Eocene-Pliocene planktonic foraminifera biostratigraphy from the continental margin of the southwest Caribbean

Daniel A. Rincón1, José E. Arenas1, Carlos H. Cuartas2, Andrés L. Cárdenas3, Carlos E. Molinare1,2, Claudia Caicedo1 and Carlos Jaramillo3

1Biostratigraphy Team, Colombian Petroleum Institute, ICP-ECOPETROL, km.7 via Piedecuesta, Santander, Colombia
2Departamento de Geología¹, Universidad EAFIT, Carrera 49 No. 7sur-50, Medellín, Colombia
3Smithsonian Tropical Research Institute, Apartado Postal 0843-03092, Balboa, Ancon, Panama

email: daniel.rincon.martinez@awi.de; drincon@eafit.edu.co

ABSTRACT: Biostratigraphy in northern Colombia has traditionally been done using foraminifera. Quantitative biostratigraphic techniques could improve the zonations that have been proposed for the region. We analyze the biostratigraphic information from 190 planktonic foraminifera species, and 1961 ditch-cutting samples from 26 oil wells in northern Colombia to produce a zonation for the region. A quantitative biostratigraphic technique known as Constrained Optimization was used to analyze the data.

The proposed zonation relies exclusively on last occurrences, which are readily applied to petroleum exploration. It has thirteen zones and eight subzones for the Eocene to Pliocene interval. Three zones and two subzones are defined for the Eocene, three zones for the Oligocene, six zones and six subzones for the Miocene, and one zone for the Pliocene. The zonation reveals three major unconformities: (1) a late Eocene - early Oligocene hiatus; (2) a late Oligocene - early Miocene hiatus; and (3) a late Miocene hiatus; the hiatuses are related to the collision of the Caribbean with the South American plate.

INTRODUCTION

Marine Cenozoic sequences from northern Colombia (southwest Caribbean) have traditionally been dated using biostratigraphic schemes developed for the southeastern Caribbean (e.g. Cushman and Renz 1941; Cushman and Stainforth 1945; Cushman and Renz 1946, 1948; Renz 1948; Bolli 1957b, 1957c; 1959a, 1959b; Blow 1959, 1969; Bermúdez 1961; Stainforth 1969; Postuma 1971; Bolli and Saunders 1985), and several local zonations, based on the analysis of a limited suite of local sections (e.g. Petters and Sarmiento 1956; Duque-Caro 1968, 1975; Stone 1968). Unfortunately, use of few sections leads to considerable subjective judgment regarding zonation, based on the perceived “true” stratigraphic order of taxa, and rarely gives insight into the actual geographic distribution of taxa and zones (Gradstein and Agterberg 2003).

Over the past 35 years the Empresa Colombiana del Petroleo (Ecopetrol) and its partners have collected a wealth of biostratigraphic data from the analysis of thousands of samples from hundreds of wells over the entire northern Colombia region. This large amount of historic micropaleontological information was used to produce a planktonic biostratigraphic zonation for the basin, which was calibrated to modern time scales and will help in the integration of other events derived from benthic foraminifera, nannoplankton, pollen/spores, and dinoflagellates to further improve the resolution of biostratigraphy in the area. Given the amount of data available, a quantitative biostratigraphic technique known as Constrained Optimization was used to analyze the biostratigraphic data. The proposed planktonic foraminiferal biostratigraphic scheme is heavily biased towards using the highest occurrence (HO) events to avoid problems related to caving, and then can be readily applied to petroleum exploration in the region. A reliable biostratigraphic model for this region helps in the reconstruction of the history of the collision of the southern Central American volcanic arc with the South American plate and the Andes uplift.

Previous Cenozoic local biostratigraphic zonations

The first zonation for the Cenozoic of northern Colombia was proposed by Petters and Sarmiento (1956) and was based on the study of benthic and planktonic foraminifera from the Carmen-Zambrano section, which is the reference stratigraphic column of northern Colombia. Even though these zones can be found in several northern Colombia localities, some of them are clearly facies dependent (e.g. Fiorini and Jaramillo, 2006). Stone (1968) applied Bolli’s (1957b) zonation to the same section used by Petters and Sarmiento. The application of Bolli’s zonation, which was based on planktonic foraminifera from Trinidad, allowed the correlation of northern Colombia with global standard biostratigraphies. Unfortunately, Stone focused only on Bolli’s (1957b) zonal markers and did not give a detailed stratigraphic distribution of the faunal elements, details which would have been useful for further analysis.

Duque-Caro (1968, 1972a, 1975) produced several biostratigraphic schemes based on benthic and planktonic foraminifera assemblages, using samples collected during geologic mapping of northern Colombia. Duque-Caro’s schemes were focused on stratigraphic unit definitions and citing characteristic taxa for geological mapping. However, his schemes do not specify operational criteria for the recognition of zones (e.g. lowest or highest occurrence events of taxa).

Martínez (1995), Jaramillo (1999), and Cuartas (2006) applied different quantitative correlation techniques to foraminiferal biostratigraphic data from discrete areas of northern Colombia.
They showed the potential that quantitative techniques have for dealing with large data sets and their application in a sequence stratigraphic sense.

**Geological Setting**

The study area (text-fig. 1) is located along the northwestern margin of South America. Its tectonic configuration results from the interactions between the Farallón (including Cocos, Nazca, and Caribbean plates) and the North and South American plates since Mesozoic times (e.g. Burke 1988; Pindell et al. 1988; Case et al. 1990; Pindell and Barrett 1990; Toto and Kellogg 1992; Coates et al. 2003; Coates et al. 2004; Corredor et al. 2003; James 2005; Kellogg et al. 2005). Relative eastward migration of the Caribbean plate along the northwestern South American margin forced the development of a series of major tectono-stratigraphic features, which include from east to west: the Guajira Province, the Lower Magdalena Valley (LMV), the San Jacinto Folded Belt (SJFB), the Sinú Fold Belt (SFB), the Urabá Basin, and the Panamá Arc (text-fig. 1).

The Guajira Sedimentary Province is located in the Guajira Peninsula, northeast of the Santa Marta Massif and north of the Oca fault (text-fig. 1). It is characterized by shallow to deep marine Cenozoic deposits locally separated by an unconformity from either Upper Cretaceous sediments or Proterozoic, Paleozoic, and Mesozoic igneous and metamorphic rocks (e.g. Kroonemberg 1982; Cardona 2003; Cordani et al. 2005). It includes the Lower and Upper Guajira basins, which are separated by the Cuiza Fault (Duque-Caro and Reyes 1999; text-fig. 1). The former records Cenozoic sedimentation commencing in Early Miocene time, whereas the latter initiates in the early Middle Eocene (e.g. Duque-Caro and Reyes 1999).

The LMV Province is located south of the Santa Marta Massif; it is bounded to the east by the Santa Marta-Bucaramanga Fault, to the west by the Romeral Fault System and to the southeast by the Central and Eastern Colombian Cordilleras foothills (text-fig. 1). It is subdivided into the San Jorge and Plato basins, which are separated by the Magangue Arch or Cicuco High...
TEXT-Figure 2
Order of events from the constrained optimization scenarios. Scenario 1 uses only HO; Scenario 2 uses HO also, but compensates for edge effects. Horizontal lines connect events between scenarios. Metric bars on both sides of the figure indicate the position of the event. Correlation between the sequences obtained in Scenario 1 and Scenario 2 is also shown. Non-concordant events are marked with the number of the position yielded in Scenario 1.
TABLE 1

Proposed sequence of events (HO) yielded by comparison between constrained optimization scenarios 1 and 2. In column A, events marked with "X" are those with the lower penalty levels (Z) and the higher Phi Index over those wells analyzed by constrained optimization scenario 2. In column B, events marked with "o" are those potential zonal markers, with a Phi Index value higher than 0.77 calculated using 70 wells. Events are ordered from younger (68) to older (1).

<table>
<thead>
<tr>
<th>Order</th>
<th>Species HO</th>
<th>A</th>
<th>B</th>
<th>Order</th>
<th>Species HO</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>68</td>
<td>Neogloborotalia pachyderma</td>
<td>X</td>
<td></td>
<td>34</td>
<td>Globigerinoidea diminita</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>67</td>
<td>Globorotalia decororopta</td>
<td>X</td>
<td></td>
<td>33</td>
<td>Catapsydrus staintori</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>66</td>
<td>Globigerinella praecoloida</td>
<td>X</td>
<td></td>
<td>32</td>
<td>Paragloborotalia mana</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>Globigerinella venenulina</td>
<td>X</td>
<td></td>
<td>31</td>
<td>Globigerinoidea primordia</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>64</td>
<td>Neogloborotulina acostaensis</td>
<td>X</td>
<td></td>
<td>30</td>
<td>Globorotaloides sutera</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>63</td>
<td>Globigerinoides obliqua</td>
<td>X</td>
<td>o</td>
<td>29</td>
<td>Catapsydrus dissimitis</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>62</td>
<td>Sphaerodinellopsis seminulina</td>
<td>X</td>
<td></td>
<td>28</td>
<td>Paragloborotalia kwugere</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>61</td>
<td>Orbulina suturalis</td>
<td>X</td>
<td></td>
<td>27</td>
<td>Dentoglobigerina tripartita</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>60</td>
<td>Globorotalia nepentes</td>
<td>X</td>
<td></td>
<td>26</td>
<td>Globorotalia onachitaensis</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>59</td>
<td>Globorotalia venezuelana</td>
<td>X</td>
<td>o</td>
<td>25</td>
<td>'Globorotalia angustiublicata'</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>58</td>
<td>Orbulina bilobata</td>
<td>o</td>
<td></td>
<td>24</td>
<td>Globorotalia opina</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>57</td>
<td>Globigerinoides triloba</td>
<td>X</td>
<td></td>
<td>23</td>
<td>Dentoglobigerina galavis</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>56</td>
<td>Sphaerodinellopsis subdehiscentes</td>
<td>X</td>
<td></td>
<td>22</td>
<td>Globigerina angulistratil</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>Globorotalia merotumida</td>
<td>X</td>
<td>o</td>
<td>21</td>
<td>Turborotalia eupertura</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>54</td>
<td>Dantoglobigerina globosa</td>
<td>X</td>
<td></td>
<td>20</td>
<td>Paragloborotalia opina</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>53</td>
<td>Globigerinoides subquadrata</td>
<td>X</td>
<td></td>
<td>19</td>
<td>Dentoglobigerina pseudovenezuelana</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>52</td>
<td>Paragloborotalia mayeri</td>
<td>X</td>
<td>o</td>
<td>18</td>
<td>Globorotalia anguliofuniculis</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>Globigerinina unda</td>
<td>X</td>
<td></td>
<td>17</td>
<td>Subbotina gortani</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Menardella praemenardii</td>
<td>X</td>
<td>o</td>
<td>16</td>
<td>Turborotalia ampliapertura</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>49</td>
<td>Fohsella fohsi</td>
<td>X</td>
<td>o</td>
<td>15</td>
<td>Subbotina senlis</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>48</td>
<td>Fohsella peripheroranda</td>
<td>X</td>
<td>o</td>
<td>14</td>
<td>Subbotina veguaensis</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>47</td>
<td>Fohsella praefohsi</td>
<td>X</td>
<td>o</td>
<td>13</td>
<td>Subbotina liamperita</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>46</td>
<td>Globorotaloides variabilis</td>
<td>X</td>
<td>o</td>
<td>12</td>
<td>Dentoglobigerina tapariensis</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>45</td>
<td>Globigerinoides bulboides</td>
<td>X</td>
<td>o</td>
<td>11</td>
<td>Paragloborotalia griffinioides</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>44</td>
<td>Menardella archeomariandii</td>
<td>X</td>
<td>o</td>
<td>10</td>
<td>Clavigerinella colombiana</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>43</td>
<td>Globigerinina juliata</td>
<td>X</td>
<td></td>
<td>9</td>
<td>Acarinina bulbrooki</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>42</td>
<td>Hirsutella praemariandii</td>
<td>X</td>
<td>o</td>
<td>8</td>
<td>Truncorotaloides rohri</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>41</td>
<td>Globigerinoides mira</td>
<td>X</td>
<td>o</td>
<td>7</td>
<td>Morozovella spinulosa</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>40</td>
<td>Globigerinina pseudociperoensis</td>
<td>X</td>
<td>o</td>
<td>6</td>
<td>Clavigerinella aneksi</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>39</td>
<td>Globigerinoides bisferica</td>
<td>X</td>
<td>o</td>
<td>5</td>
<td>Acarinina aspeni</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>38</td>
<td>Globigerinoides alliapertura</td>
<td>X</td>
<td>o</td>
<td>4</td>
<td>Igorina broadmanni</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>37</td>
<td>Praeorbulina sicana</td>
<td>X</td>
<td>o</td>
<td>3</td>
<td>Acarinina esnaensis</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>36</td>
<td>Praeorbulina transitoria</td>
<td>X</td>
<td>o</td>
<td>2</td>
<td>Acarinina pentacocertana</td>
<td>X</td>
<td>o</td>
</tr>
<tr>
<td>35</td>
<td>Praeorbulina glomerosa</td>
<td>X</td>
<td>o</td>
<td>1</td>
<td>Clavigerinella javisi</td>
<td>X</td>
<td>o</td>
</tr>
</tbody>
</table>

(text-fig. 1). Its sedimentary record extends from the Oligocene through the Quaternary. Facies vary laterally from west to east and are strongly controlled by the tectonic evolution of this margin (Duque-Caro 1975; ICP-Ecopetrol 2000; Flinch 2003; Kellogg et al. 2005).

The Sinu Province is a thick, deformed wedge of sediments, located east of the Romeral Fault System and west of the South Caribbean Marginal Fault (text-fig. 1). It is subdivided into the Sinu Folded Belt (SFB) and the San Jacinto Folded Belt (SJFB). The whole province was accreted to the South American margin during the Cenozoic (Kellogg et al. 2005). The SFB is composed of Late Cretaceous pelagic rocks, a thick Cenozoic turbidite sequence, and Pleistocene-Holocene fluviatile and lacustrine sediments (Duque-Caro 1975, 1979; ICP-Ecopetrol 2000; Flinch 2003). The SFB includes Oligocene-Miocene shales and extensive, fine-grained late Miocene and Pliocene turbidites overlain by shallow-water Pleistocene-Holocene carbonate facies composed of shales, reef limestones, sandstones, and conglomerates (Duque-Caro 1975, 1979). A very low topographic slope and abundant mud volcanism, domes, and diapirs, produced by mobilization of Oligocene-Miocene over pressured shales, characterize the SFB wedge (Duque-Caro 1975, 1979).
TEXT-Figure 3
Marginal plot of the average standardized penalty (Z) obtained in constrained optimization scenario 2 vs. \( \varphi \) value of the 68 LO events from Table 1. The square formed by the minimum values and the inflection points from the density curves of \( \varphi \) value contains the stronger LO events, with lower penalty and hence a high biostratigraphic significance. Events highly penalized are marked with numbers that correspond to the order of events presented in Table 1.

METHODS
Thousands of new and revisited biostratigraphic data, collected by Ecopetrol and partners over the last 35 years, were used in this study. A database that includes the lowest and highest appearance depths of 190 species of planktonic foraminifera was built (Appendix 1). It excludes those species with open nomenclature and those with the qualifiers *affinis* and *confer*. The study focused on the best quality data, which includes information from 1961 ditch-cutting samples and 26 wells, 19 located in the Sinú Province, five in the LMV, and two in onshore and offshore areas of the Guajira Province (text-fig. 1). The wells were selected on the basis of taxonomic consensus, sample density, and geographic and stratigraphic coverage. Highest occurrence events (HO) were used and lowest occurrence events (LO) avoided, eliminating the bias introduced by caving in the LO data. Reworked occurrences were eliminated whenever there was enough evidence to recognize them (e.g. isolated and rare occurrences). Only HO events reported in more than three wells were analyzed.

The Constrained Optimization technique was used for the biostratigraphic analysis. The technique (Kemple et al. 1995) identifies a best-fit sequence of events that is optimal in the sense that all the field data may be fit to the sequence with a minimum of range extensions. Acceptable sequences are constrained to include all observed coexistences of pairs of taxa. The technique allows many taxa to be used, and quantifies the stability of the position of each event in the best sequence of
## TABLE 2
Average constrained optimization penalty levels (Z), Phi Index (φ), number of wells where the event is recorded (n) and estimated local ages of HO events from the proposed sequence. Average penalization level, ψ(1) and n(1) correspond with the results of 68 proposed events from the analysis of 26 wells used in performing CONOP9, φ(2) and n(2) correspond with results from the regional analysis of 58 best events in 70 tested wells. Maximum values of the mean estimated age (95% confidence interval) and estimated error from the LOESS method are also presented.

<table>
<thead>
<tr>
<th>Order</th>
<th>Species</th>
<th>Z</th>
<th>ψ(1)</th>
<th>n(1)</th>
<th>ψ(2)</th>
<th>n(2)</th>
<th>Age (Min)</th>
<th>Min</th>
<th>Max</th>
<th>s.e.</th>
</tr>
</thead>
</table>

### Footnotes:
- NA = Not Available
- s.e. = Standard Error
because many observed ranges include gaps. A piecewise regression to generate false range ends in samples near these limits, top or base of a section, the edge effect may extend into the section even though CONOP disregards range ends that coincide with the limits. Edge effects concentrate false HO events at the tops of sections (only HOs were considered). The second scenario was performed with unpaired range-end regression following the algorithm described in Duggleby and Ward (1991). The breakpoint is the intersection of the two fitted regression lines and can be used as an estimated threshold (depth) representing a significant difference in HO frequencies. Those HO events located above the breakpoint were removed.

events. CONOP9 software (Sadler 2003) was used to perform the Constrained Optimization and was run under two scenarios. The first scenario was performed with unpaired range-end events (only HOs were considered). The second scenario was also performed with HO events but took into account the edge effects (artificial range truncations) at the upper limit of the biostratigraphic information in each well analyzed.

Edge effects concentrate false HO events at the tops of sections and false LO events at the bases of sections (Foote 2000). Although CONOP disregards range ends that coincide with the top or base of a section, the edge effect may extend into the section to generate false range ends in samples near these limits, because many observed ranges include gaps. A piecewise

TEXT-Figure 4

Local experimental age model for the 68 LO events from Table 1 and its calibration against the absolute chronostratigraphic time scale of Berggren et al. (1995). Regression surface (bold line) and confidence intervals of 95% (dotted lines) were defined by LOESS method. Age data (black dots) of some of the 40 stronger events are those from Appendix 4.
from each section; the rest were retained in the Constrained Optimization analysis.

The optimum sequences of events produced by the two scenarios were compared using Kendall’s Tau coefficient of concordance (e.g. Gibbons and Chakraborti 1992). In order to obtain a unique sequence, events that were not concordant between the two scenarios were removed and the remaining events were analyzed by their relative position and their 5% relaxed fit intervals in the CONOP composite sequences of both scenarios. This is because CONOP calculates, for each event, the position it gets if the misfit was increased in 5% in relation to the optimum sequence (Sadler 2003). Discordant events, those events whose 5% relaxed fit intervals of one scenario did not permit organizing them in the order obtained in the other scenario, were removed. Then, the sequence of events that maintained the same position in both scenarios was used for further biostratigraphic analysis and to build the zonation proposed in this study.

Taking into account that the resolution of biostratigraphic zonations must be given by the data (robust events), and not by the biostratigrapher, we used two methods to assess the quality of each event of the optimum sequence of events as a


**TEXT-Figure 6**

Zones and datum events of the proposed local zonation. Time scale is from Berggren et al. (1995) and Berggren and Pearson (2005). Ages for zonal datum events are discussed in the main text.
biostratigraphic marker: (1) the average standardized penalty ($Z$), obtained for each event in Scenario 2 of Constrained Optimization, and (2) the Phi index - $\phi$ (see Supplement for a detailed explanation of the index). One advantage of the Phi index is that it could be applied to wells that were not used in the Constrained Optimization analysis. Use of the average standardized CONOP penalties ($Z$) assumes that LO events whose observed range-end events need relatively large adjustments (penalty) to fit the optimal sequence are the least consistent in position among the locally observed sequences. The necessary adjustments are partly a reflection of the biostratigraphic quality of the taxa and may also reflect the sampling and preservation factors that vary from well to well. Accordingly, the local penalties obtained for each HO event “$i$” in the well “$j$” were standardized using the following equations:

$$Z_i = \frac{V_i - M_j}{S_j}$$  \hspace{1cm} (1)$$

$$\bar{Z}_i = \frac{\sum Z_{ij}, l \leq n}{l}$$  \hspace{1cm} (2)$$

where $V_i$ is the penalty increment for species “$i$” in the well “$j$” and $M_j$ is the mean penalty value for well “$j$”, $S_j$ is the penalty standard deviation for well “$j$”, and “$l$” the number of wells where the event was observed.

In general, events with low values were assumed to have higher biostratigraphic value. CONOP offers several options for the penalty that measures misfit between hypothetical sequences of events and the field observations. The “level” penalty measures range adjustments in terms of event levels. It was chosen because it favors successions seen in the most richly fossiliferous and intensely sampled sections (Cooper et al. 2001). Measures that use rock thickness can be biased by differences in accumulation rates (Sadler 2003), and we assume that accumulation rate varies with facies within the study area.

The second method, the Phi index (see Supplement), was also applied to find out the more stable events among the sequence by testing the relative position of each event in each analyzed well (for detailed explanation of the index see Supplement). The value of $\phi$ oscillates between 0 and 1, the higher the value the lower the divergence between the observed relative position of an event into the field sequence and its relative position in the optimum sequence of events.
TEXT-Figure 8
Comparison of the local proposed bioevents with: (a) the last occurrences from the planktonic zonal scheme of Stone (1968); (b) the events proposed by Martínez (1995); (c,d) the planktonic zonations of Blow (1969, 1979) and Postuma (1971); (e) the Neogene planktonic - phylogenetic framework of Kennett & Srinivasan (1983); (f) the planktonic scheme of Bolli et al. (1985); and (g) the tropical planktonic global scheme of Berggren et al. (1995).
Events with both low and high $\phi$ values were judged to possess high biostratigraphic significance. The Phi index ($\phi$) was applied then to those key events in 70 wells, including wells used in Constrained Optimization analysis. This analysis was done to further improve the measure of the quality of each event as a biostratigraphic marker.

In the absence of paleomagnetic polarity, stable isotope, and fission-track data, an experimental age model was constructed to date the optimum sequence of events. This biochronology was built by performing a nonparametric local regression, LOESS, interpolating numerical age information from several authors and the order of events in the optimal sequence, using the R 2.1.0 statistical package (R Development Core Team, 2005). Finally, we selected zonal event markers for each epoch, based on the best Phi index, their regional presence, and their taxonomic complexity.

RESULTS

The analysis yielded a sequence of 97 HO events in scenario 1, whereas scenario 2 retained 87 events (text-fig. 2). After accounting for the edge effects in scenario 2 (as described above), some of the events remained in fewer than three sections, and therefore were removed. The excluded events were the HO of the following taxa: Neogloboquadrina humerosa, Globigerinella siphonifera, Globigerinoides immatura, Globigerinita incrusta, Menardella limbata, Globigerina falconensis, Globoquadrina dehiscens, Globoquadrina praedehiscens, Turborotalia pomeroli, and Subbotina eocaena (for synonymies and species authors see Taxonomic Notes section).

Text-figure 2 compares scenarios 1 and 2. Overall concordance between both scenarios was high (Kendall’s Tau coefficient = 0.85). Exceptions were the positions of the HO of Globigerina praebulloides, Orbulina universa, Globigerina bulloides,
TEXT-Figure 10
Correlation of Cenozoic sedimentary successions in northern Colombian wells. Transect B – B’ includes wells VI and VII, also shown in text-fig. 9. Depth values (ft) per well are those reported in the biostratigraphic distribution charts, using the proposed planktonic foraminifera zonation. Main tectonic and sedimentary features are indicated: LMV-PB (Lower Magdalena Valley, Plato Basin), SJFB (San Jacinto Folded Belt), and Sinú Folded Belt (SFB). Vertical single bars at both ends of the wells indicate the vertical extension (ft) of the perforation, where there is not biostratigraphic data.
TEXT-FIGURE 11
Correlation of Cenozoic sedimentary successions in northern Colombian wells. Transect C – C’ includes wells VIII and IX, also shown in text-fig. 9. Depth values (ft) per well are those reported in the biostratigraphic distribution charts, using the proposed planktonic foraminifera zonation. Illustration of ODP site – 999A was rescaled with a magnification of ten times. Main tectonic and sedimentary features are indicated: LMV-PB (Lower Magdalena Valley, Plato Basin), Simi Folded Belt (SFB) and Colombian Basin. Vertical single bars at both ends of the wells indicate the vertical extension (ft) of the perforation, where there is no biostratigraphic data.
Cassigerinella chiplonis, Globigerinoides rubra, Menardella menardii, Hirsutella scitula, and Globigerinoides sacculifera, which were lowered to older positions in scenario 2; positions of the HO of Paragloborotalia siakensis, Globigerinella obesa, and Globorotaliina advena, on the other hand, were located in younger positions relative to the positions yielded by scenario 1. Inconsistencies, from one scenario to another, in the relative extinction levels could be attributed to the sensitivity of some events to edge effects in one or several wells.

After removing those non-concordant, edge effect-sensitive events, HOs were organized in a unique sequence, according to their relative position and their 5% relaxed fit intervals in each scenario (Appendix 2). HO events like those of Subbotina gortani, Subbotina senilis, Subbotina vaguaensis, and Turborotalia ampliapertura, whose 5% relaxed fit intervals overlapped each other, were organized in the final sequence by their potential maximum position (Appendix 2). Finally, a list of 68 events composed the resulting final sequence (Table 1).

A marginal-plot of the average standardized penalty (from scenario 2) vs. Phi index (φ) of the 68 proposed events from Table 1 (text-fig. 3) showed that a high percentage (88.9%) of HO events presented low penalty levels (< 0.35) and high φ values (φ > 0.73), thus identifying them as robust biostratigraphic events in the sequence (Tables 1 and 2). Other events, such as the HOs of Globorotalia merotumida, Tentoglobigerina galavis, Dentoglobigerina pseudovenezuelana, and Igorina broedermani, were highly penalized by CONOP9 but they have high φ values (text-fig. 3; Table 2). The opposite is characteristic of the HOs of Neogloboquadrina pachyderma, Globigerinella praecalida, Ortholina siuralis, Globoquadrina venezuelana, Sphaeroidinellopsis subdehiscens, Menardella praemenardii, and Subbotina linaperta, which have good CONOP9 penalties, but poor φ values (text-fig. 3; Table 2).

Fifty-eight robust biostratigraphic events, which remained after removing those 10 events highly penalized by CONOP9 and Phi index, were used to recalculate (p in 70 wells (Appendix 3). Regionally, 40 events were found with low departure from the proposed sequence (φ > 0.77) and they were classified as potential zonal markers (Tables 1 and 2).

The literature age assignment for 33 of the potential zonal markers is shown in Appendix 4. Age assignments of the other seven HO events were not found. In order of precedence we prefer to use the age estimates of Chaisson and D’Hondt (2000) and Pearson and Chaisson (1997) to build our own age model, due to the geographic proximity of those ODP sites to our study area. Other ages were taken from Pearson et al. (2006),
TEXT-Figure 13
Chronostratigraphic chart (Wheeler diagram) of Transect B - B’. Main tectonic and sedimentary features are indicated: LMV-PB (Lower Magdalena Valley, Plato Basin), SJFB (San Jacinto Folded Belt), and Simú Folded Belt (SFB).
TEXT-FIGURE 14
Chronostratigraphic chart (Wheeler diagram) of Transect C - C'. Main tectonic and sedimentary features are indicated: LMV-PB (Lower Magdalena Valley, Plato Basin), Simi Folded Belt (SFB) and Colombian Basin.
Berggren et al. (1995), and Kennett and Srinivasan (1983). Our age model, based on the LOESS method (text-fig. 4; Table 2), allows us to calculate local HO ages for each event within the proposed sequence and to place them within geologic epochs as shown in text-fig. 5 and Table 2.

DISCUSSION

We propose a biostratigraphic scheme for the continental margin of northwest South America composed of 68 HO events of planktonic foraminifera. The order of events is supported by high concordance between the sequences from scenarios 1 and 2 (Kendall’s Tau = 0.85) and their 5% relaxed fit intervals in both scenarios. From older to younger, HO events of Acarinina pentacamerata, Clavigerinella akersi, Paragloborotalia griffioides, Subbotina yeguaensis, Turborotalia ampliapertura, Paragloborotalia opima, Globoturborotalia ciperoensis, Paragloborotalia kugleri, Catapsydrax dissimilis, Catapsydrax stainforthi, Globigerinoides diminuta, Fohsella fohsi, Paragloborotalia mayeri, Globorotalia merotumida, Globoquadrina venezuelana, and Globigerinoides obliqua were selected as zonal and subzonal markers because of their high q values, conspicuous regional presence, easy of species identification, and their estimated age (text-fig. 5; see also Appendix 3, text-fig. 4; Table 2).

Planktonic foraminifera local zonation

The time scale used is that of Berggren et al. (1995) and dating of the sequence of events is derived from our age model (text-figs. 4, 5; Table 2). Three zones and two subzones are defined for the Eocene, three zones for the Oligocene, six zones and six subzones for the Miocene, and one zone for the Pliocene (text-fig. 6). All the zones are highest occurrence zones, where two HOs are the bounding biohorizons. First letter and numbers of the codes for the zones indicate the sequence and relative positions of the zones. Illustrations and remarks for some of the key taxa used in the zonation are found in the Taxonomic Notes.
The resolution of any biostratigraphic zonation depends on the interactions between several factors: (1) kind of samples (e.g., diatom cutting, core samples, outcrop samples); (2) sampling errors, related to judging presence or absence of fossils in discrete samples (sampling frequency); (3) fossil groups involved in the zonation (e.g., planktonic foraminifera, benthic foraminifera, pollen, dinoflagellates); (4) biostratigraphic events (e.g., HO events, LO events, high taxon abundance); (5) biostratigraphic robustness of the events (i.e., Z and \( \phi \) values); (6) evolutionary factors (i.e., speciation and extinction rates); (7) complexity of the microfossil group-environment interactions; (8) effects of variable fossil preservation; (9) geologic history of the corresponding strata; and (10) amount and quality of sedimentary rocks in a body of strata. Thus, for example, the lower planktonic biostratigraphic resolution obtained in the Paleocene and early Eocene could be related to syn-depositional seabed dissolution of calcareous microfoua, as recorded in the San Cayetano Formation (e.g., Duque-Caro 1968; see also below “Biostratigraphic correlations”). Lower planktonic resolution of late Miocene–Pliocene is possibly related to uplifting and erosion of marine sequences as recorded in the Rancho, Hibácharo, Jesús del Monte, Tubaré, Zambrano, and Cerrito formations (e.g., Duque-Caro 1968; see also below “Biostratigraphic correlations”).

Paleocene–Eocene

The oldest foraminiferal fauna was found in well S (Appendix 1). This fauna is composed of Morozovella angulata, Acarinina nitida, and Subbotina triloculinoides, among others. The assemblage suggests an Early Paleocene age (Toumarkine and Luterbacher 1985; Berggren et al. 1995; Ohson et al. 1999; Berggren and Pearson 2005). Unfortunately, there are no other sections with Paleocene fauna available to define a formal zonation for this interval.

Eco-1 Acarinina pentacamerata Interval Zone

Definition: Interval zone (partial range) of Acarinina pentacamerata. The lower boundary of the zone has been defined by the HO of Morozovella aequa. The top of the zone is defined by the HO of A. pentacamerata (text-figs. 6, 7).

Events within the zone: HO of Clavigerinella jarvisi.

Remarks: This zone is approximately equivalent to the P7 – lower P10 zones of Berggren et al. (1995) or E5 – lower E8 of Berggren and Pearson (2005). Definition of its lower boundary was done by analysis of a CONOP composite sequence (not shown here), which incorporated all the events that occur in at least one well. Pearson et al. (2006) determined that the HO of C. jarvisi occurred in the younger Zone E9 (text-fig. 4; Appendix 4). Nevertheless, our sequence of events, age model, and its confidence intervals suggest an earlier local extinction of C. jarvisi.

Estimated local age: early Eocene (Ypresian), ~ 50.8 – early middle Eocene (Lutetian), ~ 47.11 Ma.

Eco-2 Paragloborotalia griffinioides Interval Zone

Definition: Interval zone (partial range) of Paragloborotalia griffinioides. The lower boundary of this zone is defined by the HO of Acarinina pentacamerata. The top of the zone is defined by the HO of P. griffinioides (text-figs. 6, 7).

Events within the zone: HO of Clavigerinella colombiana, Acarinina bullbrooki, Truncorotaloides rohri, Morozovella spinulosa, Clavigerinella akersi, Acarinina aspensis, Igorina broedermanni, and Acarinina esnaensis.

Remarks: This zone is approximately equivalent to the upper P10 – lower P15 Eocene zones of Berggren et al. (1995) or upper E8 – lower E14 zones of Berggren and Pearson (2005). It is divided into two subzones: Eco-2.1 Clavigerinella akersi Subzone, which is equivalent to the upper P10 – lower P12 Eocene zones of Berggren et al. or upper E8 – upper E10 zones of Berggren and Pearson (2005), and Eco-2.2 Paragloborotalia griffinioides Subzone, which is equivalent to the upper P12 – lower P15 Eocene zones of Berggren et al. or upper E10 – lower E14 zones of Berggren and Pearson (2005) (text-fig. 6).

Estimated local age: early middle Eocene (Lutetian), ~ 47.11 Ma – late middle Eocene (late Bartonian), ~ 36.81 Ma.

Eco-2.1 Clavigerinella akersi Subzone

Definition: This zone is defined as the partial range of Clavigerinella akersi. The base of the zone is defined by the HO of Acarinina pentacamerata and the upper boundary is defined by the HO of C. akersi (text-figs. 6 and 7).

Additional Events: HOs of Acarinina aspensis, Igorina broedermanni, and Acarinina esnaensis.

Estimated local age: early middle Eocene (Lutetian), ~ 47.11 Ma – late middle Eocene (late Lutetian), ~ 42.59 Ma.

Eco-2.2 Clavigerinella colombiana Subzone

Definition: Interval zone (partial range) of Paragloborotalia griffinioides. Base defined by the HO of Clavigerinella akersi and the top by the HO of P. griffinioides (text-figs. 6, 7).

Additional Events: HO of Clavigerinella colombiana, Acarinina bullbrooki, Truncorotaloides rohri, and Morozovella spinulosa.

Estimated local age: middle Eocene (late Lutetian), ~ 42.59 Ma – late Eocene (early Priabonian), ~ 36.81 Ma.

Eco-3 Subbotina yeguaensis Interval Zone

Definition: Interval zone (partial range) of Subbotina yeguaensis. The lower boundary of the zone is defined by the HO of Paragloborotalia griffinioides. The top of the zone is defined by the HO of S. yeguaensis (text-figs. 6, 7).

Events within the zone: HOs of Subbotina linaperta, Dento-globigerina tapuriensis, and Turborotalia pomeroli.

Remarks: This zone is approximately equivalent to the lower P15 – P17 Eocene zones of Berggren et al. (1995) or lower E14 – E16 zones of Berggren and Pearson (2005). The HO of S. yeguaensis is positioned slightly older than the Eocene/Oligocene boundary (Berggren and Pearson 2005; Pearson et al. 2006) so we decided to delimit the Eocene/Oligocene boundary with the HO of this taxon. According to Pearson’s (1998) phylogeny of Paleogene planktonic foraminifera, the extinction of D. tapuriensis must have been later, and occurred in the Oligocene Zone P22 (O6). However, our sequence of events suggests an earlier extinction of D. tapuriensis in the northwest margin of Colombia.

Estimated local age: late Eocene (early Priabonian), ~ 36.81 Ma – late Eocene (late Priabonian), ~ 33.52 Ma.
Oligocene

**Oca-1 Turborotalia ampliapertura Interval Zone**

*Definition:* Interval zone (partial range) of *Turborotalia ampliapertura*. The lower boundary of the zone is defined by the HO of *Subbotina yegaensis*. The top of the zone is defined by the HO of *T. ampliapertura* (text-figs. 6, 7).

*Events within the zone:* LO of *Subbotina senilis*.

*Remarks:* This zone is approximately equivalent to the P18 - lower P19 Oligocene zones of Berggren et al. (1995) or O1 – lower O2 zones of Berggren and Pearson (2005).

*Estimated local age:* early Oligocene (early Rupelian), ~ 33.52 Ma – late early Oligocene (late Rupelian), ~ 31.27 Ma.

**Oca-2 Paragloborotalia opima Interval Zone**

*Definition:* Interval zone (partial range) of *Paragloborotalia opima*. The base is defined by the HO of *Turborotalia ampliapertura* and the top is defined by the HO of *P. opima* (text-figs. 6, 7).

*Events within the zone:* HO of *Dentoglobigerina pseudovenezuelana*, *Globoturborotalita angulioficialis*, and *Subbotina gortanii*.

*Remarks:* This zone is approximately equivalent to the upper P19 - P21b Oligocene zones of Berggren et al. (1995) or O2 – O5 zones of Berggren and Pearson (2005). According to Pearson et al. (2005) *D. pseudovenezuelana* became extinct in the early late Oligocene Zone P21b (O5) whereas *S. gortanii* and *G. angulioficialis* became extinct in the late late Oligocene zone O6 (P22). Our results suggest an earlier local extinction of those taxa.

*Estimated local age:* late early Oligocene (late Rupelian), ~ 31.27 Ma – early late Oligocene (early Chattian), ~ 27.17 Ma.

**Oca-3 Globoturborotalita ciperoensis Interval zone**

*Definition:* Interval zone (partial range) of *Globoturborotalita ciperoensis*. The base is defined by the HO of *Paragloborotalia opima* and the upper boundary is defined by the HO of *G. ciperoensis* (text-figs. 6, 7).

*Events within the zone:* HO of *Dentoglobigerina galavis*, *Globigerina angulisuturalis*, and *Turborotalia euapertura*.

*Remarks:* This zone is approximately equivalent to the P22 - M1a zones of Berggren et al. (1995). Kennett and Srinivasan (1983) reported the HO of *G. ciperoensis* at ~ 19.3 Ma; but in the western Atlantic (closest geographically) *G. ciperoensis* and *G. angulisuturalis* appear to become extinct earlier (~ 23.3 Ma; Pearson and Chaisson 1997).

*Estimated local age:* early late Oligocene (early Chattian), ~ 27.17 Ma – late early Oligocene (late Chattian), ~ 23.63 Ma.

Miocene

**Mir-1 Globoturborotalita ouachitaensis Interval Zone**

*Definition:* Interval zone (partial range) of *Globoturborotalita ouachitaensis* and *Globoturborotalita angusti umbilicata*.

*Remarks:* This zone is approximately equivalent to the M1 - lowest M2 early Miocene zones of Berggren et al. (1995), and it is divided into two subzones: Mir-1.1 *Paragloborotalia kugleri* Subzone, which is equivalent to the M1 to lowest M2 Miocene zones of Berggren et al., and Mir-1.2 *Catapsydrax dissimilis* Subzone, which is equivalent to much of the early Miocene M2 zone of Berggren et al. (text-fig. 6). It is present in most of the study area and exhibits high abundances of planktonic fauna, and acmes of *Globigerinoides* spp. Pearson et al. (2006) suggest that the extinction of *D. tripartita* occurred within the late Oligocene O6 zone (=P22); in our region, however, the species persists into the early Miocene.

*Estimated local age:* late Oligocene (late Chattian), ~ 23.63 Ma – middle early Miocene (early Burdigalian), ~ 19.47 Ma.

**Mir-1.1 Paragloborotalia kugleri Subzone**

*Definition:* Interval zone (partial range) of *Paragloborotalia kugleri*. The base is defined by the HO of *Globoturborotalita ciperoensis* and the upper boundary is defined by the HO of *P. kugleri* (text-figs. 6, 7).

*Events within the zone:* HO of *Dentoglobigerina tripartita*, *Globoturborotalita ouachitaensis*, and *Globoturborotalita angusti umbilicata*.

*Estimated local age:* late Oligocene (late Chattian), ~ 23.63 Ma – middle early Miocene (early Burdigalian), ~ 20.26 Ma.

**Mir-1.2 Catapsydrax dissimilis Subzone**

*Definition:* Interval zone (partial range) of *Catapsydrax dissimilis*. The base is defined by the HO of *Paragloborotalia kugleri* and the upper boundary is defined by the HO of *C. dissimilis* (text-figs. 6, 7).

*Events within the zone:* There are no local extinction events within the subzone.

*Estimated local age:* middle early Miocene (early Burdigalian), ~ 20.26 Ma – middle early Miocene (early Burdigalian), ~ 19.47 Ma.

**Mir-2 Globigerinoides primordias Interval Zone**

*Definition:* Interval zone (partial range) of *Globigerinoides diminuta*. The base of the zone is defined by the HO of *Catapsydrax dissimilis* and the upper boundary is defined by the HO of *G. diminuta* (text-figs. 6, 7).

*Events within the zone:* HO of *Catapsydrax stainforthi*, *Paragloborotalia nana*, *Globigerinoides primordia*, and *Globorotalioides suerti*.

*Remarks:* This zone is approximately equivalent to the upper M2 - lower M5 early to early middle Miocene zones of Berggren et al. (1995), and is divided into two subzones: Mir-3.1 *Catapsydrax stainforthi* Subzone, which is equivalent to the upper M2 - upper M4 Miocene zones of Berggren et al., and Mir-3.2 *Globigerinoides diminuta* Subzone, which is equivalent to the late M4 to lower M5 Miocene zones of Berggren et al. (text-figs. 6, 7).
**Estimated local age:** middle early Miocene (early Burdigalian), ~ 19.47 Ma – early middle Miocene (early Langhian), ~ 15.92 Ma.

**Mir-2.1 Catapsydrax stainforthi Subzone**

**Definition:** This zone is defined as the partial range of Catapsydrax stainforthi. The base of this zone is defined by the HO of Catapsydrax dissimilis and the upper boundary is defined by the HO of C. stainforthi (text-figs. 6, 7).

**Additional Events:** HOs of Paragloborotalia nana, Globigerinoides primordia, and Globorotaloides suteri.

**Estimated local age:** middle early Miocene (early Burdigalian), ~ 19.47 Ma – late early Miocene (late Burdigalian), ~ 16.46 Ma.

**Mir-2.2 Globigerinoides diminuta Subzone**

**Definition:** Interval zone (partial range) of Globigerinoides diminuta. Base defined by the HO of Catapsydrax stainforthi and the top by the HO of G. diminuta (text-figs. 6, 7).

**Additional Events:** There are no local extinction events within this zone.

**Estimated local age:** late early Miocene (late Burdigalian), ~ 16.46 Ma – early middle Miocene (early Langhian), ~ 15.92 Ma.

**Mir-3 Fohsella fohsi Interval Zone**

**Definition:** This zone is defined as the partial range of Fohsella fohsi. The base of this zone is defined by the HO of Globigerinoides diminuta and the top by the HO of F. fohsi s.l. which includes F. fohsi, F. robusta, and F. lobata (text-figs. 6, 7).

**Events within the zone:** HOs of Fohsella peripheronda, Fohsella praefohsi, Globorotaloides variabilis, Globigerinoides bulloides, Menardella archaemenardii, Hirsutella praescitula, Globigerina f oliata, Globigerinoides mitra, Globigerina pseudociperoensis, Globigerinoides bisphérica, Globigerinoides alhpapertura, Praeorbulina sicana, Praeorbulina transitoria, and Praeorbulina glomerosa.

**Estimated local age:** middle early Miocene (early Langhian), ~ 15.92 Ma – late middle Miocene (late Serravallian), ~ 12.2 Ma.

**Mir-3.2 Fohsella sensu lato Subzone**

**Definition:** Interval zone (partial range) of Fohsella fohsi. Base defined by the HO of Fohsella peripheronda and the top by the HO of F. fohsi s.l. which includes F. fohsi, F. robusta, and F. lobata (text-figs. 6, 7).

**Additional Events:** There are no local extinction events within this subzone.

**Estimated local age:** late middle Miocene (late Serravallian), ~ 12.2 Ma – late middle Miocene (late Serravallian), ~ 11.55 Ma.

**Mir-4 Paragloborotalia mayeri Interval Zone**

**Definition:** This zone is defined as the partial range of Paragloborotalia mayeri. The base of this zone is defined by the HO of F. fohsi s.l. which includes F. fohsi, F. robusta, and F. lobata and the top is defined by the HO of P. mayeri (text-figs. 6, 7).

**Events within the zone:** HO of Menardella praemenardii.

**Remarks:** This zone is approximately equivalent to the upper M11 – lower M13a Miocene zones of Berggren et al. (1995).

**Estimated Age:** late middle Miocene (late Serravallian), ~ 11.55 Ma – earlier late Miocene (early Tortonian), ~ 9.38 Ma.

**Mir-5 Globorotalia merotumida Interval Zone**

**Definition:** This zone is defined as the partial range of Globorotalia merotumida. The base of this zone is defined by the HO of Paragloborotalia mayeri and the top is defined by the HO of G. merotumida (text-figs. 6, 7).

**Events within the zone:** HOs of Dentoglobigerina globosa and Globigerinoides subquadrata.

**Remarks:** This zone is approximately equivalent to the upper M13a – lower M13b Miocene zones of Berggren et al. (1995).

**Estimated Age:** earlier late Miocene (early Tortonian), ~ 9.38 Ma – late Miocene (late Messinian), ~ 7.03 Ma.

**Mir-6 Globoquadrina venezuelana Interval Zone**

**Definition:** This zone is defined as the partial range of Globoquadrina venezuelana. The base of this zone is defined by the HO of Globorotalia merotumida and the top is defined by the HO of G. venezuelana (text-figs. 6, 7).

**Events within the zone:** HOs of Orbulina bilobata, Globigerinoides triloba, and Sphaeroidinellopsis subdehiscent.

**Remarks:** This zone is approximately equivalent to the upper M13b to lower P12 zones of Berggren et al. (1995). The Miocene / Pliocene boundary could not be delimited here. The boundary is traditionally defined on the basis of evolutionary appearances, either Neogloboquadrina humerosa (e.g. Bolli and

---

Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there. Chaisson and D’Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lin...
Saunders 1985) or Globorotalia tumida (e.g. Berggren et al. 1995).

**Estimated Age:** late Miocene (early Messinian), ~7.03 Ma – early Pliocene (late Zanclean), ~3.97 Ma.

### Pliocene

#### Pli-1 Globigerinoidea obliqua Interval zone

**Definition:** This zone is defined as the partial range of Globigerinoidea obliqua. The base of the zone is defined by the HO of Globorotaliinae venezuelana and the top by the HO of G. obliqua (texts-desc. 6, 7).

**Events within the zone:** HOs of Sphaeroidinellopsis seminulina, Orbulina suturalis, and Globoturborotalita nepenthes.

**Remarks:** This zone is approximately equivalent to the upper PI2 - upper Pt1a zones of Berggren et al. (1995). According to Bolli and Saunders (1985), the HO of G. venezuelana is younger than HO of G. obliqua, but our data suggest the opposite. Chaisson and D’Hondt (2000) also observed this sequence at ODP site 999, western Colombia Basin.

**Estimated Age:** early Pliocene (late Zanclean), ~3.97 Ma – early Pleistocene (late Calabrian), ~0.85 Ma.

### Pleistocene-Recent

Few wells studied contain sediments of this age and hence the upper section of the sequence cannot be effectively analyzed. Younger extinctions in our planktonic foraminifera sequence are those of Neogloboquadrina pachyderma, Globorotalia decoroperta, Globigerinella praecallida, Globigerina juvenilis, and Neogloboquadrina acostaensis.

**Comparison with other biostratigraphic sequences**

Comparisons between our proposed local zonation with those of Stone (1968), Martínez (1995), Blow (1969, 1979), Postuma (1971), Kennett and Srinivasan (1983), Bolli et al. (1985), and Berggren et al. (1995) are displayed in text-fig. 8. High concordance (Kendall’s $\tau = 1.00$) between the HO events used by Stone to define zonal boundaries in the Carmen-Zambrano Section and our events shows the good biostratigraphic value of the HO events of Paragloborotalia opima, Globorotalia decoroperta, incertae sedis, C. stainforthi, Fohsella peripheroronda, and C. foehsi.

Martínez’s (1995) results closely correspond to our proposed zonation (Kendall’s $\tau = 0.78$, text-fig. 8b). Martinez used RASC (Ranking and Scaling) in 18 wells. The primary differences with Martínez’s sequence are related to the HOs of Globigerina juvenilis and Paragloborotalia mayeri. In our sequence of events, G. juvenilis is positioned in the uppermost part, but its $\varphi$ value in the CONOP wells is extremely low (0.14), suggesting that in some areas of the basin its local extinction occurs much earlier, as Martinez (1995) suggested. Bolli (1957b) suggested G. juvenilis could be found as late as our Mir-4 Paragloborotalia mayeri Zone. On the other hand, in the Martínez sequence P. mayeri is placed at a younger position, above the HOs of Globorotalia venezuelana and Globigerinoides obliqua. This order is rare and could be related to an unrecognized redeposition within the younger sequences.

High concordance was also obtained in a comparison of the proposed local zonation with global zonations of Blow (1969, 1979; Kendall’s $\tau = 0.90$), Postuma (1971; Kendall’s $\tau = 0.87$), Kennett and Srinivasan (1983; Kendall’s $\tau = 0.73$), Bolli et al. (1985; Kendall’s $\tau = 0.88$), and Berggren et al. (1995; Kendall’s $\tau = 0.99$). The correspondence between the order of those events from global frameworks and our sequence of events suggests that our zonation can be reliable at a local level.

### Biostratigraphic correlations

The modeled ages correspond to an ideal sequence of evolutionary events, which we can test for the order of its events. However, the same order in two sections may either indicate synchrony or, at the other extreme, imply a substantial difference in age between the sections (i.e. Spencer-Cervato et al. 1994; Kucera and Kennett 2000). Given the sampling resolution of the wells, and for interpretative purposes, we assume that age errors between sections may not necessarily be significant at geological time scales, and that in theory the events are synchronous.

Correlations shown in text-figs. 9, 10, and 11 illustrate the regional framework of the proposed Cenozoic biostratigraphic zones in northern Colombia. A heterochronous unconformity and its correlative surfaces between the Oca-2 and Mir-1 zones are exhibited in wells III, IV, IX, XIII, and XVI. In some areas this unconformity extends from the Eco-2 trough the Mir-1 zones, displaying the complete absence of the Oligocene (e.g. well VI, VII, XVI; text-figs. 9, 10). Another unconformity and its correlative surfaces are recognized by the absence of Mir-4 and/or Mir-5 zones in the Lower Guajira wells XI, XII, XIII, and in Sini Province wells VIII, IX, XV, XVI, XIX (text-figs. 9, 10, 11).

Other notable features displayed, in text-figs. 9, 10, 11, are the high accumulation rates during the middle Miocene Mir-3 Zone (e.g. wells II, VI, X, XIII, XIV, XV, and XVIII), and during the Pleistocene to recent sequences in well XVII. The former was also recorded by Stone (1968), in the Carmen-Zambrano section, and could be related to uplift of the Andean mountain belt, and the development of north-south drainages during the Middle Miocene (e.g. Restrepo et al. 2005); the latter could be attributed to the sediment transport caused by the Ancestral Magdalena River, which appears to have gradually changed course in the Middle Pleistocene, migrating from east of the Santa Marta Massif to the region of Galerazamba, near well XVII (e.g. Bourdine 1974; Martínez and López 2005).

In general, marine Cenozoic sedimentation in the study area is not recorded continuously. Our chronostratigraphic framework suggests it began during the Early Paleogene in the Sini Province (e.g. wells VII, IX, XVI), followed by a regional hiatus (text-figs. 12, 13, 14), possibly related to the first pre-Andean tectonic events, Paleogene diapirism, and tectonic diastrophism (e.g. Bürgl 1965; Duque-Caro 1968, 1972b, 1979; Pindell et al. 1988; Kellogg et al. 2005). During the late Eocene – middle to late Oligocene, we found the development of an Eocene-Oligocene hiatus (text-figs. 12, 13), which could be attributed to pre-Andean diastrophism, partial uplifting, and main deformation of the SJB3 caused by the interaction between the Caribbean and South American plates. The pre-Andean orogeny marks the end of the deep-sea deposition in the Cansonian Stage and the onset of the shallow marine sedimentation during the Carmanian Stage (late Middle Eocene), as described by Duque-Caro (1979, 1991).
During the Oligocene, marine sedimentation commenced in the LMV Province, "SFB Basin", and Upper Guajira Basin, while some areas probably exhibited emergent tectono-structural features (Lower Guajira y Magangué Arch) that were covered by sediments starting in the Early Miocene (text-figs. 12, 13). In both situations, the older sediments are characterized by the presence of reworked Eocene and/or Oligocene sedimentary successions (text-figs. 12, 13, 14). These sequences are capped by an Oligocene–Miocene hiatus (text-figs. 12, 13, 14), as pointed out by other authors (Stainforth 1965; Bürgi 1962, 1965; Duque-Caro 1968, 1972b, 1991). This hiatus has been attributed to regional tectonic processes that occurred along the northern and southern boundaries of the Caribbean Plate, driving normal faulting in the Plato-San Jorge basins, and an intensive accretion in the Sinú-San Jacinto Province (e.g. Duque-Caro 1979; Pindell and Barrett 1990; Flinch 2003; James 2005). In most of the region, the Oligocene sequence is not recorded (text-figs. 12, 13, 14), probably owing to the amalgamation of the E-O and O-M hiatuses (i.e. well XVI; text-fig. 13).

During the Early Miocene a regional deepening is observed. This deepening is not isochronous; it begins in the SFB Basins during the middle early Miocene, and in the LMV and Guajira Basins during the late early Miocene (text-figs. 12, 13, 14). Following the deepening, a middle to late Miocene hiatus developed. It could be related to the initial collision of the Central American arc with South America and its effects on water circulation between the Atlantic and Pacific oceans and preservation of calcium carbonate (e.g. Duque-Caro 1990, 1991; Roth et al. 2000; Coates et al. 2004). A rapid shallowing across the region is observed in the LMV Province (e.g. wells I, II) and a loss of sedimentary record in Sinú and Guajira provinces (text-figs. 12, 13, 14). After the initial collision of the Central American Arch, the northeastern areas of the Sinú and Guajira basins (wells VIII, IX, XI, XII, XIII, XII) probably experienced a latest Neogene relative sea-level rise, whereas areas such as the LMV, SJFB, and the southern Sinú Basin were still emergent (text-fig. 12, 13, 14).

**TAXONOMIC NOTES**

Only planktonic foraminifera from Table 1 have been considered in this section. All taxa reported here belong to morphospecies, which include a set of intermediate evolutionary forms. Taxonomic notes are exclusively restricted to original type descriptions. References to subsequent well-illustrated figures are also included in order to clarify the morphological concepts taken into account in the identification of foraminifera.

There has been a recent trend to refrain from using subgenus and subspecies categories. For simplicity, we have adopted this treatment. General classification for foraminifera, provided by Loeblich and Tappan (1964, 1988), has been followed. We discovered some uncertainties related to placement of some morphospecies into higher taxonomic categories, and therefore their location into the taxonomy systematic is provisional. For original description and extended discussion of the considered taxa, the reader is referred to the following studies: Bolli et al. (1957) and chapters there in, Blow (1969, 1979), Postuma (1971), Kennett and Srinivasan (1983), Olsson et al. (1999) and Pearson et al. (2006).

Genera are listed in alphabetical order by higher taxonomic category name. Under the genus subheading, taxa are listed in alphabetical order by species name. Taxonomic remarks were included in some species, depending on the complexity of identification. Illustrated specimens (Plates I to X) are housed in the Systematic Collections of Instituto Colombiano del Petróleo (SC-ICP (HD) and SC-ICP).

**Subphylum SARCODINA** Schmarda 1871
Class RHIZPODA von Siebold 1845
Order FORAMINIFERIDA Eichwald 1830
Suborder GLOBIGERININA Delage and Hérouard 1896
Superfamily GLOBIGERINACEA Carpenter, Parker and Jones 1862
Family GLOBIGERINIDAE Carpenter, Parker and Jones 1862
Genus *Catapsydrax* Bolli, Loeblich and Tappan 1957
Genus *Globigerinita* Brönnimann 1951

Subfamily GLOBIGERINIDAE Carpenter, Parker and Jones 1862
Genus *Globigerina* d'Orbigny 1826
Genus *Globigerinella* Cushman 1927
Genus *Globigerinoides* Cushman 1927
Genus *Globorotaloides* Bolli 1957
Genus *Globoturbo* Hoffker 1976
Genus *Subbotina* Broten and Posarias 1961

Subfamily ORBULININAE Schultz 1854
Genus *Orbulina* d'Orbigny 1839
Genus *Prerorbulina* Olsson 1964

Subfamily SPHAEROIDINELLAENAE Banner and Blow 1959
Genus *Sphaeroidinellopsis* Banner and Blow 1959

Family GLOBOQUADRINIDAE Blow 1979
Genus *Dentoglobigerina* Blow 1979
Genus *Globoquadrina* Finlay 1947

Family GLOBOROTALIIDAE Cushman 1927
Genus *Fohsella* Bandy 1972
Genus *Hirsutella* Bandy 1972
Genus *Menardella* Bandy 1972
Genus *Neogloboquadrina* Bandy, Frerichs and Vincent 1967
Genus *Paraglobo* Cifelli 1982
Genus *Turborotalia* Cushman and Bermúdez 1949

Family HANTKENINIDAE Cushman 1927
Subfamily HASTIGERINIDAE Cushman 1927
Genus *Clavigerinella* Bolli, Loeblich and Tappan 1957

Family TRUNCOROTALOIDIDAE Loeblich and Tappan 1961
Genus *Acarinina* Subbotina 1953
Genus *Igorina* Davidzon 1976
Genus *Morozovella* McGowan 1968
Genus *Truncorotaloides* Brönnimann and Bermúdez 1953

**Genus Catapsydrax** Bolli, Loeblich and Tappan 1957
Type Species: *Globigerina dissimilis* Cushman and Bermúdez 1937

*Catapsydrax dissimilis* Cushman and Bermúdez 1937
Plate 1, 1 a-d; Plate 4, 1 a-c, 2 a-c

*Globigerina dissimilis* CUMSHAN and BERMÜDEZ 1937: p. 25, pl. 3: figs 4-6.

283

Genus Globigerina Brönnimann 1951

Type Species. Globigerina naparimaensis Brönnimann 1951

Globigerinoides uvula (Ehrenberg 1861)


Globigerinoides juvenilis (Bolli 1957)

Globigerinoides juvenilis Bolli 1957b: p. 110, pl. 24: figs. 5a-c, 6. – BLOW 1959: p. 178, pl. 10: figs. 43a, b.

PLATE 1

Globigerinidae: Catapsydrax, Globigerinoides, Globoturborotalita and Subbotina. SEM images.

1 Catapsydrax dissimilis (Cushman and Bermúdez 1937). a) dorsal view, b) axial view, c) ventral view. Scale bar: 150µm; d) wall texture detail, scale bar: 20µm. Late Oligocene, Paragloborotalia opima zone. Carmen Formation (lower segment), Toluviejo, Carmen-Zambrano Section, SJFB – Sinú Sedimentary Province. Bolívar, Colombia. TV-11 Sample. (Repository: SC-ICP (HD) - PF-00003).


7 Subbotina linaperta (Finlay 1939). a) ventral view, scale bar: 100 Fm; b) wall texture detail, scale bar: 20 Fm. Late Eocene, Subbotina yeguaensis zone. San Jacinto Formation, Arroyo Alférez, Carmen-Zambrano Section, SJFB – Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-063 Sample. (Repository: SC-ICP-PF-00045).

8 Subbotina yeguaensis (Weinzierl and Applin 1929). a) ventral view, scale bar: 100 Fm; b) wall texture detail, scale bar: 20 Fm. Late Eocene, Subbotina yeguaensis zone. San Jacinto Formation (upper segment), Arroyo Alférez, Carmen-Zambrano Section, SJFB – Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-131 Sample. (Repository: SC-ICP-PF-00046).
Remarks: A penultimate whorl with only four chambers (in-

Genus Globigerina d’Orbigny 1826
Type Species: Globigerina bulloides d’Orbigny 1826

Globigerina foliata Bolli 1957
Globigerina foliata Bolli 1957. — BERMUDEZ 1961: p. 1187, pl. IV: fig. 4a, b.

Globigerina pseudociperoensis Blow 1969

Remarks: A penultimate whorl with only four chambers (in-

Globigerinoides Cushman 1927
Type Species: Globigerina rubra d’Orbigny 1839

Although the International Code of Zoological Nomenclature (International Commission on Zoological Nomenclature – ICZN 1999) specifies that “a compound genus-group name ending in the suffix [...] – oides [...] is to be treated as masculine [...]” (Article 30.1.4.4.), and that a species-group name “must agree in gender with the generic name with which it is at any time combined” (Article 31.2), the ICZN also makes it clear that “a species-group name that is a simple or compound noun (or noun phrase) in apposition need not agree in gender with the generic name with which it is combined (the original spelling is to be retained, with gender ending unchanged” (Article 31.2.1, italic ours). Therefore, the neuter species-group name ending (-a) of those species grouped under Globigerinoides, the type species of which first belonged to genus Globigerina (e.g. Globigerinoides conglobata Brady 1879, Globigerina quadrilobata d’Orbigny 1846, or Globigerina fistulosa Schubert 1810), has been retained here.

The ‘Globigerinoides’ word belongs to a substantivized adject-

PLATE 2

Globorotaliidae: Fohsella and Paragloborotalia. SEM images.

1 Fohsella peripheraloronda (Blow and Banner 1966). a) dorsal view, b) axial view, c) ventral view. Scale bar: 100µm; d) wall texture detail, scale bar: 20µm. Middle Miocene, Globigerinoides primordius zone - Globigerinoides diminuta subzone, Buenavista-1 Well, Plato Basin, LMV Sedimentary Province. Magdalena, Colombia. 9480ft - 9500ft Sample. (Repository: SC-ICP-PF- 00031).

2 Paragloborotalia griffinioides Olsson and Pearson 2006. a) dorsal view, b) axial view, c) ventral view. Scale bar: 75 Fm; d) wall texture detail, scale bar: 10µm. Middle Eocene, Paragloborotalia griffinioides zone - Clavigerinella colombiana subzone, Chengu Formation, Arroyo El Limón, Carmen-Zambrano Section, SJFB - Sinú Sedimentary Province. Bolivar, Colombia. AL-006st Sample. (Repository: SC-ICP-PF- 00030).


4 Paragloborotalia mayeri (Cushman and Ellisor 1939). a) dorsal view, b) axial view, c) ventral view. Scale bar: 100 Fm; d) wall texture detail, scale bar: 20 Fm. Middle Miocene. Fohsella foohi zone - Fohsella foohi sensu lato subzone. Tayrona-1 Well, LGB - Guajira Sedimentary Province. Guajira, Colombia. 12380ft Sample. (Repository: SC-ICP-PF- 00043).

5 Paragloborotalia opima (Bolli 1957). a) dorsal view, b) ventral view. Scale bar: 100µm; c) wall texture detail, scale bar: 20µm. Late Oligocene, Paragloborotalia opima zone. Carmen Formation, Arroyo Alférez, +Carmen-Zambrano Section, SJFB - Sinú Sedimentary Province. Bolivar, Colombia. G05-CB-446 Sample. (Repository: SC-ICP-PF- 00044).
ending when the type-species name ends in neuter form. Furthermore, Cushman retained the neuter form of Globigerinina rubra d’Orbigny species-name when he proposed his genus Globigerinoides. Taking the arguments given above into account, we have retained here the ending of those species first described in combination with Globigerinoides whose species-group name ends in neuter form (e.g. Globigerinoides immatura Leroy 1939 or Globigerinoides tenella Parkera 1958).

However, following the ICNZ recommendations, we have preserved a masculine ending ( -us) when a species-group name in apposition with Globigerinoides was first published using this ending (e.g. Globigerinoides primordius Blow and Banner 1962 or Globigerinoides bulloideus Crescenti 1966). Globigerinoides altiapertura Bolli 1957

Globigerinoides triloba altiapertura Bolli 1957b: p. 113, pl. 25: figs. 7 a-c and 8. – Blow 1959: p. 197, pl. 10: figs. 61a, b. 


*Globigerinoides altiapertura* Bolli 1957 – Kennett and Srinivasan 1983: p. 54, pl. 11: figs. 4-6.

Globigerinoides bispherica Todd 1954


Globigerinoides mitra Todd 1957

Globigerinoides mitra Todd 1957: p. 302, pl. 78: figs. 3, 6. – BOLLI 1957b: p. 114, pl. 27: figs. 2a, b.

PLATE 3

Globorotaliidae: *Turborotalia*; Globocuoquadriiidae: *Globoquadrina*; Hankeniniidae: *Clavigerinella*; and Truncorotaliidae: *Acarina* and Morozovella. SEM images.


2 *Globoquadrina venezuelana* (Hedberg 1937). a) dorsal view, b) ventral view, scale bar: 10 Fm; c) wall texture detail, scale bar: 10 Fm. Middle Miocence, *Fohsella fohsi* zone - *Fohsella fohsi* sensu lato subzone. Tayrona-1 Well, LGB - Guajira Sedimentary Province. Guajira, Colombia. 12030ft Sample. (Repository: SC-ICP-PF- 00017).


Daniel A. Rincon et al.: Eocene - Pliocene planktonic foraminifera biostratigraphy from the continental margin of Southwest Caribbean

Globigerinoides primordius Blow and Banner 1962

Globigerinoides obliqua Bolli 1957

Globigerinoides obliqua Bolli 1957b [in part]: p. 113, pl. 25: figs. 10a-c. - BLOW 1959: p. 191, pl. 11: figs. 8a-b.


Globigerinoides subquadratea BRÖNNIMANN 1954


Globigerinoides subquadratea BRÖNNIMANN 1954

Globigerinidae: Catapsydrax, Globigerioides and Globorotaliidae. Optical images.

PLATE 4


Remarks: Both an equatorial and axial subquadrature profile, with very moderately depressed intercameral sutures, a distinctive shallow umbilicus, and only one arecate supplementary aperture (instead of two) directly opposed to the main aperture characterize this morphospecies. Furthermore, the initial part of the test is fundamentally restricted to the first chamber of the last whorl.

Globigerinoides triloba (Reuss 1850)


Genus Globorotaliidae Bolli 1957

Type Species: Globorotaliidae variabilis Bolli 1957


Remarks: Both an equatorial and axial subquadrature profile, with very moderately depressed intercameral sutures, a distinctive shallow umbilicus, and only one arecate supplementary aperture (instead of two) directly opposed to the main aperture characterize this morphospecies. Furthermore, the initial part of the test is fundamentally restricted to the first chamber of the last whorl.

Globigerinoides triloba (Reuss 1850)


Genus Globorotaliidae Bolli 1957

Type Species: Globorotaliidae variabilis Bolli 1957

Globorotaliidae sutleri Bolli 1957

Plate 4, 7a-c


Remarks: Both an equatorial and axial subquadrature profile, with very moderately depressed intercameral sutures, a distinctive shallow umbilicus, and only one arecate supplementary aperture (instead of two) directly opposed to the main aperture characterize this morphospecies. Furthermore, the initial part of the test is fundamentally restricted to the first chamber of the last whorl.

Globigerinoides triloba (Reuss 1850)


Genus Globorotaliidae Bolli 1957

Type Species: Globorotaliidae variabilis Bolli 1957

Globorotaliidae sutleri Bolli 1957

Plate 4, 7a-c

Globorotaloides variabilis Bolli 1957
Globorotaloides variabilis BOLLI 1957b: p. 117, pl. 27, figs. 15a, b 16a, b 17a, b 18a, b 19a-c and 20a-c. – BLOW 1959: p. 208, pl. 16 figs. 103a-c 104 and 105. – BERMÚDEZ 1961: p. 1306, pl. XVIII, figs. 3a, b. – KENNEDT and SRINIVASAN 1983: p. 214, pl. 53: figs. 6-8.

Genus Globoturborotalita Høfler 1976
Type Species: Globigerina rubescens Høfler 1956

The phylogenetic relationship between species of ‘ciperoensis-group’ has been established by Kennett and Srinivasan (1983) through the lineage ‘Globigerina (Globigerina) angustiumbilicata - G. (G.) ciperoensis - (G. (G.)) angulisuturalis’. Previously, Blow and Banner (1962) regarded Globigerina officinalis as the stem species of Globigerina ouachitaensis ciperoensis and Globigerina angulisuturalis through G. ouachitaensis ouachitaensis (Lineage D); later Blow (1969) considered his Globigerina angulisuturalis species a “phylogenetically advanced [taxon] [...] of the lineage which leads to G. officinalis to G. angulisuturalis”, establishing it as an ancestral form that “gradually evolves into G. angulisuturalis”. Recently, taking Globoturborotalita bassriverensis Olsson and Hemleben, 2006 as the first species of the genus, the ‘ciperoensis-group’ species are characterized by a small globular test, slightly embracing chambers, an umbilical-position aperture with development of lip and, a moderate to distinctive cancelate wall texture. Taking the possible phylogenetic relationships and morphological features into account, we have also included the species Globigerina angulisuturalis and Globigerina ciperoensis here in Globoturborotalita.

Globoturborotalita angulisuturalis (Bolli 1957)

Globigerinidae: Globoturborotalita. Optical images.


8 Globoturborotalita decoraperta (Takayanagi and Saito, 1962). a) dorsal view, b) axial view, c) ventral view. Scale bar: 50 Fm. Early Pliocene, Globotruncanita venezuelana zone. DSM Leg 15 Site 154A, Colombian Basin. Caribbean Sea, Colombia. 114.01m Sample. (Repository: SC-ICP (HD) - PF-00020).


Globigerina (Globigerina) angulisuturalis Bolli 1957 – KENNEDY and SRINIVASAN 1983: p. 32, pl. 5: figs. 1-3.

‘Globoturborotalita angustiumbilicata’
Plate 1, 3a,b; Plate 5, 4a-c, 5a-c.

Globigerina ciperoensis angustiumbilicata Bolli 1957b [in part]: p. 109, pl. 22: figs. 12a-c, 13a-c.

Globigerina ciperoensis angustiumbilicata BOLLI 1957c: p. 164, pl. 36: figs. 6a-b


[N] Globigerina (Globoturbinia) angulisuturalis Bolli 1957 – KENNEDY and SRINIVASAN 1983. p. 31, pl. 4: figs. 3-5.


Tenuitellinata angustiumbilicata (Bolli 1957). – PEARSON and CHAISSON 1997 [in part]: p. 64, pl. 2, fig. 15.

Remarks: Largely because of its wall microstructure characteristics and apertural details, Li (1987) considered Globigerina angulisuturalis to be the type species of genus Tenuitellinata, pointing out differences between G. angulisuturalis and the two remaining Bolli’s subspecies of Globigerina ciperoensis. Under ‘Globoturborotalita angustiumbilicata’ we have provisionally placed the homeomorphic ‘Globoturborotalita angustiumbilicata’ specimens of T. angustiumbilicata, classified by a moderate to distinctive cancellate wall texture sharing the same features of the ‘ciperoensis’-group species (see SEM image Plate 1, 3b and compare it with Plate 1, 4c and 5). The specimens included under this morphospecies have been found only in analyzed samples containing late Eocene to early Miocene planktonic assemblages; this accords with the initial stratigraphic range of Globigerina ciperoensis angustiumbilicata (Bolli 1957b, c; Bolli and Saunders 1985). Probably ‘Globoturborotalita angustiumbilicata’ specimens had been also included with material studied by Bolli (1957b) when he proposed his subspecies. It is possible that ‘Globoturborotalita angustiumbilicata’ belonged to a late Eocene to early Miocene restricted form of T. angustiumbilicata (Bolli 1957) adapted to special conditions.

Globoturborotalita ciperoensis (Bolli 1957)
Plate 1, 4a-c, 5; Plate 5, 6a-c, 7a-c.


Globigerina (Globigerina) ciperoensis Bolli 1954. – KENNEDY and SRINIVASAN 1983: p. 28, pl. 4: figs. 6-8.


Globoturborotalita decoraperta (Takayanagi and Saito 1962)
Plate 5, 8a-c

Globigerina druryi Akers subspp. decoraperta TAKAYANAGI and SAI TO 1962: p. 85, pl. 28: figs. 10-a-c.

Globigerina (Zeaglobigerina) decoraperta Takayanagi and Saito 1962 – KENNEDY and SRINIVASAN: p. 48, pl. 9, figs. 4-6.

Globoturborotalita nepenthes (Todd 1957)

Globigerina (Zeaglobigerina) nepenthes Todd 1956 – KENNEDY and SRINIVASAN 1983: p. 48, pl. 9, figs. 1-3.


Globoturborotalita nepenthes (Todd 1956) – CHAISSON and D’HONDT 2000: p. 33, pl. 1: fig. 16 (transitional specimen between Globoturborotalita druryi (Akers 1955) and G. nepenthes (Todd 1956)).

PLATE 6
Globigerinidae: Subbotina. Optical images.


Subbotina gortanii (Borsetti 1959)
Plate 6, la-c; Plate 5, 9a-c.

Remarks: Under Subbotina gortanii (Borsetti 1959) only the specimens that strictly match the description of Globigerina gortanii gortanii (= Globigerina turritilina turritilina Blow and Banner 1962) have been included. In the present study, we retained the subspecies G. gortanii praeturritilina (G. turritilina praeturritilina Blow and Banner 1962). The specimens included in this subspecies are characterized by being less inflated chambers than S. gortanii.

Subbotina linaperta (Finlay 1939)
Plate 1, 6a-c; Plate 5, 9a-c.

Remarks: Under Subbotina linaperta (Finlay 1939), only the following restricted morphological variation was considered: specimens with (1) a test with a sub-square to slightly sub-ovoid equatorial profile, a periphery weakly lobulate and, an oval to ovoid axial profile; (2) a subcircular last chamber broader than high, with a ventral face from circular to flattened (in both ventral and axial views), and an apertural face from subcircular to slightly flat; and (3) an apertural constituted by a very low arch with a distinctive lip, nearly in contact with the first chambers of the last whorl.

Subbotina senilis (Bandy 1949)
Plate 6, 6a-d.

Remarks: Under Subbotina senilis we include those forms with an inflated (not flattened) last chamber and an apertural face restricted to the umbilical area. By apertural face we mean the area of the last chamber that is directly in contact with the aperture. Other authors, such as Pearson et al. (2006), have regarded the morphotype associated with Globigerina ouachitensis senilis Bandy 1949 as part of the morphologic variation of Subbotina jacksonensis (Bandy 1949) species.

Subbotina yeguaensis (Weinzierl and Applin 1929)
Plate 1, 8a, b; Plate 7, 1a-c, 2a-c, 3a-c, 4a-c.

Remarks: Under Globigerina yeguaensis Weinzierl and Applin 1929 – Berggren 1960: p. 73, pl. II: figs. 1a-c, 3a-c; pl. IV: figs. 1a-c, 2a-c; pl. VIII: figs. 1a-c, 2a-c – Postuma 1971: p. 162, 163.

Globoturborotaliata ouachitensis (Howe and Wallace 1932)
Plate 1, 6a-c; Plate 7, 6a-c.


Genus Subbotina Broten and Pozaryska 1961
Type Species: Globigerina triloculinoides Plummer 1926


PLATE 7

Daniel A. Rincón et al.: Eocene-Pliocene planktonic foraminifera biostratigraphy from the continental margin of Southwest Caribbean

Subbotina yeguaensis (Weinziera and Applin 1929) – Pearson et al., 2006 [in part]: p. 152, pl. 6.18: figs. 1-3 (illustrated holotype - SEM), 4-8, 12(7), 13-15.

Genus Orbulina d’Orbigny 1839
Type Species: Orbulina universa d’Orbigny 1839

Orbulina bilobata (d’Orbigny 1839) – Blow 1956: p. 201, fig. 24: 1.

Orbulina bilobata d’Orbigny 1839: p. 164, pl. 20: figs. 7-9.

Orbulina universa (d’Orbigny 1839) – Blow 1956: pi. 13: figs. 82a-b.


Orbulina sicana (De Stefani 1950) – Cushman and Stainforth 1945 [in part]: p. 68, pl. 13: fig. 6.


Subbotina yeguaensis (Weinziera and Applin 1929) – Pearson et al., 2006 [in part]: p. 152, pl. 6.18: figs. 1-3 (illustrated holotype - SEM), 4-8, 12(7), 13-15.

Genus Orbulina d’Orbigny 1839
Type Species: Orbulina universa d’Orbigny 1839

Orbulina bilobata (d’Orbigny 1839) – Blow 1956: p. 201, fig. 24: 1.

Orbulina bilobata d’Orbigny 1839: p. 164, pl. 20: figs. 7-9.

Orbulina universa (d’Orbigny 1839) – Blow 1956: pi. 13: figs. 82a-b.


Orbulina sicana (De Stefani 1950) – Cushman and Stainforth 1945 [in part]: p. 68, pl. 13: fig. 6.


PLATE 8
Globoquadrinidae: Dentoglobigerina and Globobquadrina; Globorotaliidae: Turborotalia. Optical images.


Genus Sphaeroidinellopsis Banner and Blow 1959
Type Species: Globigerina seminulina Schwager 1866

Sphaeroidinellopsis subdehiscens (Schwager 1866)

Sphaeroidinellopsis seminulina seminulina (Schwager 1866). - KENNEDY and SRINIVASAN 1983: p. 206, pl. 57: figs. 6-8.

Sphaeroidinellopsis multiloba (Banner and Blow 1965).

Sphaeroidinellopsis subdehiscens subdehiscens (Blow 1959). – BLOW 1959: p. 183, pl. 2: figs. 1-3 (re-illustrated holotype); pl. 16: figs. 4-5.


Dentoglobigerina globosa (Bolli 1957)

Globorotalia merotumida (Cushman and Jarvis 1936) subsp. globosa BOLLI 1957b: p. 111, pl. 24: figs. 9a-c, 10a-c. – BLOW 1959: p. 183, pl. 11: figs. 52 a-c.


Dentoglobigerina pseudovenezuelana (Bolli and Banner 1962)

Plate 8, 1a-c


2, 3 Globorotalia merotumida Blow and Banner 1965. a) dorsal view, b) axial view, c) ventral view. Scale bar: 100 Fm. Late Miocene, Globoquadrina merotumida zone. Perdices Formation, Lurucuo - Rotinet section. SFB, Sint Sedimentary Province. Córdoba, Colombia. HD-1143 Sample. (Repository: SC-ICP (HD) - PF-00096).

4 Hirsutella praescutula (Bolli 1959) - Menardella archeomenardii (Bolli 1957) transitional morphotype (?). a) dorsal view, b) axial view, c) ventral view. Scale bar: 100 Fm. Middle Miocene, Globigerinoides primordius zone - Globigerinoides diminuta subzone. Buena Vista-1 Well. Plato Basin, LVM Sedimentary Province. Magdalena, Colombia. 10240ft - 10260ft Sample. (Repository: SC-ICP-PF-00080).

5 Menardella praemenardii (Cushman and Stainforth, 1945), reworked specimen. a) dorsal view, b) axial view, c) ventral view. Scale bar: 200 Fm. Late Miocene, Globoquadrina venezuelana zone. Buenavista-1 Well. Plato Basin, LVM Sedimentary Province. Magdalena, Colombia. 4500ft Sample. (Repository: SC-ICP-PF-00081).

6 Neogloboquadrina acostaensis (Blow 1959). a) dorsal view, b) axial view. Scale bar: 100 Fm. Late Miocene to early Pliocene, Globoquadrina venezuelana zone. Perdices Formation, Puerto Escondido, marginal terrace. SFB, Sinu Sedimentary Province. Córdoba, Colombia. HD-1151 Sample. (Repository: SC-ICP (HD) - PF-00066).

7 Neogloboquadrina pachyderma (Ehrenberg, 1872). a) dorsal view, b) axial view, c) ventral view. Scale bar: 100 Fm. Early Pliocene, Globoquadrina venezuelana zone. DSDP Leg 15 Site 154A, Caribbean Sea, Colombia. 145.87m Sample. (Repository: SC-ICP (HD) - PF-00031).
**Dentoglobigerina tapuriensis** (Blow and Banner 1962)
Plate 8, 2a-c.


Genus *Globoquadrina* Finlay 1947
Type Species: *Globoquadrina dehiscens* Chapman, Parr and Collins 1934

**Globoquadrina venezuelana** (Hedberg 1937)
Plate 3, 2a-c; Plate 8, 4a-c, 5a-c.


**Genus Fohsella Bandy 1972**
(Type Species: *Globoquadrina* (Globoquadrina) praefohsi Blow and Banner 1966)

*Globoquadrina* (Fohsella) praefohsi BANDY 1972

**PLATE 10**

Globorotaliidae: Paragloborotalia; Truncorotaloididae; Acarinina and Truncorotaloides. Optical images.


Genus Globorotalia (sensu Bandy 1972) (nomen translatum, ex subgenus) Type Species: Pulvinulina menardii (d’Orbigny) var. tumida Brady 1877 Globorotalia (Globorotalia) tumida (Brady 1877) – Bandy 1972


Genus Hirsutella Bandy 1972 (nomen translatum, ex subgenus) Type Species: Rotalina hirsuta d’Orbigny 1839 Globorotalia (Hirsutella) hirsuta (d’Orbigny 1839) – Bandy 1972

Hirsutella praescitula (Blow 1959) Plate 9, 4a-c. [Transitional form H. praescitula – M. archeomenardii]

Globorotalia scitula (Brady) subsp. praescitula BLOW 1959: p. 221, pl. 19: figs. 128a-c. – GIBSON 1983: p. 373, pl. 5: figs. 1, 2.

Genus Menardella Bandy 1972 (nomen translatum, ex subgenus) Type Species: Pulvinulina menardii Parker, Jones and Brady 1865 Globorotalia (Menardella) menardii (Parker, Jones and Brady 1865) – Bandy 1972


Globorotalia (Menardella) archeomenardii Bolli 1957 – KENNETT and SRINIVASAN 1983: p. 122, pl. 28: figs. 3-5.

Menardella praemenardii (Cushman and Stainforth 1945) Plate 9, 5a-c.


Globorotalia (Globorotalia) praemenardii Cushman and Stainforth 1945. – BLOW 1969: p. 171, pl. 6: figs. 1-3 (re-drawn holotype).

Globorotalia (Menardella) praemenardii Cushman and Stainforth 1945 – KENNETT and SRINIVASAN 1983, p. 122, pl. 28: figs. 6-8.

Genus Neogloboquadrina Bandy, Freirichs and Vincent 1967 Type Species: Globigerina dutertrei d’Orbigny 1839

Neogloboquadrina acostaensis (Blow 1959) Plate 9, 6a, b


Neogloboquadrina pachyderma (Ehrenberg 1872) Plate 9, 7a-c.


Paragloborotalia akeri (Bolli 1957) - Clavigerinella akersi Bolli, Loeblich and Tappan 1957
Type Species: Clavigerinella akersi Bolli, Loeblich and Tappan 1957

Paragloborotalia opima (Bolli 1957) - Portage 1957: p. 294-296, pl. 1: figs. 1a-b, 2a-d and 3a-b; pl. 2: figs. 4a; pl. 3: figs. 1a-b, 2a-b, 3a-b; pi.4: figs. 2, 3a-b, 4a-b. - POSTUMA 1971: p. 202, fig. 26: 24-29.
Genus Acarinina Subbotina 1953
Type Species: Acarinina acarinata Subbotina 1953

Acarinina aspensis (Colom 1954)

Acarinina bullbrooki (Bolli 1957)

Acarinina esnaensis (LeRoy 1953)
Plate 10, 7a-c
Globigerina esnaensis LEROY 1953; p. 31, pl. 6: figs. 8 - 10. Globorotalia esnaensis LeRoy 1953. – LOEBLICH and TAPPAN 1957: p. 189, pl. 57: figs. 7a-c; pl. 61: fig. 1a-c, 2a-c, 9a-c. – BERGGREN 1960b: p. 92, pl. V: figs. 3a-c, pl. VI: figs. 1a-c, pl. X: figs. 3a-c.
Globorotalia colomi BERMUEDEZ 1961: p. 1167, pl. II: figs. 6a-c.

Acarinina pentacamerata (Subbotina 1947)
Plate 3, 5a-c

Genus Igorina Davison 1976
Type Species: Acarinina tadjikistanensis Bykova 1953

Igorina broedermanni (Cushman and Bermúdez 1949)
Plate 3, 6a-c
Postgloborotalia broedermanni (Cushman and Bermúdez 1949) – BERMUEDEZ 1961: p. 1340, pl. XVI: figs. 6a-c.
Acarinina broedermanni (Cushman and Bermúdez 1976) – TOUMARKINE and LUTEBACHER 1985: p. 130, fig. 29: 15-17, 19, 20 a-c (7).
Igorina broedermanni (Cushman and Bermúdez 1949) – PEARSON et al. 2006: p. 381, pl. 12.1: figs. 1-3 (illustrated holotype - SEM), 4-12.

Genus Morozovella McGowan 1968
Type Species: Pulvinulina velascoensis Cushman 1925

Morozovella spinulosa (Cushman 1927)
Plate 10, 8a-c
“Globorotalia (Globorotalia) spinulosa Cushman 1927” – BLOW 1969: p. 172, pl. 50: figs. 2-5.

Morozovella spinulosa (Cushman 1927). – TOUMARKINE and LUTEBACHER 1985: p. 130, fig. 3b: 2, 3a-c, 4a, b, and 5-8.
Morozovelloides crassata (Cushman 1925) – PEARSON et al. 2006 [in part]: p. 337, pl. 10.3: figs. 5-7 (illustrated holotype of Globorotalia spinulosa - SEM).

Genus Truncorotaloides Brönnimann and Bermúdez 1953
Type Species: Truncorotaloides rohri Brönnimann and Bermúdez 1953

Truncorotaloides rohri Brönnimann and Bermúdez 1953
Genus Acarinina Subbotina 1953

CONCLUSIONS
We propose a planktonic foraminifera biozonation for the continental margin of the northwestern South Caribbean based upon the quantitative analysis of 26 wells and 1961 samples. The zonation is composed of 68 events, thirteen zones and eight subzones delimited by HOs (high occurrence events) of planktonic foraminifera for the Eocene-Pliocene interval. Three zones and two subzones were defined for the Eocene, three zones for the Oligocene, six zones and six subzones for the Miocene, and one zone for the Pliocene.

We recognize three major hiatuses: (1) late Eocene – early Oligocene hiatus; (2) late Oligocene – early Miocene hiatus; and (3) late Miocene hiatus. We speculate that these hiatuses are related to the collision history of the Caribbean plate with the South American plate, which resulted in the Andean orogeny.

ACKNOWLEDGMENTS
Supported by the Instituto Colombiano del Petróleo (ICP) and the Smithsonian Paleobiology Endowment Fund. Museo Geológico José Royo y Gómez de INGEOMINAS supported samples and information. For critical reading the manuscript and valuable advice the authors are indebted to Dr. E. Molina (Universidad de Zaragoza, Spain), Dr. P. Sadler (University of California, Riverside), Dr. H. Duque-Caro (Duque-Caro & Cia, Bogota), Dr. S. Moodley, Dr. W. A. Berggren, Dr. B. O’Neill, Dr. R. Reymont, and Dr. R. L. Fleischer. Carlos Jaramillo thanks specially to M. I. Barreto for her continuous support and source of ideas and to all members of Grupo de Bioestratigrafía at ICP-ECOPETROL.

REFERENCES


Daniel A. Rincón et al.: Eocene - Pliocene planktonic foraminifera biostratigraphy from the continental margin of Southwest Caribbean


ROTH, J. M., DROXLER, A. W. and KAMEO, K., 2000. The Caribbean carbonate crash at the Middle to Late Miocene transition: link-
The Phi index (φ) was employed to evaluate the position of a particular event in a well versus an ideal sequence of events proposed for a basin. Weight and categorization of relative position of each event are evaluated to calculate φ. It is calculated for each event in a given stratigraphic succession of events. It basically compares the position of an event versus other events in a section, versus its ideal position in an ideal sequence of events (i.e. constrained optimization composite sequence). Then, a weighting of those differences is required, penalizing more those events that are far apart in the ideal sequence and are mismatched in the stratigraphic section. Finally, sum all the weighted differences for each event. The index ranges from 0, when the event is totally out of sequence, to 1 when the event fully agrees with the sequence predicted by the ideal sequence.

Definition: Let \( \{n_1, n_2, n_3, \ldots n_t\} \) the set of events recorded in a given stratigraphic succession. Suppose that \( n_t \) is the event to be evaluated and \( m_t \) is another event from the same set. The Phi index for \( n_t \) event is defined as:

\[
\phi = \frac{\sum_{i=1}^{t} C_i}{\sum_{i=1}^{t} W_i} = \frac{\sum_{i=1}^{t} [A_{ai} * W_{ai}]}{\sum_{i=1}^{t} [A_{a\text{ideal}} * W_{ai}]} \quad (1)
\]

where \( A_{ai} \) and \( A_{a\text{ideal}} \) are the 'categorization' function evaluated in \( m_{ai} \) condition for studied and ideal sequences respectively; and \( W_{ai} \) is the Weight function evaluated in the absolute difference between \( n_t \) position and \( n_i \) position in a reference sequence (i.e. \( \Delta_{\text{Events}} \)).

\( m_{ai} \): Condition that indicates the departure between the target event \( (n_t) \) position with respect to \( n_i \) event position, both recorded into the analyzed stratigraphic sequence of events.

\[
m_{ai} = \begin{cases} 
> 0 & \text{if } n_i \text{ position is above } n_t \text{ position, } \forall n_i > n_t \text{ or} \\
< 0 & \text{if } n_i \text{ position is below } n_t \text{ position, } \forall n_i < n_t \\
= 0 & \text{if } n_i \text{ position is above } n_t \text{ position, } \forall n_i < n_t 
\end{cases} \quad (2)
\]

where 'above' and 'below' refer to the observed stratigraphic position. These alternatives allow the categorization function to be calculated. This function employs the following categories: 1) Right sensu stricto when the \( n_t \) and \( n_i \) behavior observed in stratigraphic succession fits the expected behaviour found in the ideal sequence \( (m_{ai} > 0) \); 2) Wrong when this behavior is not the expected, \( (m_{ai} < 0) \); and 3) Right sensu lato, when there is the same probability that this behaviour could be right or wrong \( (m_{ai} = 0) \). For this work, we have employed the following values:

\[
A_{ai} = \begin{cases} 
1.0 & \text{if } m_{ai} > 0, \\
0.0 & \text{if } m_{ai} < 0, \text{ or} \\
0.5 & \text{if } m_{ai} = 0
\end{cases} \quad (3)
\]

\( \Delta_{\text{Events}} \): Parameter that establishes the absolute difference between the \( n_0 \) and \( n_i \) position in the ideal sequence of events.

\[
\Delta_{\text{Event}} = [n_i - n_0] \in [0,n_{i+1}] \quad (4)
\]

However, given that for any \( A_{ai} \) set for specific target event \( (n_0) \), the more outstanding \( A_{ai} \) values are those that indicate the relationship between the \( n_i \) events more close to \( n_0 \) event; it has considered suitable penalize for departure between \( n_i \) position in relation to \( n \) position in the ideal sequence of events (i.e. \( \Delta_{\text{Events}} \)) employing the Weight function:

\[
W = e^{a\cdot \beta \cdot \delta} < 0 \text{ and } dx = (A_{\text{Events}} - 1) \quad (5)
\]

where \( \beta \) is the parameter that restricts the function concavity:

\[
\hat{a} = e^{-1 \text{Ln} pC(-1)} \quad (6)
\]

with \( \eta = \text{maximum Event} \) reported for \( \{n_i\} \) recorded in analyzed stratigraphic succession, and \( p \) is a value that indicates change rate expected when the \( x \) is a discrete variable:

\[
p = e^{1/ \hat{a}} \approx 0.36788, \forall k \in Z \quad (7)
\]

This weight function strongly penalizes a mismatch of event sequences that are far apart in the ideal sequence, and slightly penalizes a mismatch of events that are close to each other in the ideal sequence.

The following is the basic method employed to calculate \( \phi \) for given \( n_0 \): 1) Define the ideal sequence of events; 2) Indicate \( \eta \) value and to calculate \( \beta \) (equation 6); 3) Calculate the Weight function for all possible \( x \) (\( \Delta_{\text{Events}} \)) values (equations 4 and 5); 4) Indicate the relative position that take \( \{n_i\} \), including \( n_0 \), in the analyzed section (in strict stratigraphic order); 5) Arrange the \( n_i \) events set (recorded in stratigraphic succession) in accordance with the order that these same \( n_i \) events have in the ideal sequence; 6) Calculate \( m_{ai} \) and \( A_{ai} \) (equations 2 and 3), and to ascribe the specific \( \Delta_{\text{Events}} \) values and their respective \( W \) values for each \( n_i \) - \( n_0 \) pair; and 7) Calculate \( C_{ai}, \Sigma_{W} \) and \( \Sigma_{C} \). The following matrix illustrates the process for calculating the \( \phi \) index for \( n_0 \) into a \( n_i \) events set:

\[
\begin{array}{cccccccc}
\text{ni} & m_{ai} & A_{ai} & A_{\text{Events}} & W & C_i \\
1 & m_1 & A_1 & [n_1 - n_0] & W_1 & C_1 \\
2 & m_2 & A_2 & [n_2 - n_0] & W_2 & C_2 \\
3 & m_3 & A_3 & [n_3 - n_0] & W_3 & C_3 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
4 & m_k & A_k & [n_k - n_0] & W_k & C_k \\
\end{array}
\]

\[
\sum_{i=1}^{n} W_i \sum_{i=1}^{n} C_i
\]
Example. Suppose a sedimentary stratigraphic section, which the biostratigraphic distribution of certain taxa has been studied (text-fig. 15a), and that the following LO (Last Occurrences) events were recorded: W, N, D, E, B and J. Phi index will be calculated for each event of the stratigraphic succession compared to an ideal sequence of events (text-fig. 15b). Let’s also assume that the ideal sequence has 20 LO events (text-fig. 15b), the \( \eta \) value is 19 and \( \beta \) is approx. \(-0.2076\) (equation 6). Next, the Weight function is calculated (equation 5) for all possible \( x \) values (text-fig. 15d). Next, the \( n_i \) events set (recorded in stratigraphic succession) are arranged in accordance with the ideal sequence (text-fig. 15e), and the \( m_{ai} \) \( A_{ai} \) and \( \Delta_{Events} \) (equations 2, 3 and 4) parameters are estimated employing a matrix set (text-fig. 15e). To illustrate their use, consider that \( n_i = n_{14} \) and \( n_a = n_{10} \). Both events are recorded in the same position in the stratigraphic succession, therefore the \( m_{ai} \) (in this case, \( m_{10-14} \)) condition is 0 (text-fig. 15a, c and c-M matrix); and the categorization function \( (A_{10-14}) \) is 0.5 (equation 3, text-fig. 15e-A matrix). Given that \( \Delta_{Events} \) value between \( n_{14} \) and \( n_{10} \) is 4, its respective \( W \) value is 0.54 (Weight function evaluated for \( x = 3 \) (\( \Delta_{Events} = 1 \)); text-fig. 15d and c-\( \Delta E \) and \( W \) matrices). Lastly, \( C_{ai} \) parameter (\( C_{10-14} \), in this case) is calculated multiplying \( A_{10-14} \) by \( W_{10-14} \) values (0.27; text-fig. 15e-C Matrix). The same process is performed for all \( n_i \) events recorded next to target event \( (n_{10}) \) into analyzed stratigraphic section, (in the example \{\( n_{3}, n_{13}, n_{17}, n_{16}, n_{20} \}\}), allowing to calculate that \( \varphi \) for \( n_{10} \) as 0.44 (equation 1; text-fig. 15e-W and C matrices and f).

The lowest \( \varphi \) Index, 0.22, corresponds to the last occurrence of species E (\( n_3 \)), which is the event more misplaced in the sequence, compared to the ideal sequence. It has the last occurrences of species W (\( n_{13} \)), N (\( n_{14} \)), and D (\( n_{10} \)) below it. The highest index value, 1.00, corresponds to the last occurrence of species K (\( n_{17} \)). This event fully agrees with the ideal sequence, because it has events B (\( n_{16} \)) and J (\( n_{20} \)) above it, and events W (\( n_{13} \)), N (\( n_{14} \)), and D (\( n_{10} \)) below it.

The \( \varphi \) Index values could help to detect: a) an unexpected biological behaviour (e.g. N taxon maybe could have taken refuge into region, text-fig. 15a, f), or a subtle change into paleoecological conditions (N & D taxa, text-fig. 15a, f); b) reworking (e.g. E taxon, text-fig. 9a, f) or c) cavings.

1 For example, given the following \( n_i \): set = \{\( n_1, n_2, n_{(h+1)}), n_{(h+2)}, n_{(h+3)}, n_{(h+10)} \)\} with \( n_{(h+2)} \) as \( n \) (event to be evaluated), the \( A_i \) set is = \{\( A_{(h+2)}), A_{(h+2)}(h+1), A_{(h+2)}(h+3), A_{(h+2)}(h+10) \}\), where \( A_{(h+2)}(h+1) \) and \( A_{(h+2)}(h+3) \) are the more significant relationships, because \( n_{(h+1)} \) and \( n_{(h+3)} \) positions represent the minimum and the maximum values (respectively) in an open interval where the \( n_{(h+2)} \) (\( n_{ai} \)) position should be, fulfilled with its behaviour into ideal sequence.