic correlation process; whereas those accepted were assumed to be of higher biostratigraphic value (Table 1).

**Comparison of CONOP9, graphcor 3,0 and "manual" successions**

The biostratigraphic successions generated by CONOP9 and GraphCor 3,0 were compared with one another and with the "Manual" biostratigraphic succession (Rincon *et al*., in prep.). For unfiltered FO and LO events, CONOP9 and GraphCor 3,0 biostratigraphic successions are relatively highly correlated as shown by a Kendall's Tau value of ~0,7 (Figure 6). Data located towards the upper right-hand side of Figure 6 are highly spread and associated to LO events of benthonic and planktonic foraminifera. Furthermore, some benthonic foraminifera LO events occur away from the general trend of the data thus reducing the concordance, i.e. *Uvigerina proboscidea* (182), *Ammodiscus incertus* (133), *Uvigerina subproboscidea* (201), *Eponides visksburgensi* (168) and *Cibicidoides mexicana* (200). The concordance coefficient changes from 0,7 to 0,8 when the best CONOP9 and GraphCor 3,0 biostratigraphic successions of events are compared (Figure 6). In this way, a considerable decrease in the spread of values on the upper right-hand side of the graph is achieved, but not in the middle of the graph where spread persists, mainly in response and corresponds to the location of benthonic foraminifera (Figure 6).

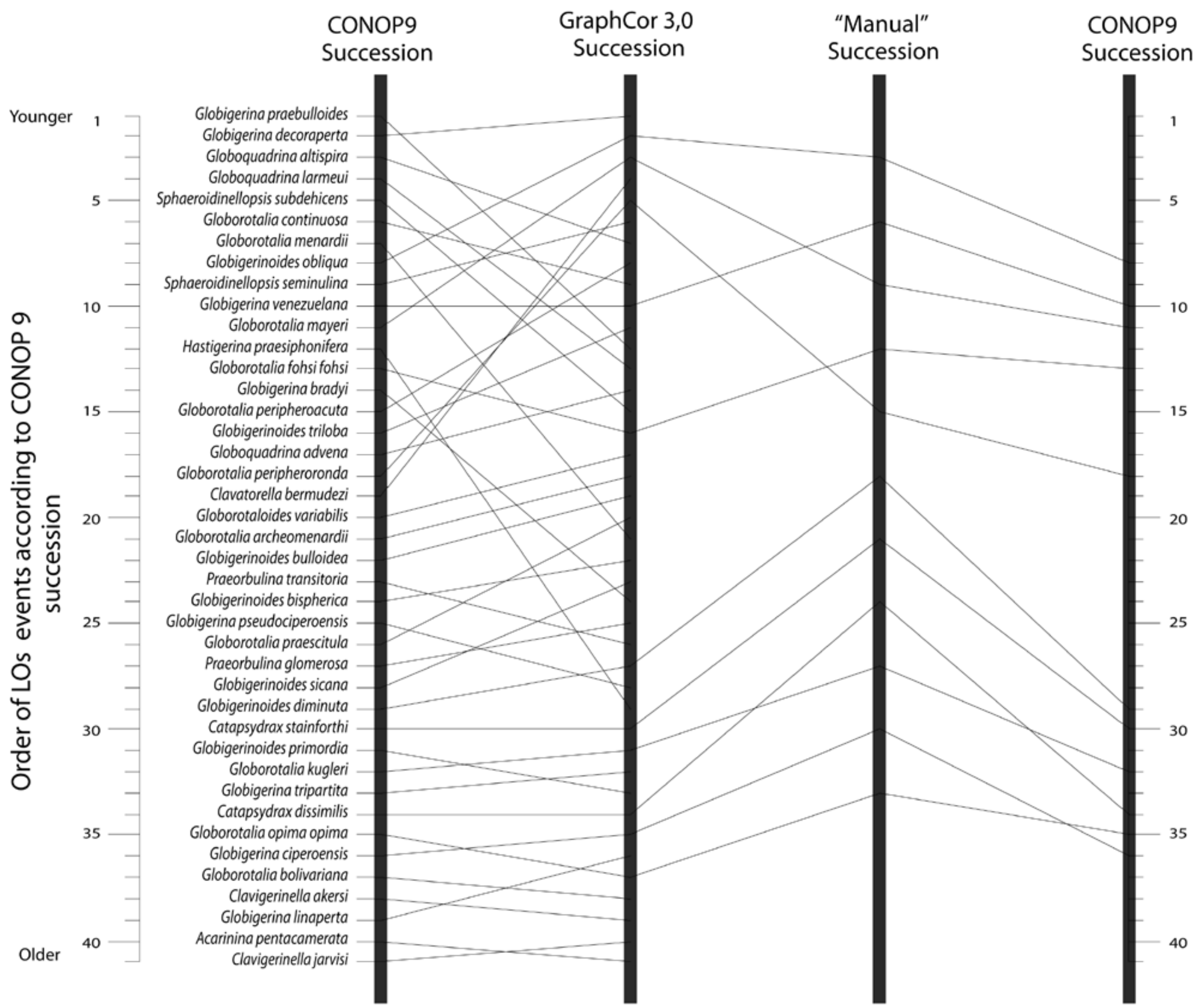


Figure 7. Comparison between CONOP9 and GraphCor 3,0 biostratigraphic successions and the "Manual" sequence of LO events of planktic foraminifera with high biostratigraphic value. Events are listed according to CONOP9 biostratigraphic succession. The "Manual" sequence (Rincón *et al*. in prep.) is defined with a lower number of LO events than those in CONOP9 and GraphCor 3,0. Note a better correspondence between the "Manual" and CONOP9 biostratigraphic successions

Graphic comparison between the CONOP9 and GraphCor 3,0 LO biostratigraphic successions for planktonic foraminifera with high biostratigraphic values show a better concordance than those taxa with a lower value (Figure 7). For instance, CONOP9 and GraphCor 3,0 resulted in 7 and 21, and 38 and 39 values for *Globorotalia menardii* and *Clavigerinella akersi*, respectively. Biostratigraphic events with the strongest influence on the decrease of the concordance are the LO events of *Globigerina praebulloides, Sphaeroidinellopsis subdehiscens, Hastigerina praesiphonifera, Globigerina bradyi, Globorotalia peripheroronda* and *Clavatorella bermudezi* because they show more contradictions in the succession of events generated by CONOP9 and GraphCor 3,0 (Figure 7).

The "Manual" succession was established on the ranges of planktonic foraminifera in 49 wells, 16 of which are located in the LMV and the rest in the Guajira Province, east of the Sierra Nevada de Santa Marta. This succession contains 11 zones and four subzones that range from the Oligocene to the Pleistocene, and correspond majority to the Berggren *et al*. (1995) zonation scheme for the same time interval (Rincon *et al*., en prep). In our comparison, *Turborotalia ampliapertura* and *Globigerinoides sacculifera* are excluded because of their absence in the data analyzed (Figure 7).

The agreement between the succession of events, when comparing GraphCor 3,0 and the "Manual" successions is affected by: (1) disagreements between *Globorotalia (Paragloborotalia) mayeri* and *Globorotalia (Fohsella) peripheroronda* with *Globigerina venezuelana* and *Globorotalia (Fohsella) fohsi fohsi* in the upper part and (2) disagreements between *Globorotalia (Paragloborotalia) kugleri* and *Catapsidrax dissimilis* in the lower (Figure 7). The CONOP9 and "Manual" successions show no evidence of contradictions in their higher parts. This is not the case for the lower part where several "event lines" cross each other, as is the case between *Globorotalia kugleri* and *Catapsidrax dissimilis*, and between *Globorotalia (Paragloborotalia) opima opima* and *Globigerina ciperoensis* (Figure 7). In summary: there is a larger agreement between biostratigraphic successions when CONOP9 and the "Manual" successions are compared. Conversely, the agreement is smaller when the "Manual" succession and GraphCor 3,0 are compared.

## EXPERIMENTAL TIME-CALIBRATION OF THE COMPOSITE SUCCESSION OF THE LMV AND THE GLOBAL RELATIVE SEA-LEVEL CURVE

The CONOP9 composite biostratigraphic succession was calibrated against the global time scale of Berggren *et al*. (1995) by LOESS regression, using and the R 2.1.0 software (*R Development Core Team*, 2005) set to a "span" parameter of 0,6 and based upon the ages of some last appearance data (LAD) of planktonic foraminifera from the western Caribbean (e.g. Berggren *et al*., 1995; Pearson, & Chaisson, 1997; Chaisson, & D´Hondt, 2000; Stewart, and Pearson, 2000). Similarly, the eustatic variations from Haq *et al*.'s (1987) sea-level curve, also calibrated against Bergreen *et al*.'s (1995) time scale, were evaluated with LOESS regression model for the LMV (Figure 8).

The mean response curve suggests three major changes in sediment accumulation rates for the LMV Basin between the middle Eocene to the Pliocene (Figure 8). From the middle Eocene to the late Oligocene, low accumulation rates are indicated, except for the later Oligocene when they apparently increased. From the early to the middle Miocene, sediment accumulation rates were extremely low, or deposition was absent and even erosion periods occurred during most of the early Miocene to increase, then considerably by the end of the middle Miocene. A third interval, the late Miocene to the Pliocene, is suggested, when sediment accumulation rates first conspicuously decreased during the late Miocene to finally increase during the Pliocene.

Correlation with Haq *et al*.'s (1987) eustatic curve, in chronologic units ( Berggren *et al*., 1995), predicts three major relative sea-level fluctuations (Figure 8). According to this model, relative sea-level variations during the middle Eocene to the Pliocene suggest a steady drop, except for some major episodic rises. The first one, from middle Eocene to early Miocene (Aquitanian), shows high values followed by a conspicuous fall towards the late early Miocene (Aquitanian). The second one, early Miocene (Burdigalian) to middle Miocene (Serravallian), suggests that sea-level rose again though by a lower amount than during the Eocene to Oligocene interval. By the end of the middle Miocene the highest drop in relative sea-level in the basin occurred. Two major drops in sea-level, during the Langhian and the Langhian/Serranvallian boundary, are conspicuous during the middle Miocene. A third change started in the middle to late Miocene boundary, when relative sea-level was the lowest recorded, followed by marked fluctuations that were, however, smaller than those from previous periods (Figure 8).

## Sediment accumulation rates and unconformities

The composite time-calibrated succession of biostratigraphic events was plotted against the level at which CONOP9 located them in the optimization process. In this way, age-depth well graphs were drawn in order to estimate quantitatively those intervals with either, very low sediment accumulation rates, no accumulation or erosion surfaces, i.e. unconformities (Chaisson *et al*., 1997; Cooper *et al*., 2001).

Sedimentation rate results are in accord with the calibration process as defined in the previous section. For most of the wells, high sediment-accumulation rates were recorded for the early Miocene to Pliocene interval. They appear as steep lines disrupted by parallel lines to the time-axis (Figure 9). Those apparent unconformities located at the top and base of the wells represented by (*), were discarded owing to edge effects. The edge wells, i.e. bottom and top wells, could show unreliable apparitions and extinctions of taxas

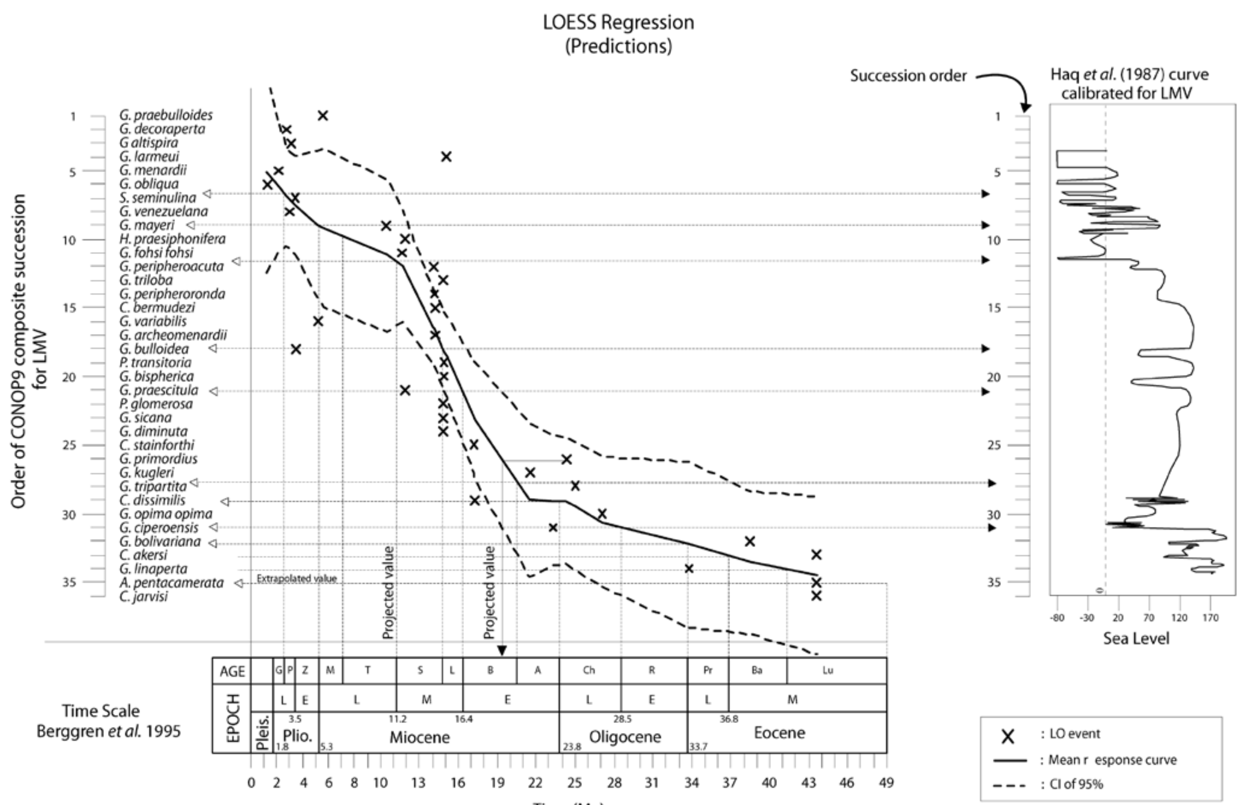


Figure 8. Time-calibration of the CONOP9 biostratigraphic succession of LO events of planktonic foraminifera from the LMV Basin when compared to Berggren *et al*. (1995) global chronostratigraphic review and Haq *et al*. (1987) relative sea-level curve. Similarly Berggren *et al*. (1995) ages are projected on the Composite CONOP9 biostratigraphic succession for the correlation model. The mean response curve reveals changes in the accumulation rates for the LMV Basin. Three major changes in the sedimentation rates are recorded: (1) Eocene-Oligocene, (2) Early Miocene to middle Miocene and, (3) Late Miocene to Pliocene. Steeper slopes on the curve mean high sedimentation rates. Note the changes on each interval. Haq *et al*. (1987) relative sea-level curve suggests three major eustatic changes and minor fluctuations within. Note the steady decrease in sea-level from the middle Eocene to the Pliocene. CI: confidence bands

(edge effects). Probably, much of them go across the well but we could found different geological periods in the same level and the unconformities interpretation become more difficult. This is the case of the Tubará-4, Santa Rita-1, Remolino-1, Polo Nuevo-1, Campeche-1 and Molinero-1 wells, where, besides, sampling intervals and stratigraphic resolution were quite low to take reliable decisions (Figure 9). The (?) sign was applied to unconformities between the middle Eocene to the early-Miocene which likely were of shorter duration (Figure 9). This uncertainty resulted from the regression model for the Eocene to Oligocene interval where the number of time-calibrated species was low and, therefore, the confidence intervals were wider than for other points of the model. Those wells with a better sampling coverage and stratigraphic resolution reflect the depositional history of the LMV Basin with a higher precision. This is the case of the Media Luna-1, Guamito-1 and Ligia-1 well and, in a lesser degree, the Pivijay-1, Polo Nuevo-1, Cienaga-1, Barranquilla-1, Caracoli-1, Algarrobo-1 and Danta-1 wells (Figure 9).

The age-depth well plot for the Barranquilla-1 well suggests the presence of three possible unconformities. The first one, spanning the middle Eocene to about the middle Miocene, would represent a missing record of ~26 my, though it could be as short as ~7 my. as discussed above. The second one, spanning from around the middle middle Miocene to the late middle Miocene, would represent a missing record of ~4 my. Finally the last one, spanning from the late late Miocene to around the Pliocene would represent a missing record of ~5 my (Figure 9). Sediment accumulation rates were high, at least where deposition was clearly recorded, as evidenced by the steep slopes

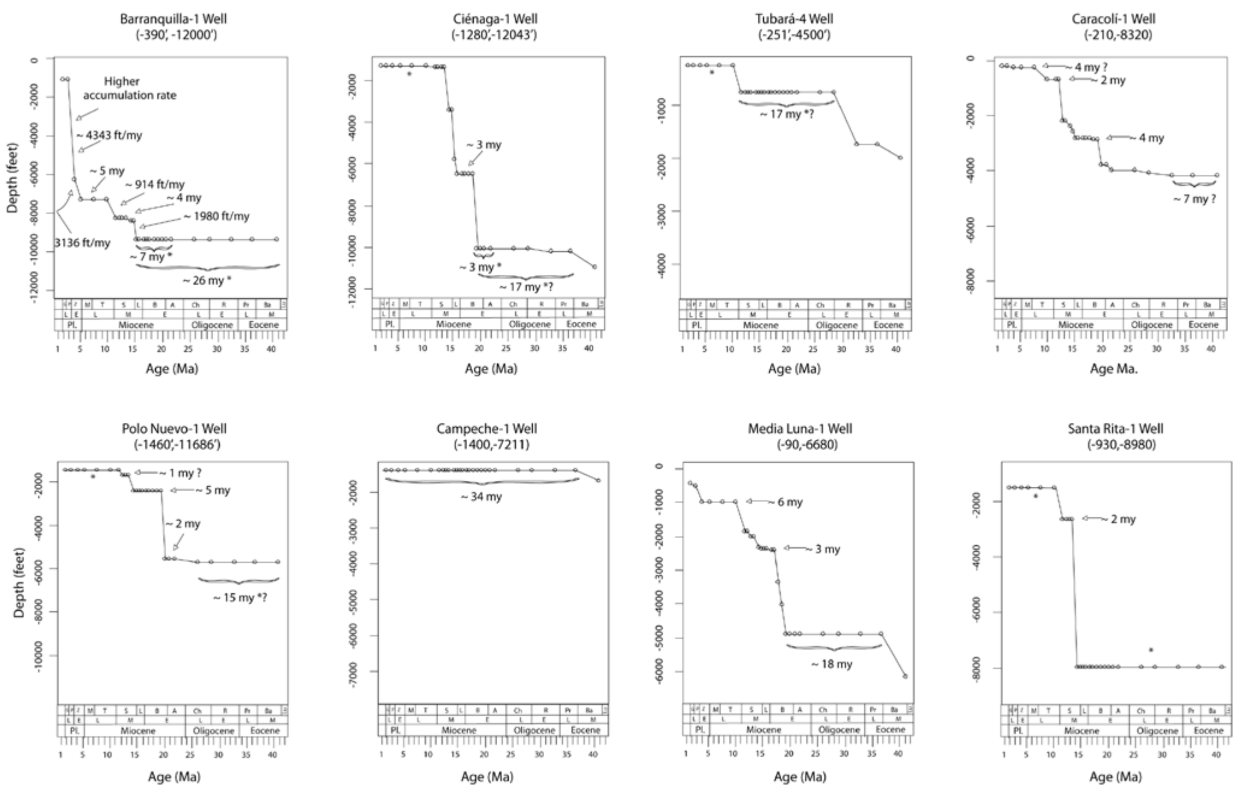


Figure 9. Age- Well Depth plots for 8 wells from the LMV. The Time axis corresponds to the composite biostratigraphic succession of events calibrated for the LMV Basin, whereas the depth axis corresponds to those levels where CONOP9 located each event during the optimization process. Lines with steeper slopes mean high sediment accumulation rate periods. The horizontal lines mean periods with quite low sediment accumulation rates, no accumulation or unconformities. Note that sedimentation accumulation rates are high for the Miocene and low for the Eocene-Oligocene. *=Geological events rejected by edge effect. ?= uncertain ages

of the age-depth well plots. However, it was during early Pliocene to late late Pliocene period, when most sediments were deposited with sediment accumulation rates of ~4342 feet/ my (~ 1303 m/my). This suggests that during the last ~1,2 my, 5210 feet, equivalent to 43% of the total thickness, would have accumulated. Sediment accumulation rates would have decreased to 3136 feet/my,914 feet/my and to 1980 feet/my for the remaining intervals (Figure 9). Figure 9 also shows sediment accumulation rates and unconformities for other wells. Slopes suggest an analogous behavior to those calculated for the Barranquilla-1 well: sediment accumulation rates that oscillated between ~ 914 y 4342 feet/ my. Age-depth well plots for the middle Eocene to early Miocene interval suggest very low sediment accumulation rates, no deposition, or erosion periods for most wells. In some of them, where middle Eocene to Oligocene taxa were not recorded in the data bases, CONOP9 results evidenced the presence of these periods. This is due to the capacity of CONOP9 to predict the stratigraphic position of species. However, and according to observed field data from the 16 wells, 10 recorded middle Eocene to Oligocene ages, and 4 began at the early Miocene. As pointed out above, for intervals whose temporal extent is uncertain, there are two possibilities: (1) that the whole interval is involved and unconformities range from ~34 to ~17 my and, (2) that unconformities range from 3 my to 7 my. Nevertheless, some wells, like Media Luna-1, and Algarrobo-1, suggest changes in the accumulation rates toward the middle Eocene -late Eocene (Figure 9).

A correlation model for unconformities for the LMV was obtained using the wells with the best biostratigraphic resolution (Figure 10). Ages-depth well plots were geographically ordered from north to south, reversing the axes. This allowed incorporation of information from Figure 9. Uncertainties on the existence of middle Eocene to early Miocene unconformities remain. We suspect that a long period of slow deposition, no-deposition, or, erosion affected most of the basin, ending at around the early Miocene when sediment accumulation rates dramatically changed.

Figure 10 suggests the continuous presence of heterochronous unconformities all through the geographic area and history of the LMV. For instance, according to our model, during the early Miocene (~Aquitanian-Burdingalian) a large area of the basin was affected by a regional unconformity as recorded in most of the wells, but was apparently of a longer duration in the Algarrobo-1, Apure-2, and Pivijay-1 wells. Likewise, the model suggests an early to middle Miocene (~ Burdigalian\Langhian boundary) unconformity, that would have affected the basin as evidenced in the Barranquilla-1, Caracoli-1, Media Luna-1, Danta-1, Apure-2 and Guamito-1 wells. This unconformity likely is related to a major drop in sea level (compare Figures 8 and 10).

**Biostratigraphic correlation of 16 wells in the LMV Basin**

The time-calibrated composite biostratigraphic succession was used as a correlation model for 16 wells from the LMV Basin. The correlation graph was built by joining corresponding LO event levels after missing events had been inserted and observed ranges extended in each well by the minimum amounts required to match the optimal sequence. The biostratigraphic correlation model shows the way chronostratigraphic units were recorded in the LMV (Figure 11). This figure hints that some time intervals were relatively well represented in the stratigraphic record of the basin; the middle and later Eocene (?), the late early Miocene (Burdingalian), late middle Miocene (Serravallian) and, maybe, the Pliocene.

The Langhian (middle Miocene) is less well represented in the basin, but is in general thicker north and south of it. By contrast, the Ruperlian (early Oligocene) is apparently most restricted to the north of the LMV while the Chatian and Aquitanian (Oligocene\Miocene bound) is most restricted to the south. It means that those were locally recorded in the basin.

To sum up, Figure 11 suggests that rock-time thickness increases southward, except during the Pliocene. This is the case for the Barranquilla-1 well located in the north.

## DISCUSSION

The comparison between GraphCor 3,0 and CONOP9 biostratigraphic successions of filtered LO

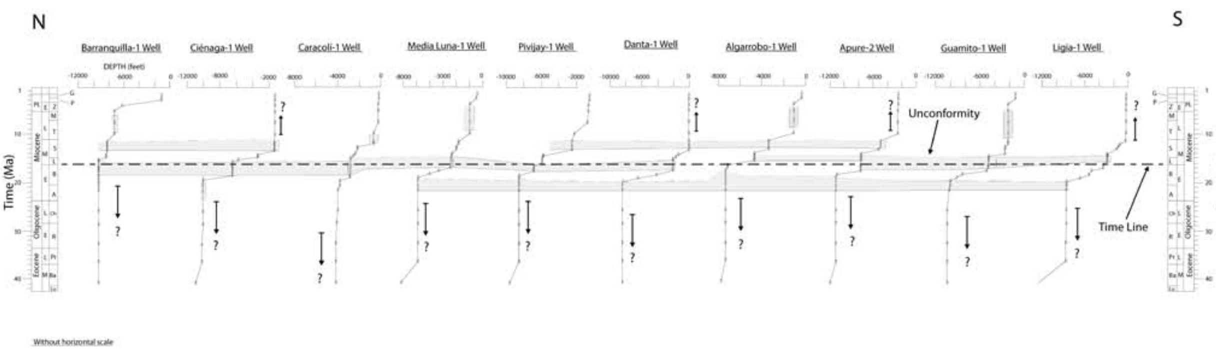


Figure 10. Correlation of unconformities from Age-Well Depth plots. Age corresponds to the calibrated composite biostratigraphic succession of events for the LMV. Well Depth corresponds to those levels where CONOP9 located each event during the optimization process. The Lines with steep slopes mean high sediment accumulation rate periods. Horizontal lines indicate very low sedimentation rates, no accumulation, or erosion (unconformities). Note the heterochronous unconformities. The arrow: uncertain ages

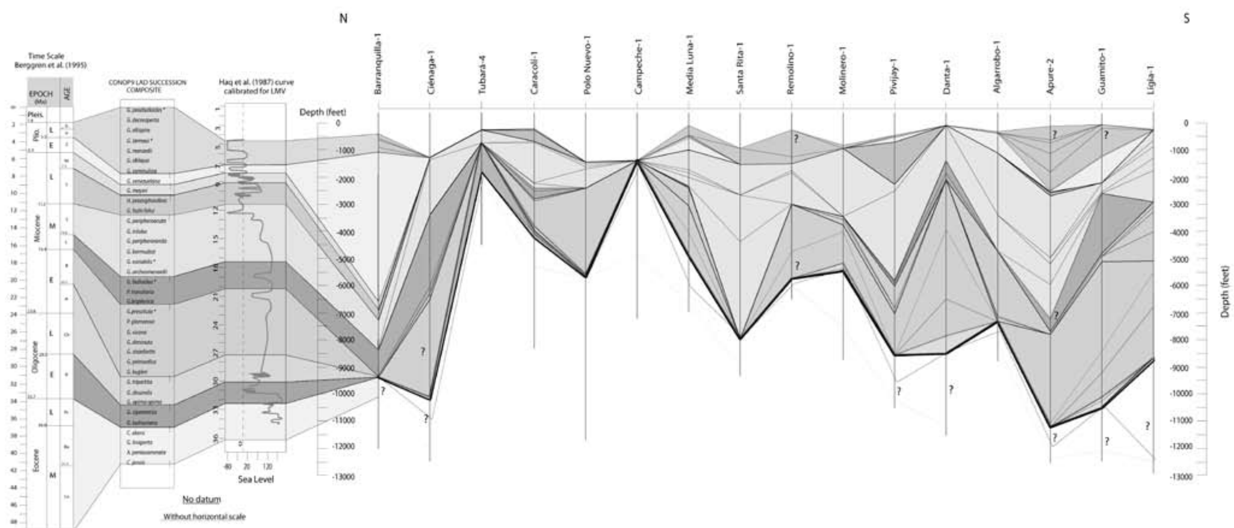


Figure 11. Correlation model for 16 wells of LMV Basin. Whole events are located by CONOP9 in whole wells, according to constrained optimization process and to the predictions CONOP9 does. Note the continuity and the thickness of each rock-time unit throughout the basin. Note besides that wells located southward record thicker rock-time units than those in the north. Wells whose lines of correlation are closed could represent unconformities. Graph built without a datum. ?: Uncertain zones

events for the LMV, shows slightly less agreement than the previous experiment of this kind. For the Taranaki Basin (New Zeland), where the Kendall's tau is 0,92 (Cooper *et al*., 2001) compared to 0,8 for the LMV (Figure 6). The major disagreement in the biostratigraphic successions found by *GraphCor* 3,0 and CONOP9 for the LMV is, perhaps, related to operational differences between the two methods. While CONOP9 orders and spaces biostratigraphic events in separate steps, *GraphCor* 3,0 does both task simultaneously (Kemple *et al*., 1995). It means that the biostratigraphic succession determined by *GraphCor* 3,0 is more influenced by different sediment accumulation rates. Although both methods are deterministic, there are several difference between them. For instance, while GraphCor 3,0 requires a standard section CONOP does not. GraphCor 3,0 works section by section whereas CONOP9 is fully automated. While GraphCor 3,0 builds a composite by interpolation of missing events in successive section by section plots via the LOC, CONOP9 uses intensive mechanism of search to find the best multidimensional line of correlation and composites sequence (Cooper *et al*., 2001). Owing to GraphCor 3,0 is partially automated and the composite sequence is built section by section, in some case the biostratigraphic problems, like facies control, could be more clearly understood but when the data increased it is hard to keep in mind all of them.

When analyzing the differences found between the “Manual” and CONOP9 biostratigraphic successions it is important to bear in mind three aspects equally applicable to Graphcor 3,0. The first one concerns to the numbers of wells used by both methods. For the “Manual” succession we used 57 wells compared to 16 wells used in CONOP9. In the “Manual” succession, 33 (~58%) of the wells are located in the Guajira Province east of the LMV. It appears evident that the incorporation of more wells and events with CONOP9 would result in a more reliable biostratigraphic succession of events and a better fit with the “Manual” method (Cooper *et al*., 2001). The second aspect concerns the observed data, or the “Manual”

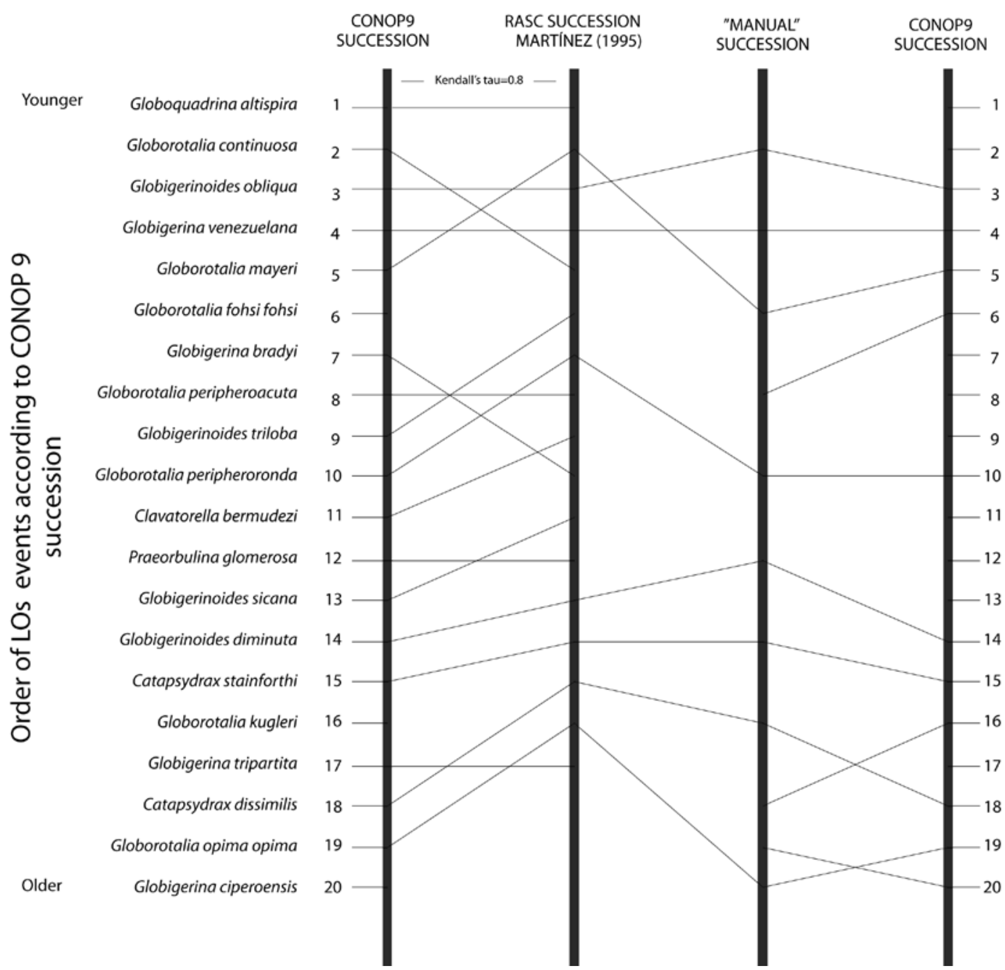


Figure 12. Comparison between the CONOP9, RASC (Martinez, 1995), and the “Manual” LO biostratigraphic succession of planktonic foraminifera with high biostratigraphic value. Events are listed according to CONOP9. Note how CONOP9 and RASC biostratigraphic events cross each other, particularly on species close in the succession

succession (Rincón *et al*. in prep.), that is in accord with previous biostratigraphic schemes and the *Ocean Drilling Program* (ODP) (Stone, 1968, Berggren *et al*., 1995, Pearson *et al*., 1997, & Chaisson *et al*., 2000). It means, for example, that *Catapsidrax dissimilis* LAD should occur above *Globorotalia kugleri* LAD. However, the *C. dissimilis* LAD, in CONOP9, not only occurs below the *G. kugleri* LAD, but also below the LADs of *Globigerinoides primordius* and *Globigerina tripartita*, thus contradicting Bolli *et al*. (1988) biostratigraphic scheme. Accepting as true the biostratigraphic succession of LADs of: *G. tripartita, G. kugleri, G. primordius* and *C. dissimilis*, and assuming that the first three events behave as "one LAD event" and favoring it over *C. dissimilis* in those wells where all they are in the same level, like conventional biostratigraphy does, we conclude that in four of five wells where the species were observed, *C. dissimilis* occurs in a lower position making CONOP9 results consistent. A different situation was observed between *Globorotalia opima opima* and *Globigerina ciperoensis* LADs. The numbers of wells where they succeeded each other was equal and, there were no species in between them that could help to resolve the uncertainty in their stratigraphic position.

Alternatively, the disagreement between the "Manual" and CONOP9 succession could be the result of two scenarios: sedimentary reworking or tectonic processes. The former process apparently is common the Danta-1 well where the LO of *C. dissimilis* occurs well under of *G. kugleri*. However, the co-currence of *G. kugleri* with *Globigerina tripartita* and *Globigerinoides primordius* is more consistent than the one with *C. dissimilis* LO at the base of the well. With regard to the tectonic scenario, the LOESS regression model suggests drastic changes in the depositional history of the LMV Basin that could be related to tectonics events which might have caused the inversion of the succession (Figure 8).

Martínez (1995) applied the RASC (*Ranking and Scaling*) tool of probabilistic correlation, in 18 wells of the LMV, five of which are common to this study; Caracolí-1, Media Luna-1, Apure-2, Guamito-1 and Ligia-1. Thirty- one species comprise the RASC biostratigraphic succession, 21 of which are common to those found herein. The comparison shows some discrepancies between the three methods: CONOP9, RASC and "Manual" (Figure 12). The disagreement between the "Manual" and the RASC methods is evident in the upper part of the succession, mainly with the LO of *Globorotalia mayeri*. The absence of *Globorotalia fohsi fohsi* is conspicuous from the middle part of the succession and that of *G. kugleri* and *Globigerina ciperoensis* from the lower part. This is likely due to the higher number of wells that RASC demands, i.e. species common to at least 6 wells (Figure 12).

Despite the high number of different wells used in CONOP9 and RASC studies, the results are satisfactory because the Kendall's tau for the successions found by both methods was 0,8 (Figure 12). By standardizing the run parameters for CONOP9 and RASC and using the same wells, the Kendall's tau would probably increase.

The precision of the time-calibration of the CONOP9 biostratigraphic succession depends on the quality of the absolute ages obtained. Calibrations of planktonic foraminifera, or another biostratigraphic group, against absolute ages are not available for the LMV or any sedimentary basin of Colombia with marine environments. For this reason, approximately half of the calibrated ages used here were obtained from secondary sources (Steward & Pearson, 2000). The best ages used in our model come from ODP Core 999, from the Colombia Basin in the Caribbean. This leaves our model susceptible to significant improvement when new data are collected and incorporated.

It appears evident that the calibration of the biostratigraphic succession contributes to a better understanding of the depositional history of the basin and the correlation of unconformities (Figure 10). However, interpretations at the extremes of the model time interval require of a more careful analysis because of data limitations.

Predictions of Haq *et al*.'s (1987) relative sea-level curve, when time-calibrated on the Berggren et al. (1997) global chronostratigraphic model, were made on the LOESS mean response-curve regression. The curve calibrated in this way for the LMV, if correct, would show sediment accumulation rates in relation to changes in global fluctuations of sea level (Figure 8). However, Haq *et al*.'s (1987) relative sea-level curve has been questioned as a global sea-level template, on the basis of: (1) the lack of original data on which the curve was built in Haq's publications, and (2) the postulate that changes in sediment accumulation rates are exclusively due to sea level fluctuations (Miall, 1992, 1997). Despite this questioning, Haq *et al*.'s (1987) relative sea-level curve is still widely used (Wood, 2000; Jarvis, Mabrouk, Moody, & Cabrera, 2002). During the last 100 Ma sea level changes have been tested and several of many of them match in number and timing but no in amplitude with those of Exxon Production Research (Haq *et al*.,1987; Miller *et al*., 2005). Accepting the uncertainties in the Haq *et al*. (1987) global curve, changes in the regression model do suggest relative sea-level changes in the LMV Basin. Sea level tends to decrease from the Oligocene to the Pliocene which is in accord to ODP Core 627, located in Bahamas (Melillo, 1988). Both the relative sea-level curve and microfaunal content are similar in ODP Core 627 and the LMV. It is from the *G. fohsi* group upwards where a conspicuous decrease in relative sea-level began, just where regional sediment accumulation rates in the model change (Figure 8).

Changes in the global sea level are owing to changes in the volume of the water in the ocean or the volume of the ocean basins (Miller *et al*., 2005). During Phanerozoic links between the sea level changes and the ice volume have been showed (Miller *et al*., 2005). The Figure 8 suggests that the first big fall of the sea level in the basin was during approximately the early Oligocene-late Oligocene boundary close to the first formation of large Antartic ice sheets (Eocene-Oligocece boundary). For the middle Miocene have been registered two ice-growth events in the Antarctica (Miller *et al*., 2005) and it could be reflected in the Figure 8 where just in the earliest Middle Miocene the sea level shows two falls. Besides, for this time changes of deep facies to sallower facies are reported owing to the beginning of the Andean orogeny (Reyes, Montenegro, & Gómez 2004). However, the main fall of the sea level in the LMV is proposed here during the Medium Miocene-Late Miocene boundary, where Miller *et al*. (2005) sea level curve show a fall later to relatively big peak. Additionally, tectonic phenomena related to uplift of the Isthmus of Panamá could be related to this fall since it is initiated just later 14,8-12,8 Ma (Coates, Collins, Aubry M-P., & Berggren, 2004).

During the Pliocene- Pleistocene the basin sea level shows big and quick changes (Figure 8). During this interval large ice sheets are formed in the Northern hemisphere (Miller *et al*., 2005) and during which the Andean orogeny has the highest pulse (Reyes *et al*., 2004).

An early attempt to build a paleobathymetric curve is due to Petters and Sarmiento (1956). They studied assemblages of benthonic foraminifera in the Carmen-Zambrano section, located west of our study area. Complementary to this study, Stone (1968) recognizes the *G. fohsi fohsi* planktonic zone, above the Peters and Sarmiento (1956) *Guttulina caudriae/Planulina karsteni* subzone, when apparently there was a dramatic sea-level decreasing.

The time location of unconformities, in our study, is similar in some places to those proposed by Duque-Caro (1990) and Martínez (1995). However, our results suggest that hiatuses are heterochronous, at least within the middle Eocene to Pliocene interval (Figure 10). Duque-Caro (1990), identifies four unconformities for the Colombian Caribbean: early middle Miocene, middle Miocene, late Miocene and early Pliocene, correlated to hiatus recorded globally (Keller and Barron, 1983; Keller 1986). According to this comparison, the minimum mean duration of unconformities was ~1 Ma. This contrasts with our estimate that the minimum mean duration is ~2.5 Ma.

## CONCLUSIONS

From the application of the quantitative biostratigraphic methods, CONOP9 and GraphCor 3,0, for the correlation of 16 exploratory wells from the LMV Basin, it is concluded that:

- The biostratigraphic model proposed herein is compatible with some conventional models but according to methodological development it could improve the biostratigraphic resolution.

- The LMV was affected by regional geological events during the middle Eocene (?) to Pliocene interval that acted differentially.

- At least during the middle Eocene (?) to Pliocene interval, the LMV Basin was affected by a continuous retreat of the sea, excepting for some episodic incursions.
- Regional unconformities are of heterochronous character across the basin.
- Our model suggests that the minimum mean duration of unconformities was ~2,5 Ma
- The third quartile of net misfit values suggested as a suitable filter for excluding biostratigraphic events from the sequencing model.
- The correspondence between the CONOP9 and GraphCor 3,0 biostratigraphic successions is high (Kendall's tau values of ~ 0,8).
- CONOP9 performs better than GrahCor 3,0 in the sequencing of biostratigraphic events.

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