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

Daniel A. Rincón[1*], José E. Arenas[1], Carlos H. Cuartas[1,2], Andrés L. Cárdenas[1], Carlos E. Molinares[1,2,3], Claudia Caicedo[1] and Carlos Jaramillo[3]
[1]*Biostratigraphy Team, Colombian Petroleum Institute, ICP-ECOPETROL, km.7 vía Piedecuesta, Santander, Colombia*
[2]*Departamento de Geología1`, Universidad EAFIT, Carrera 49 No. 7sur-50, Medellín, Colombia*
[3]*Smithsonian 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 benthonic 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.

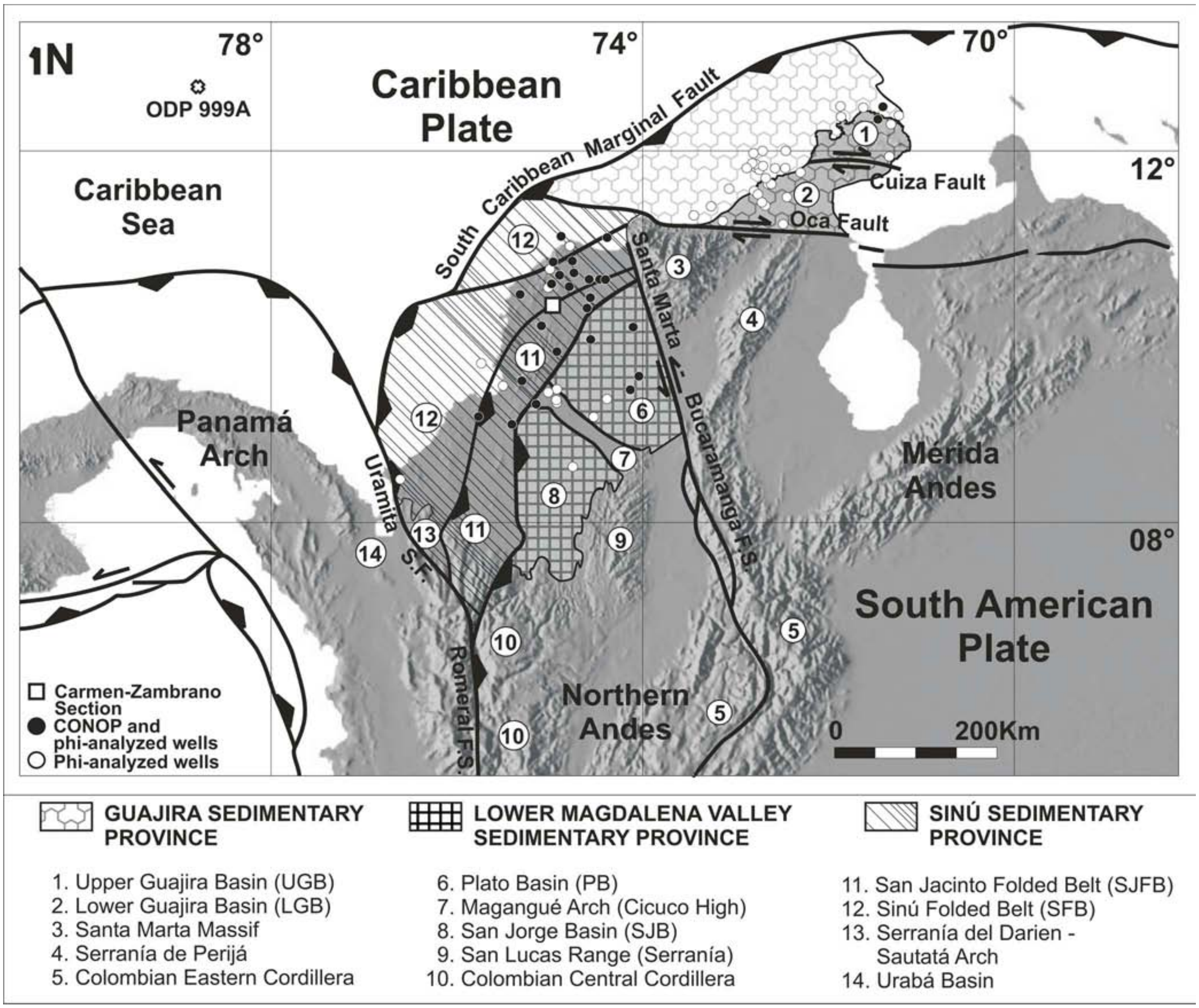
*Current address: Alfred Wegener Institute, Bremerhaven - Germany.

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.



TEXT-FIGURE 1
Tectonic and geomorphologic map of the study area. The image shows the main sedimentary provinces and tectonic features (from Pindell et al. 1988; Case et al. 1990; Cediel et al. 2003) and the location of CONOP+Phi-analyzed (black circles) and Phi-analyzed wells (white circles).

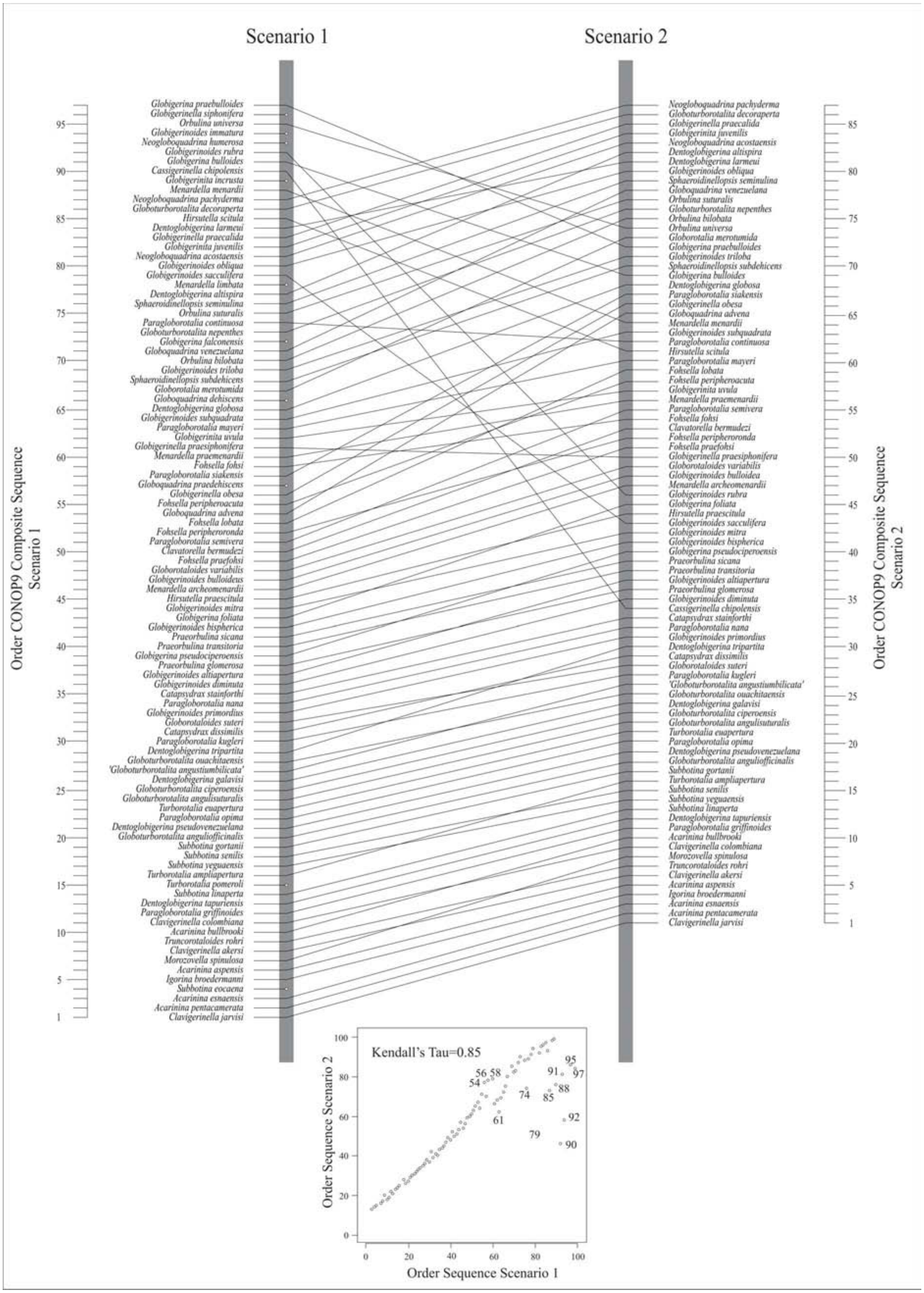
They showed the potential that quantitative techniques have for dealing with large data sets and their application in a sequence stratigraphic sense.

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 Farallon (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 Barret 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. Kroonenberg 1982; Cardona 2003; Cordanii 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



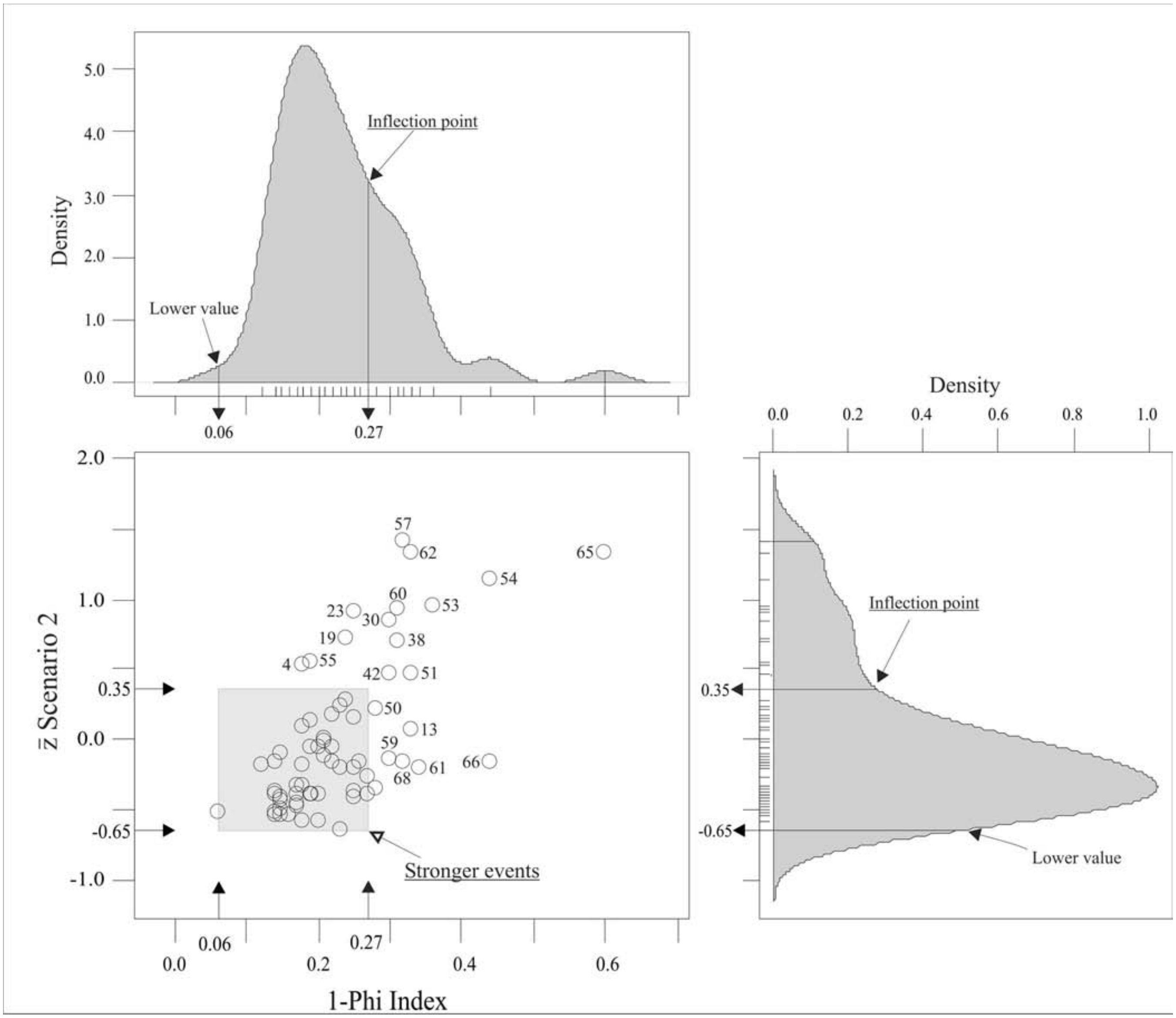
TEXT-FIGURE 2
Order of events from the constrained optimization scenarios. Scenario 1 uses only HO; Scenario 2 uses HO also, but compensates for edge effects. Horizontal lines connect events between scenarios. Metric bars on both sides of the figure indicate the position of the event. Correlation between 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 ($\bar{Z}$) 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).

Order	Species HO	A	B	Order	Species HO	A	B
68	*Neogloboquadrina pachyderma*	X		34	*Globigerinoides diminuta*	X	o
67	*Globoturborotalita decoraperta*	X		33	*Catapsydrax stainforthi*	X	o
66	*Globigerinella praecalida*	X		32	*Paragloborotalia nana*	X	
65	*Globigerina juvenilis*			31	*Globigerinoides primordia*	X	o
64	*Neogloboquadrina acostaensis*	X		30	*Globorotaloides suteri*		
63	*Globigerinoides obliqua*	X	o	29	*Catapsydrax dissimilis*	X	o
62	*Sphaeroidinellopsis seminulina*			28	*Paragloborotalia kugleri*	X	o
61	*Orbulina suturalis*	X		27	*Dentoglobigerina tripartita*	X	o
60	*Globoturborotalita nepenthes*			26	*Globoturborotalita ouachitaensis*	X	o
59	*Globoquadrina venezuelana*	X	o	25	*'Globoturborotalita angustiumbilicata'*	X	o
58	*Orbulina bilobata*		o	24	*Globoturborotalita ciperoensis*	X	o
57	*Globigerinoides triloba*			23	*Dentoglobigerina galavisi*	X	
56	*Sphaeroidinellopsis subdehiscens*	X		22	*Globigerina angulisuturalis*	X	
55	*Globorotalia merotumida*	X	o	21	*Turborotalia euapertura*	X	
54	*Dentoglobigerina globosa*			20	*Paragloborotalia opima*	X	o
53	*Globigerinoides subquadrata*			19	*Dentoglobigerina pseudovenezuelana*	X	
52	*Paragloborotalia mayeri*	X	o	18	*Globoturborotalita anguliofficinalis*	X	
51	*Globigerinita uvula*			17	*Subbotina gortanii*	X	
50	*Menardella praemenardii*	X	o	16	*Turborotalia ampliapertura*	X	o
49	*Fohsella fohsi*	X	o	15	*Subbotina senilis*	X	
48	*Fohsella peripheroronda*	X	o	14	*Subbotina yeguaensis*	X	o
47	*Fohsella praefohsi*	X	o	13	*Subbotina linaperta*	X	
46	*Globorotaloides variabilis*	X		12	*Dentoglobigerina tapuriensis*	X	o
45	*Globigerinoides bulloideus*	X	o	11	*Paragloborotalia griffinoides*	X	o
44	*Menardella archeomenardii*	X	o	10	*Clavigerinella colombiana*	X	o
43	*Globigerina foliata*			9	*Acarinina bullbrooki*	X	o
42	*Hirsutella praescitula*	X	o	8	*Truncarotaloides rohri*	X	o
41	*Globigerinoides mitra*	X	o	7	*Morozovella spinulosa*	X	o
40	*Globigerina pseudociperoensis*	X		6	*Clavigerinella akersi*	X	o
39	*Globigerinoides bispherica*	X	o	5	*Acarinina aspensis*	X	o
38	*Globigerinoides altiapertura*			4	*Igorina broedermanni*	X	o
37	*Praeorbulina sicana*	X	o	3	*Acarinina esnaensis*	X	o
36	*Praeorbulina transitoria*	X		2	*Acarinina pentacamerata*	X	o
35	*Praeorbulina glomerosa*	X	o	1	*Clavigerinella jarvisi*	X	o

(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 Sinú 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 SJFB is composed of Late Cretaceous pelagic rocks, a thick Cenozoic turbidite sequence, and Pleistocene-Holocene fluvial 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 ($\bar{Z}$) obtained in constrained optimization scenario 2 vs. φ 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 and the φ 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.

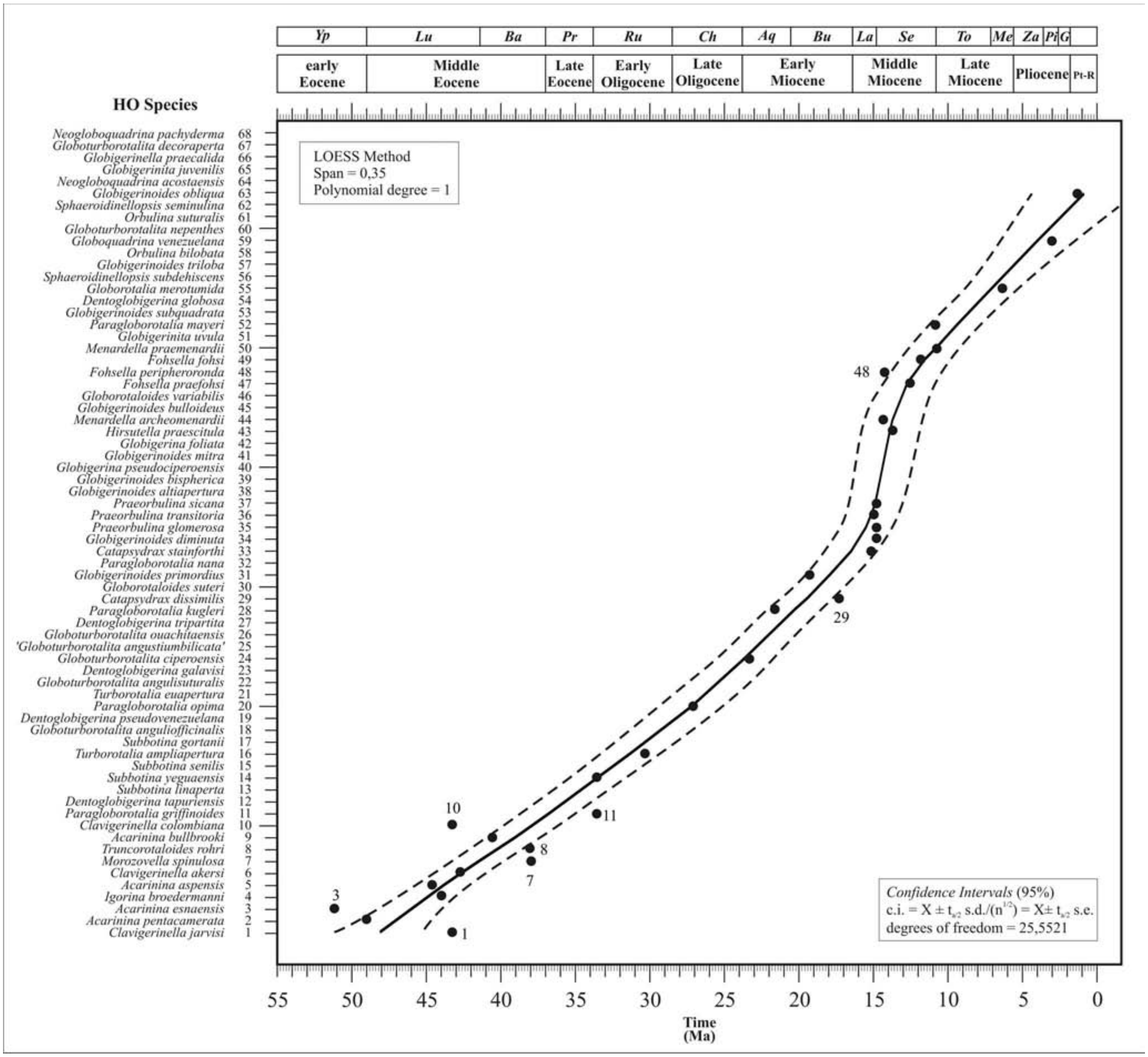
METHODS

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 ($\overline{Z}$), 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, φ(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 and minimum values of the mean estimated age (95% confidence interval) and estimated error from the LOESS method are also presented.

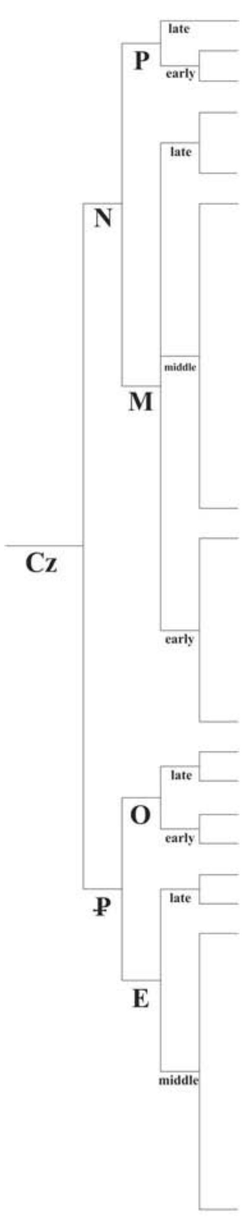
Order	Species	$\overline{Z}$	φ (1)	n (1)	φ (2)	n (2)	Age (Ma)		Min	Max	s.e.
68	*Neogloboquadrina pachyderma*	-0.17555	0.68426	5	0.64551	8	NA	NA	NA	NA	NA
67	*Globoturborotalita decoraperta*	-0.52406	0.86401	5	0.65001	12	NA	NA	NA	NA	NA
66	*Globigerinella praecalida*	-0.14285	0.56347	3	0.54218	3	NA	NA	NA	NA	NA
65	*Globigerina juvenilis*	1.26032	0.40139	6	-	16	NA	NA	NA	NA	NA
64	*Neogloboquadrina acostaensis*	-0.62641	0.77500	11	0.73426	34	NA	NA	NA	NA	NA
63	***Globigerinoides obliqua***	-0.34594	0.72923	15	0.79623	50	0.84964	+/- 3.46684	-2.61721	4.31648	1.68621
62	*Sphaeroidinellopsis seminulina*	1.18478	0.59965	10	-	19	1.62998	+/- 3.21628	-1.58630	4.84626	1.56434
61	*Orbulina suturalis*	-0.16690	0.70292	14	0.72311	42	2.41569	+/- 2.97009	-0.55440	5.38578	1.44460
60	*Globoturborotalita nepenthes*	1.05288	0.68966	5	-	17	3.19849	+/- 2.73568	0.46281	5.93417	1.33058
59	***Globoquadrina venezuelana***	-0.15011	0.69560	21	0.72952	64	3.97012	+/- 2.51715	1.45297	6.48727	1.22429
58	*Orbulina bilobata*	0.00467	0.80870	3	0.82937	6	4.73597	+/- 2.31181	2.42416	7.04778	1.12442
57	*Globigerinoides triloba*	1.49661	0.67861	6	-	22	5.50395	+/- 2.12330	3.38064	7.62725	1.03273
56	*Sphaeroidinellopsis subdehiscens*	-0.27678	0.71946	5	0.72686	24	6.26956	+/- 1.95858	4.31097	8.22814	0.95262
55	***Globorotalia merotumida***	0.61198	0.81223	4	0.82938	9	7.02832	+/- 1.81548	5.21284	8.84379	0.88301
54	*Dentoglobigerina globosa*	0.96673	0.55987	3	-	6	7.79992	+/- 1.70660	6.09331	9.50652	0.83006
53	*Globigerinoides subquadrata*	0.98071	0.64315	8	-	19	8.59114	+/- 1.66139	6.92976	10.25253	0.80807
52	***Paragloborotalia mayeri***	-0.39376	0.75283	21	0.80696	55	9.37814	+/- 1.67328	7.70487	11.05142	0.81385
51	*Globigerinita uvula*	0.52964	0.67470	6	-	8	10.13707	+/- 1.69259	8.44448	11.82966	0.82325
50	*Menardella praemenardii*	0.28491	0.71729	13	0.77505	23	10.84409	+/- 1.66490	9.17919	12.50899	0.80978
49	***Fohsella fohsi***	-0.21995	0.73178	15	0.79000	34	11.55342	+/- 1.66544	9.88797	13.21886	0.81004
48	***Fohsella peripheroronda***	0.52590	0.76036	18	0.83075	54	12.19836	+/- 1.70868	10.48968	13.90703	0.83107
47	*Fohsella praefohsi*	-0.17420	0.85970	5	0.84119	8	12.68142	+/- 1.75948	10.92195	14.44090	0.85578
46	*Globorotaloides variabilis*	0.36147	0.77259	9	0.69910	24	13.06225	+/- 1.79945	11.26280	14.86170	0.87522
45	*Globigerinoides bulloideus*	0.02870	0.85468	3	0.80426	5	13.37130	+/- 1.83976	11.53154	15.21106	0.89482
44	*Menardella archeomenardii*	0.03558	0.78906	7	0.85679	12	13.63904	+/- 1.92223	11.71681	15.56127	0.93494
43	*Hirsutella praescitula*	0.13080	0.82434	11	0.83195	19	13.86255	+/- 2.01800	11.84455	15.88054	0.98152
42	*Globigerina foliata*	0.41683	0.69527	5	-	19	14.03279	+/- 2.05554	11.97725	16.08834	0.99978
41	*Globigerinoides mitra*	-0.01453	0.79522	5	0.80152	5	14.17106	+/- 2.04347	12.12759	16.21453	0.99391
40	*Globigerina pseudociperoensis*	-0.40235	0.75303	4	0.74509	5	14.29863	+/- 1.99801	12.30063	16.29664	0.97179
39	*Globigerinoides bispherica*	0.36063	0.81181	10	0.82664	26	14.43680	+/- 1.93357	12.50323	16.37037	0.94045
38	*Globigerinoides altiapertura*	0.92960	0.68620	5	-	10	14.60684	+/- 1.85922	12.74762	16.46606	0.90429
37	*Praeorbulina sicana*	-0.18937	0.75172	12	0.78397	24	14.83004	+/- 1.78119	13.04885	16.61124	0.86634
36	*Praeorbulina transitoria*	-0.31180	0.85841	7	0.76168	20	15.09400	+/- 1.75592	13.33809	16.84992	0.85405
35	*Praeorbulina glomerosa*	-0.30975	0.82921	7	0.83978	15	15.47007	+/- 1.71822	13.75185	17.18829	0.83571
34	***Globigerinoides diminuta***	-0.40085	0.85683	13	0.84404	32	15.91681	+/- 1.68754	14.22927	17.60435	0.82079
33	***Catapsydrax stainforthi***	-0.09528	0.77667	15	0.83229	35	16.45904	+/- 1.66846	14.79058	18.12750	0.81151
32	*Paragloborotalia nana*	-0.12401	0.74375	14	0.72937	23	17.16308	+/- 1.63839	15.52468	18.80147	0.79688
31	*Globigerinoides primordia*	-0.45454	0.83030	7	0.85327	10	17.91523	+/- 1.61135	16.30387	19.52658	0.78373
30	*Globorotaloides suteri*	1.02456	0.70019	6	-	11	18.69183	+/- 1.61901	17.07282	20.31084	0.78746
29	***Catapsydrax dissimilis***	-0.35986	0.80323	17	0.81030	32	19.46924	+/- 1.69875	17.77049	21.16798	0.82624
28	***Paragloborotalia kugleri***	-0.31543	0.83157	8	0.83162	10	20.25880	+/- 1.79709	18.46170	22.05589	0.87407
27	*Dentoglobigerina tripartita*	-0.06302	0.78153	9	0.77281	18	21.08061	+/- 1.85031	19.23030	22.93092	0.89996
26	*Globoturborotalita ouachitaensis*	-0.19669	0.82230	6	0.79986	8	21.92416	+/- 1.87734	20.04683	23.80150	0.91310
25	*'Globoturborotalita angustiumbilicata'*	0.18624	0.78386	7	0.83173	15	22.77893	+/- 1.90628	20.87264	24.68521	0.92718
24	***Globoturborotalita ciperoensis***	-0.55266	0.85821	8	0.79622	13	23.63438	+/- 1.96541	21.66897	25.59979	0.95594
23	*Dentoglobigerina galavisi*	0.88612	0.75418	4	0.67447	6	24.49121	+/- 2.04754	22.44368	26.53875	0.99588
22	*Globigerina angulisuturalis*	-0.35087	0.81997	6	0.73728	12	25.36182	+/- 2.12373	23.23809	27.48556	1.03295
21	*Turborotalia euapertura*	0.23026	0.92559	6	0.71946	9	26.25326	+/- 2.18913	24.06413	28.44239	1.06475
20	***Paragloborotalia opima***	-0.47162	0.85265	9	0.80076	17	27.17259	+/- 2.23654	24.93605	29.40913	1.08781
19	*Dentoglobigerina pseudovenezuelana*	0.82265	0.75850	5	0.74953	5	28.12685	+/- 2.25552	25.87133	30.38237	1.09704
18	*Globoturborotalita anguliofficinalis*	-0.59497	0.80426	3	0.70059	5	29.12310	+/- 2.23345	26.88965	31.35655	1.08631
17	*Subbotina gortanii*	-0.59497	0.82410	4	0.72376	7	30.16840	+/- 2.15839	28.01001	32.32679	1.04980
16	***Turborotalia ampliapertura***	0.24229	0.75495	6	0.79373	10	31.26980	+/- 2.02466	29.24514	33.29446	0.98476
15	*Subbotina senilis*	-0.20261	0.77050	3	0.76096	3	32.39715	+/- 1.90556	30.49159	34.30270	0.92683
14	***Subbotina yeguaensis***	-0.49616	0.85238	5	0.80048	6	33.51511	+/- 1.88296	31.63215	35.39806	0.91583
13	*Subbotina linaperta*	0.05312	0.67426	8	0.65748	9	34.62295	+/- 1.92107	32.70188	36.54402	0.93437
12	*Dentoglobigerina tapuriensis*	-0.53871	0.94154	4	0.94295	4	35.71996	+/- 1.92521	33.79475	37.64516	0.93638
11	***Paragloborotalia griffinoides***	-0.52301	0.84951	10	0.84294	11	36.80540	+/- 1.81052	34.99488	38.61591	0.88060
10	*Clavigerinella colombiana*	-0.57176	0.85723	4	0.85510	4	37.95840	+/- 1.78741	36.17099	39.74581	0.86936
9	*Acarinina bullbrooki*	0.45962	0.80997	3	0.80611	3	39.08062	+/- 1.78669	37.29393	40.86731	0.86901
8	*Truncarotaloides rohri*	-0.38363	0.84872	3	0.84404	3	40.24350	+/- 1.68149	38.56201	41.92499	0.81784
7	*Morozovella spinulosa*	-0.42429	0.83486	3	0.82731	3	41.48859	+/- 1.65210	39.83650	43.14069	0.80355
6	***Clavigerinella akersi***	-0.12019	0.78804	8	0.76856	9	42.58605	+/- 1.64819	40.93786	44.23423	0.80165
5	*Acarinina aspensis*	-0.18296	0.87757	3	0.87341	3	43.83407	+/- 1.65210	42.18198	45.48617	0.80355
4	*Igorina broedermanni*	0.50015	0.82469	5	0.81965	5	44.99174	+/- 1.72783	43.26391	46.71957	0.84038
3	*Acarinina esnaensis*	-0.39972	0.81306	4	0.80849	4	46.00080	+/- 2.00805	43.99275	48.00885	0.97668
2	***Acarinina pentacamerata***	-0.43678	0.83773	6	0.82790	6	47.10636	+/- 2.46507	44.64129	49.57143	1.19896
1	*Clavigerinella jarvisi*	-0.54987	0.85344	4	0.84262	4	48.14879	+/- 3.04098	45.10781	51.18977	1.47908



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.

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 regression (e.g. Yeager and Ultsch 1989) was performed on the frequency of HO events as a function of position (depth) in the section in order to estimate the extent of edge effect near the upper boundary of each section. Piecewise regression assumes that there are two different regression functions for the same data and attempts to perform a two-segment fit on the data, trying all possible positions of the intersection and choosing the one that produces the lowest residual sum of squares. The two linear regressions were chosen as the models to fit by the piecewise 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



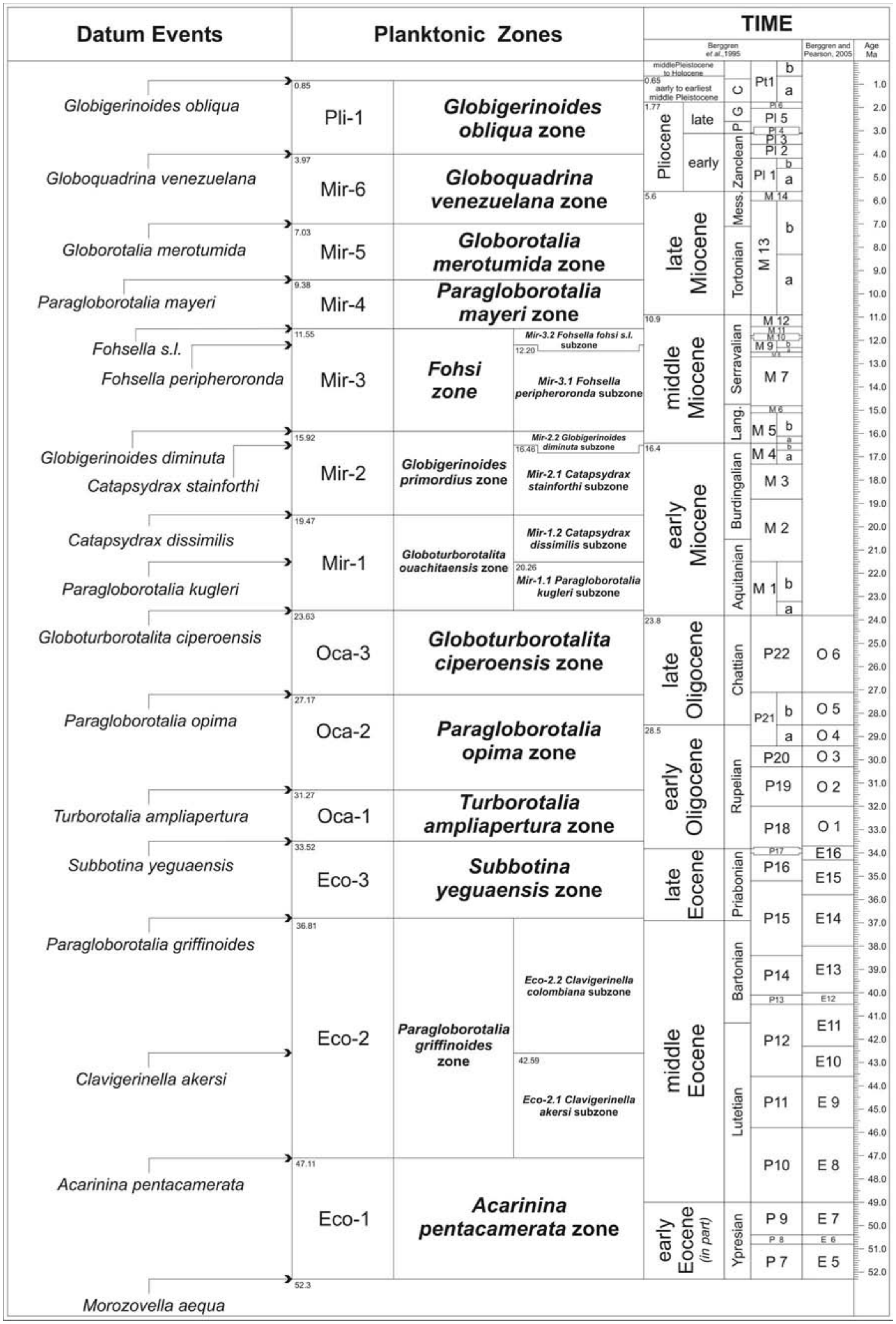
	HO Species	Age (Ma)	Phi (2)	n (2)
63	Globigerinoides obliqua	0,85 ± 3,47	0,79623	50
59	Globoquadrina venezuelana	3,97 ± 2,52	0,72952	64
58	Orbulina bilobata	4,74 ± 2,31	0,82937	6
55	Globorotalia merotumida	7,03 ± 1,82	0,82938	9
52	Paragloborotalia mayeri	9,38 ± 1,67	0,80696	55
50	Menardella praemenardii	10,84 ± 1,66	0,77505	23
49	Fohsella fohsi	11,55 ± 1,67	0,79000	34
48	Fohsella peripheroronda	12,20 ± 1,71	0,83075	54
47	Fohsella praefohsi	12,68 ± 1,76	0,84119	8
45	Globigerinoides bulloideus	13,37 ± 1,84	0,80426	5
44	Menardella archeomenardii	13,64 ± 1,92	0,85679	12
43	Hirsutella praescitula	13,86 ± 2,02	0,83195	19
41	Globigerinoides mitra	14,17 ± 2,04	0,80152	5
30	Globigerinoides bispherica	14,44 ± 1,93	0,82664	25
37	Praeorbulina sicana	14,83 ± 1,78	0,78397	25
35	Praeorbulina glomerosa	15,47 ± 1,72	0,83978	15
34	Globigerinoides diminuta	15,92 ± 1,69	0,84404	32
33	Catapsydrax stainforthi	16,46 ± 1,67	0,83229	35
31	Globigerinoides primordius	17,92 ± 1,61	0,85327	10
29	Catapsydrax dissimilis	19,47 ± 1,70	0,81030	32
28	Paragloborotalia kugleri	20,26 ± 1,80	0,83162	10
27	Dentoglobigerina tripartita	21,08 ± 1,85	0,77281	18
26	Globoturborotalita ouachitaensis	21,92 ± 1,88	0,79986	8
25	'Globoturborotalita angustiumbilicata'	22,78 ± 1,91	0,83173	15
24	Globoturborotalita ciperoensis	23,63 ± 1,97	0,79622	13
20	Paragloborotalia opima	27,17 ± 2,24	0,80076	17
16	Turborotalia ampliapertura	31,27 ± 2,02	0,79373	10
14	Subbotina yeguaensis	33,52 ± 1,88	0,80048	6
12	Dentoglobigerina tapuriensis	35,72 ± 1,93	0,94295	4
11	Paragloborotalia griffinoides	36,81 ± 1,81	0,84294	11
10	Clavigerinella colombiana	37,96 ± 1,79	0,85510	4
9	Acarinina bullbrooki	39,08 ± 1,79	0,80611	3
8	Truncorotaloides rohri	40,24 ± 1,68	0,84404	3
7	Morozovella spinulosa	41,49 ± 1,65	0,82731	3
6	Clavigerinella akersi	42,59 ± 1,65	0,76856	9
5	Acarinina aspensis	43,83 ± 1,65	0,87341	3
4	Igorina broedermanni	44,99 ± 1,73	0,81965	5
3	Acarinina esnaensis	46,00 ± 2,01	0,80849	4
2	Acarinina pentacamerata	47,11 ± 2,47	0,82790	6
1	Clavigerinella jarvisi	48,15 ± 3,04	0,84262	4

TEXT-FIGURE 5
Estimated local ages, φ values, and number of wells (n), where the potential zonal markers were found in a regional analysis of 70 wells. Their distribution into geological epochs is shown in the left margin and selected zonal markers are emphasized with a gray bar.

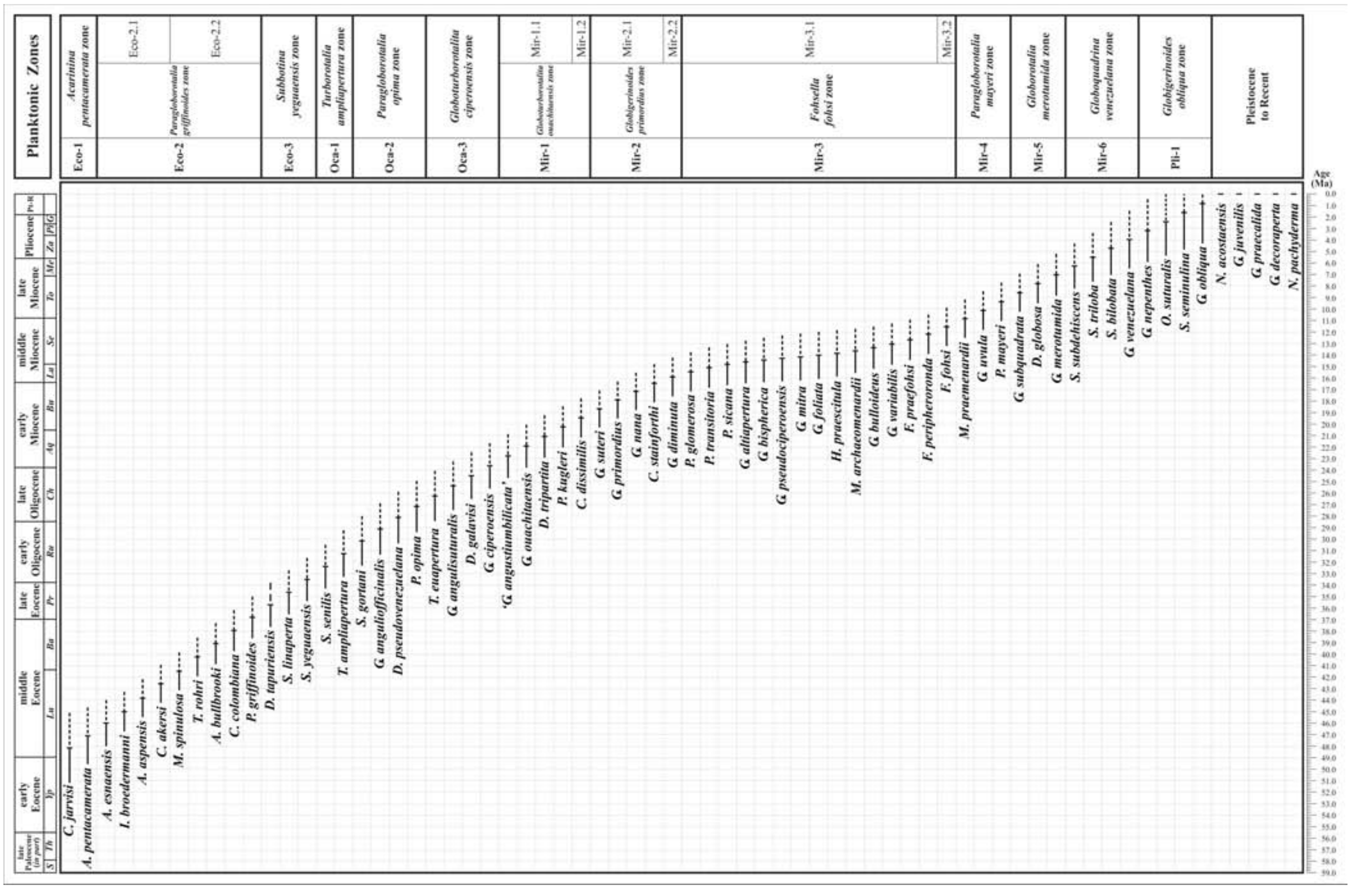
from each section; the rest were retained in the Constrained Optimization analysis.

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 optimal 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.



TEXT-FIGURE 7
Distribution of planktonic HO events and their confidence intervals. Time scale is from Berggren et al. (1995) and Berggren and Pearson (2005). Age (bold lines) and confidence intervals of 95% (dashed lines) for HO events are those defined by LOESS method (see also text-fig. 4).

biostratigraphic marker: (1) the average standardized penalty ($\overline{Z}$), obtained for each event in Scenario 2 of Constrained Optimization, and (2) the Phi index - φ (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 ($\overline{Z}$) 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:

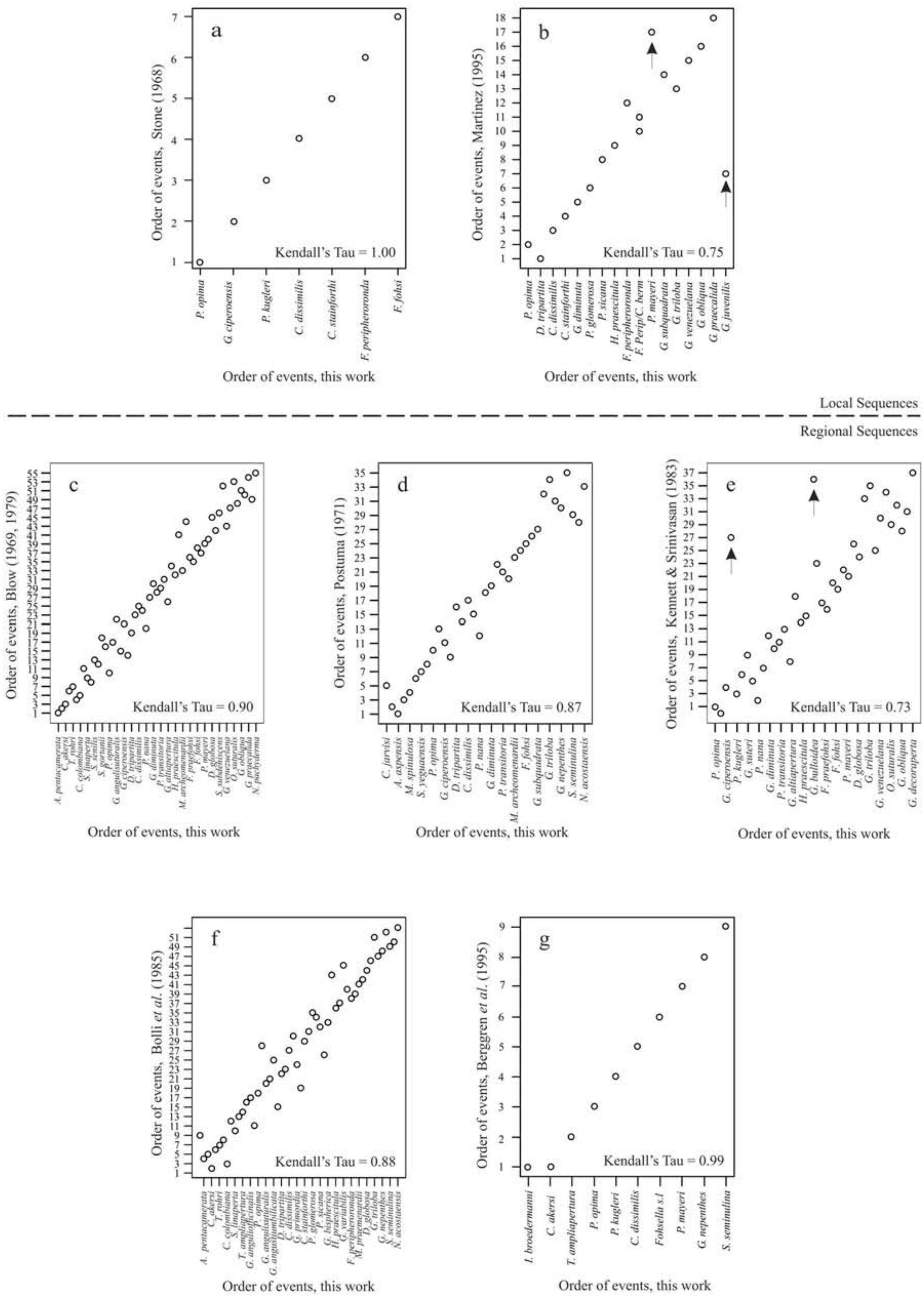
$$Z_i = \frac{V_i - M_j}{S_j} \quad (1)$$

$$\overline{Z}_i = \sum_{1}^{l} \frac{Z_i}{l}, l \leq n \quad (2)$$

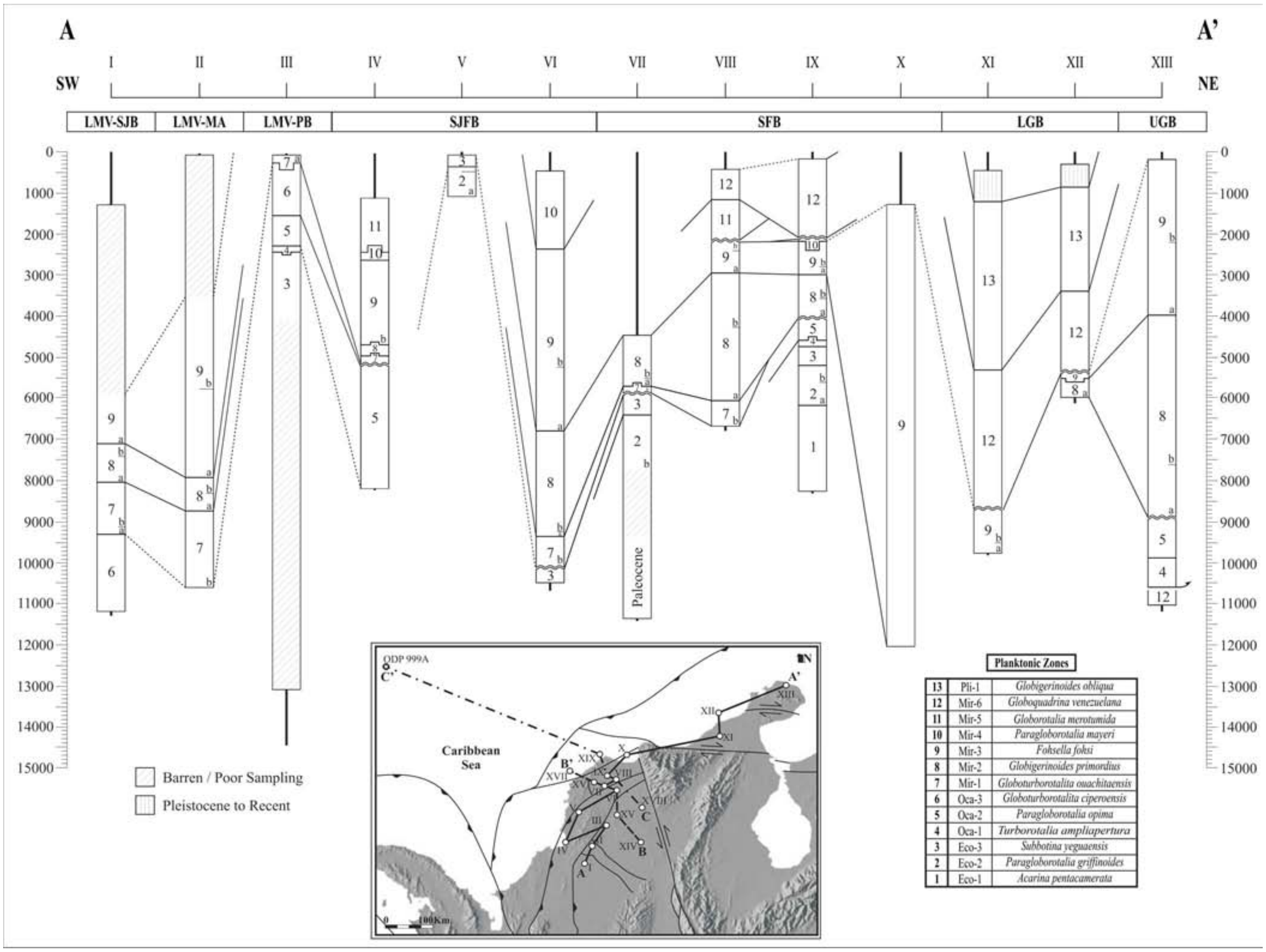
where V_i is the penalty increment for species "*i*" in the well "*j*" and M_j is the mean penalty value for well "*j*", S_j is the penalty standard deviation for well "*j*", and "*l*" the number of wells where the event was observed.

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 φ 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).



TEXT-FIGURE 9
Correlation of Cenozoic sedimentary successions in 13 northern Colombian wells. 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-SJB (Lower Magdalena Valley, San Jorge Basin), LMV-MA (Lower Magdalena Valley, Magangué Arch), SJFB (San Jacinto Folded Belt), Sinú Folded Belt (SFB), Lower Guajira Basin (LGB) ad Upper Guajira Basin (UGB). Vertical single bars at both ends of the wells indicate the vertical extension (ft) of the perforation, where there is not biostratigraphic data.

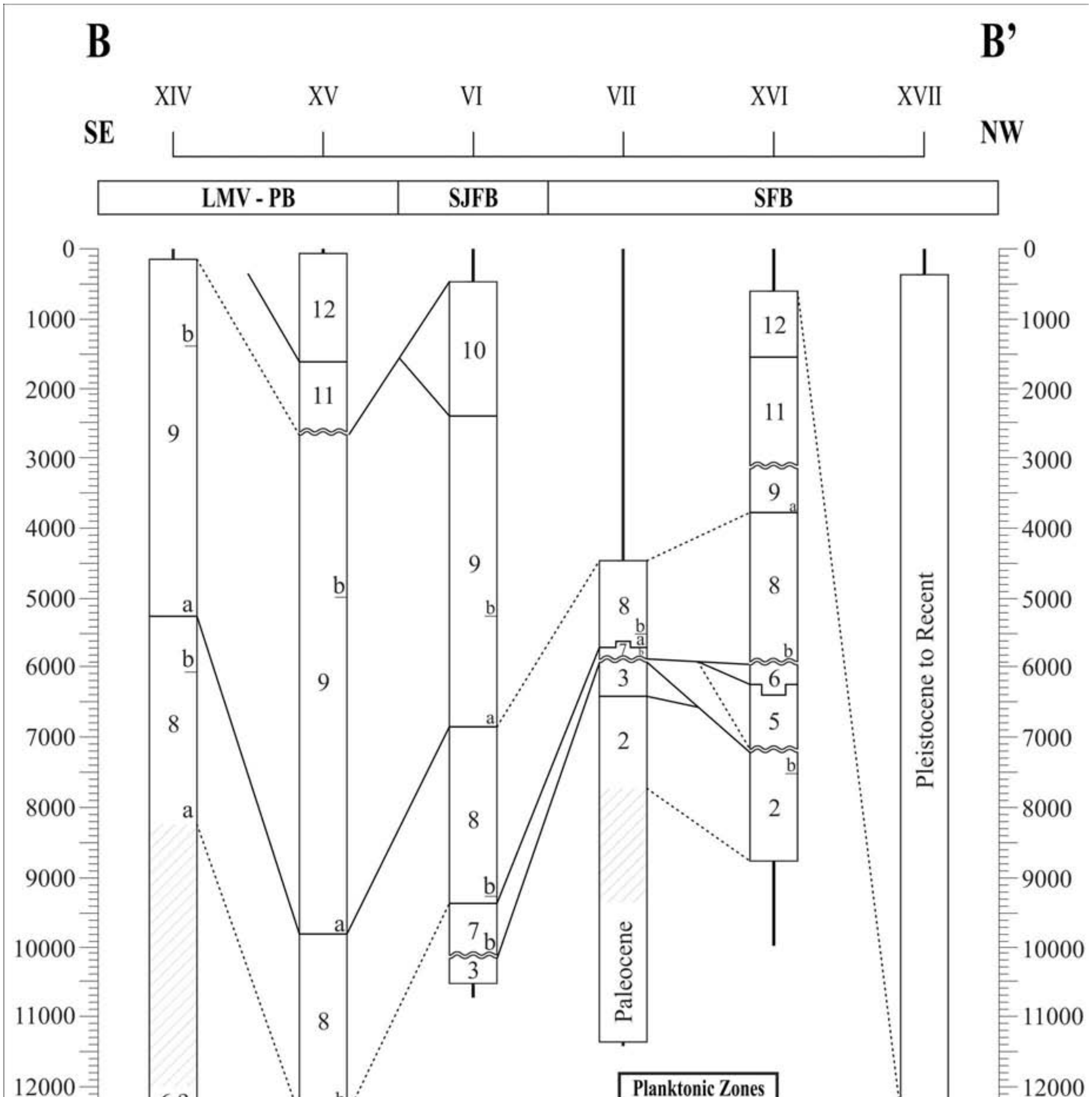
Events with both low and high φ values were judged to possess high biostratigraphic significance. The Phi index (φ) was applied then to those key events in 70 wells, including wells used in Constrained Optimization analysis**.** This analysis was done to further improve the measure of the quality of 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

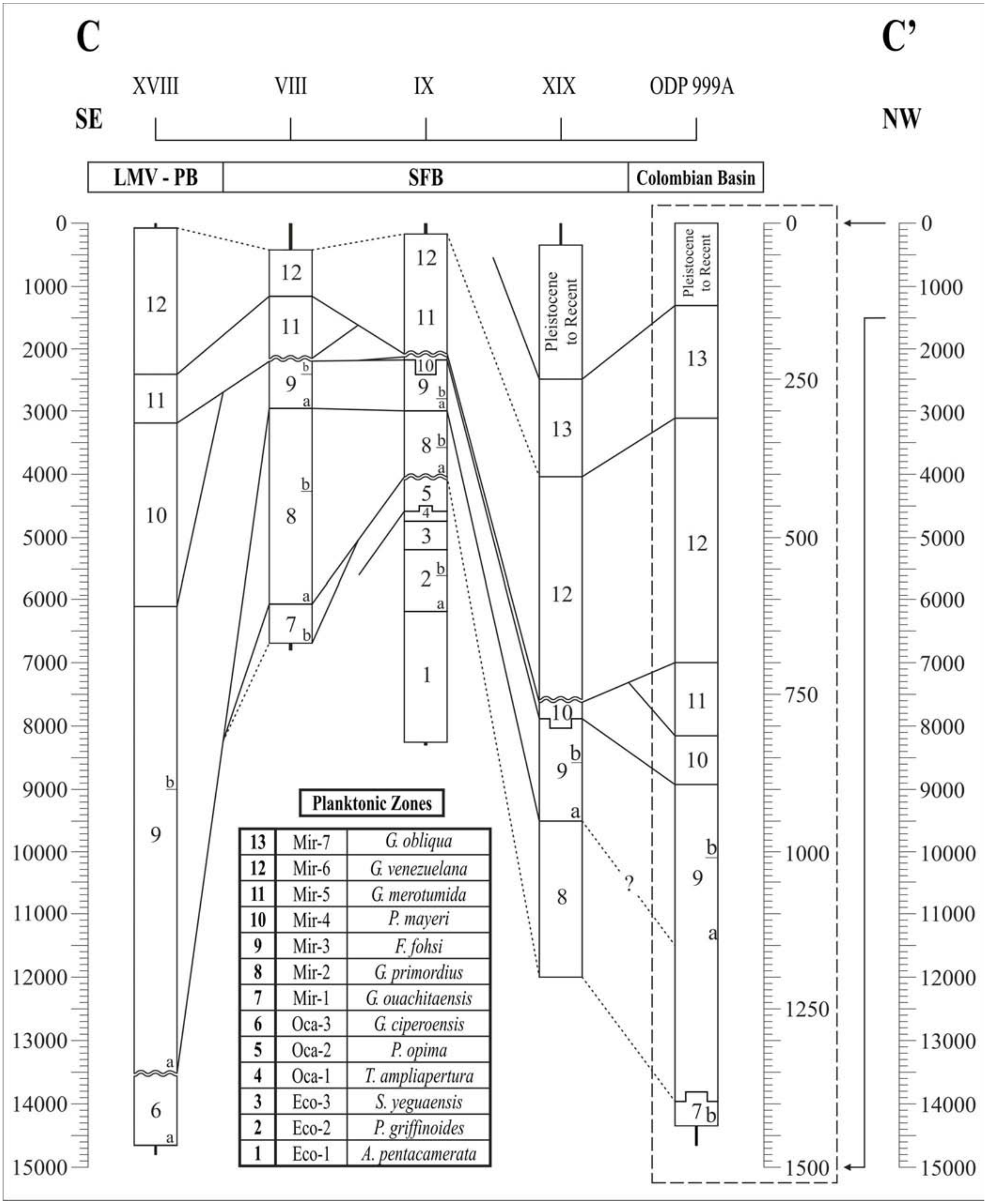
The analysis yielded a sequence of 97 HO events in scenario 1, whereas scenario 2 retained 87 events (text-fig. 2). After accounting for the edge effects in scenario 2 (as described above), some of the events remained in fewer than three sections, and therefore were removed. The excluded events were 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*,

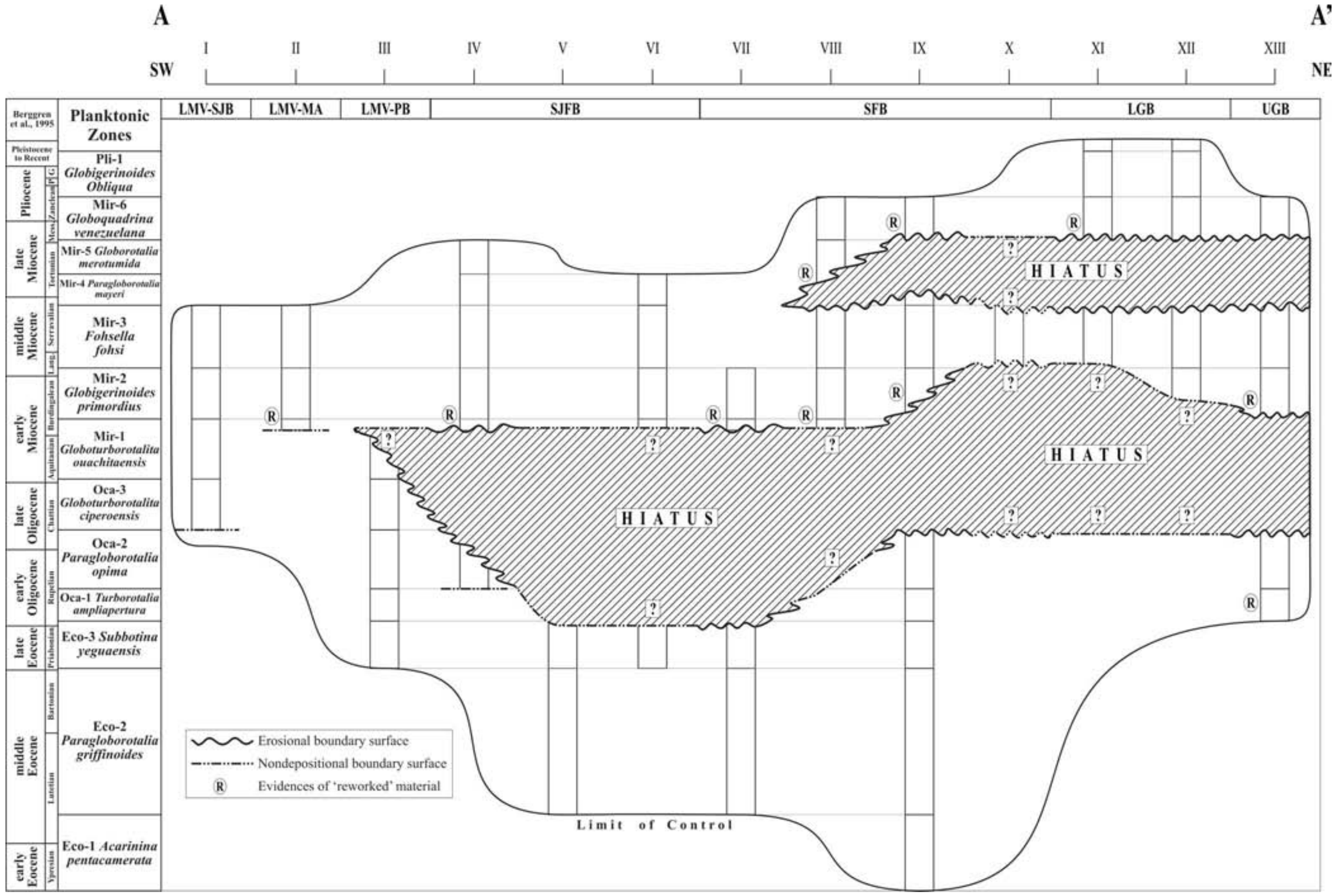


13	Pli-1	*Globigerinoides obliqua*
12	Mir-6	*Globoquadrina venezuelana*
11	Mir-5	*Globorotalia merotumida*
10	Mir-4	*Paragloborotalia mayeri*
9	Mir-3	*Fohsella fohsi*
8	Mir-2	*Globigerinoides primordius*
7	Mir-1	*Globoturborotalita ouachitaensis*
6	Oca-3	*Globoturborotalita ciperoensis*
5	Oca-2	*Paragloborotalia opima*
4	Oca-1	*Turborotalia ampliapertura*
3	Eco-3	*Subbotina yeguaensis*
2	Eco-2	*Paragloborotalia griffinoides*
1	Eco-1	*Acarina pentacamerata*

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), Sinú 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 not biostratigraphic data.



TEXT-FIGURE 12
Chronostratigraphic chart (Wheeler diagram) of Transect A - A'. Main tectonic and sedimentary features are indicated: LMV-SJB (Lower Magdalena Valley, San Jorge Basin), LMV-MA (Lower Magdalena Valley, Magangué Arch), SJFB (San Jacinto Folded Belt), Sinú Folded Belt (SFB), Lower Guajira Basin (LGB) ad Upper Guajira Basin (UGB).

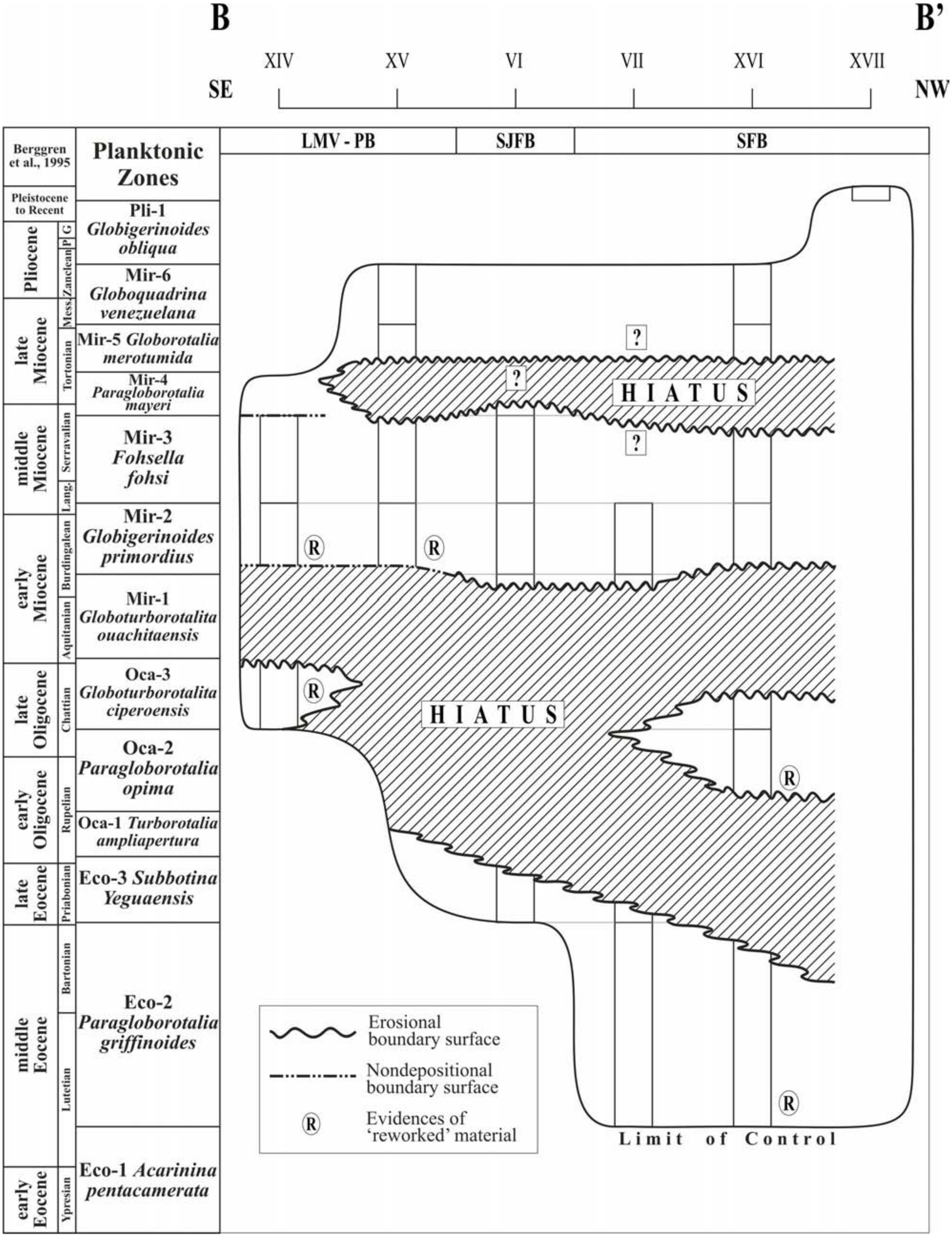
Cassigerinella chipolensis, *Globigerinoides rubra*, *Menardella menardii*, *Hirsutella scitula*, and *Globigerinoides sacculifera*, which were lowered to older positions in scenario 2; positions of the HO of *Paragloborotalia siakensis*, *Globigerinella obesa*, and *Globoquadrina advena*, on the other 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 gortanii*, *Subbotina senilis*, *Subbotina yeguaensis*, 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).

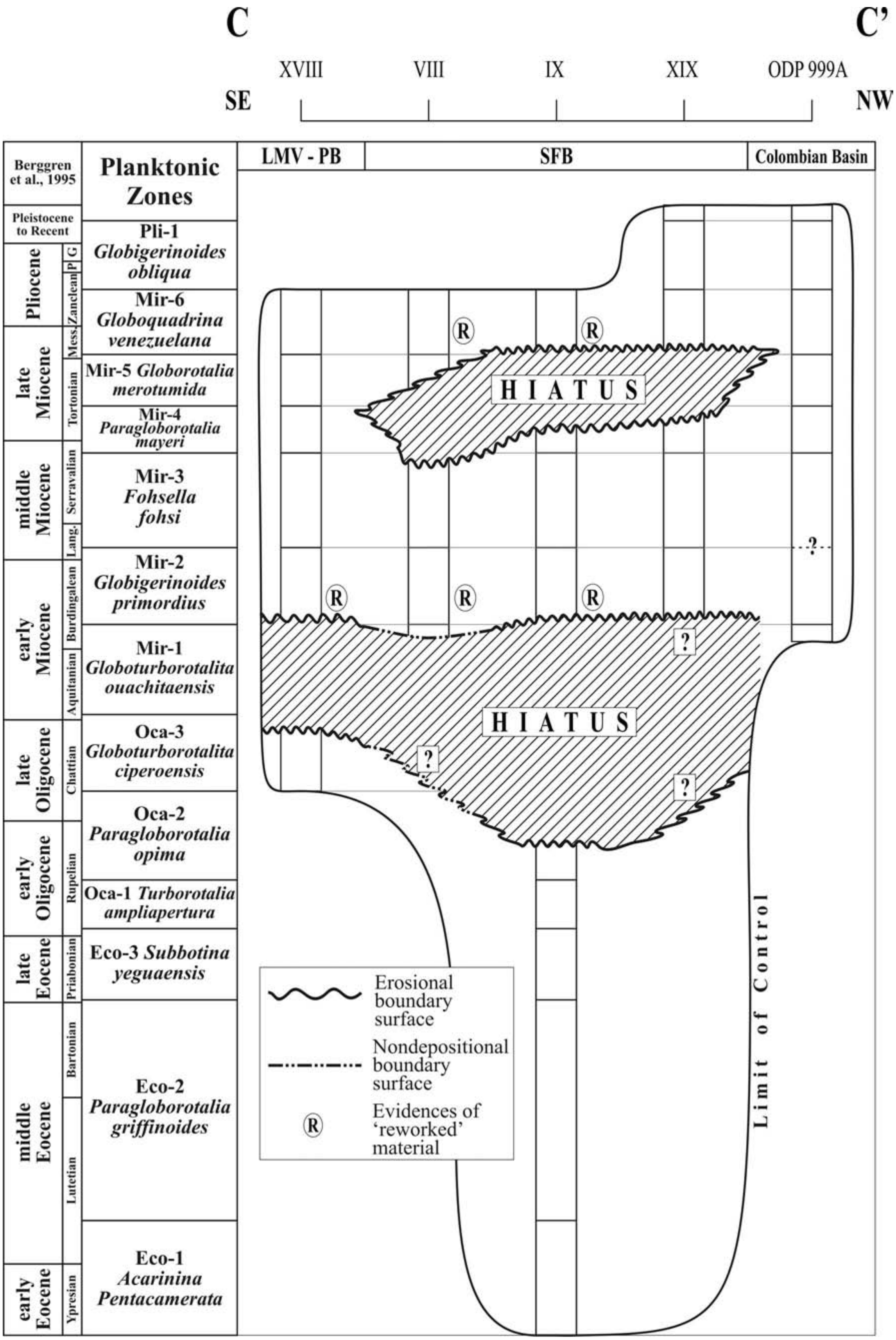
A marginal-plot of the average standardized penalty (from scenario 2) vs. Phi index (φ) of the 68 proposed events from Table 1 (text-fig. 3) showed that a high percentage (88.9%) of HO events presented low penalty levels (< 0.35) and high φ values (φ > 0.73), thus identifying them as robust biostratigraphic events in the sequence (Tables 1 and 2). Other events, such as the HOs of *Globorotalia merotumida*, *Dentoglobigerina galavisi*, *Dentoglobigerina pseudovenezuelana*, and *Igorina broedermanni*, 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*, *Orbulina suturalis*, *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 CONOP and Phi index, were used to recalculate φ 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).

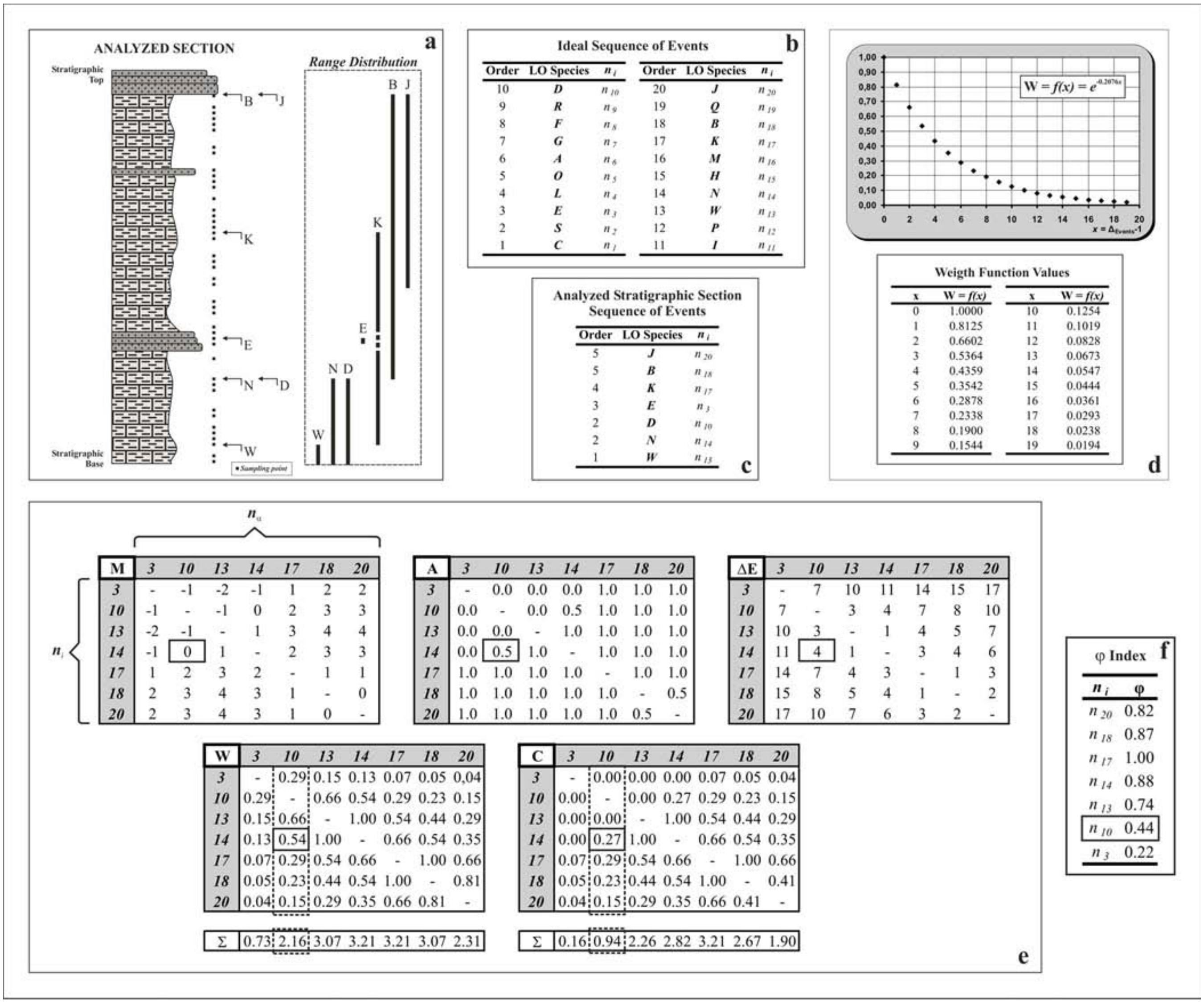
The literature age assignment for 33 of the potential zonal markers is shown in Appendix 4. Age assignments of the other seven HO events were not found. In order of precedence we prefer to use the age estimates of Chaisson and D'Hondt (2000) and Pearson and Chaisson (1997) to build our own age model, 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 Sinú 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), Sinú Folded Belt (SFB) and Colombian Basin.



TEXT-FIGURE 15
Schematic methodology employed to demonstrate the Phi index calculus for the events from a hypothetical stratigraphic sequence. Detailed explanations are given in Supplement text.

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 griffinoides*, *Subbotina yeguaensis*, *Turborotalia ampliapertura*, *Paragloborotalia opima*, *Globoturborotalita ciperoensis*, *Paragloborotalia kugleri*, *Catapsydrax dissimilis*, *Catapsydrax stainforthi*, *Globigerinoides diminuta*, *Fohsella peripheroronda*, *Fohsella fohsi, Paragloborotalia mayeri*, *Globorotalia merotumida*, *Globoquadrina venezuelana*, and *Globigerinoides obliqua* were selected as zonal and subzonal markers because of their high φ 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. ditch 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. $\bar{Z}$ and φ 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 microfauna, 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, Tubará, 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; Olsson 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 griffinoides* Interval Zone

Definition: Interval zone (partial range) of *Paragloborotalia griffinoides*. 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. griffinoides* (text-figs. 6, 7).

Events within the zone: HOs 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 griffinoides* 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 griffinoides*. Base defined by the HO of *Clavigerinella akersi* and the top by the HO of *P. griffinoides* (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 griffinoides*. 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*, *Dentoglobigerina 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 yeguaensis*. 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: HOs of *Dentoglobigerina pseudovenezuelana*, *Globoturborotalita anguliofficinalis*, and *Subbotina gortanii*.

Remarks: This zone is approximately equivalent to the upper P19 - P21b Oligocene zones of Berggren et al. (1995) or upper 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. anguliofficinalis* 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: HOs of *Dentoglobigerina galavisi*, *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 Oligocene (late Chattian), ~ 23.63 Ma.

Miocene

Mir-1 *Globoturborotalia ouachitaensis* Interval Zone

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

Events within the zone: HOs of *Paragloborotalia kugleri*, *Dentoglobigerina tripartita*, *Globoturborotalia ouachitaensis*, and *´Globoturborotalita angustiumbilicata`*.

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: HOs of *Dentoglobigerina tripartita*, *Globoturborotalia ouachitaensis*, and *´Globoturborotalita angustiumbilicata`*.

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 primordius* 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: HOs of *Catapsydrax stainforthi*, *Paragloborotalia nana*, *Globigerinoides primordia*, and *Globorotaloides suteri*.

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 the 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 the 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 peripheroronda*, *Fohsella praefohsi*, *Globorotaloides variabilis*, *Globigerinoides bulloideus*, *Menardella archaeomenardii*, *Hirsutella praescitula*, *Globigerina foliata*, *Globigerinoides mitra*, *Globigerina pseudociperoensis*, *Globigerinoides bispherica*, *Globigerinoides altiapertura*, *Praeorbulina sicana*, *Praeorbulina transitoria*, and *Praeorbulina glomerosa*.

Remarks: This zone is approximately equivalent to the upper M5 - lower M11 Miocene zones of Berggren et al. (1995) and is divided into two subzones: Mir-3.1 *Fohsella peripheroronda* Subzone, which is equivalent to the upper M5 – M9a Miocene zones of Berggren et al., and Mir-3.2 *Fohsella* sensu lato Subzone, which is equivalent to the upper M9a – lower M11 Miocene zones of Berggren et al. (1995). The upper boundary of the zone is defined by the HO of *F. fohsi s.l.*, which includes the younger fohsellid taxa *Fohsella fohsi, Fohsella robusta*, and *Fohsella lobata*. The last two *Fohsella* species are rare, suggesting that fohsellids were not fully developed in the area. Chaisson and D'Hondt (2000) suggest the Caribbean Sea was a suboptimal environment for this lineage which did not develop well there.

Estimated local age: early middle Miocene (early Langhian), ~ 15.92 Ma – late middle Miocene (late Serravallian), ~ 11.55 Ma.

Mir-3.1 *Fohsella peripheroronda* Subzone

Definition: Interval zone (partial range) of *Fohsella peripheroronda.* Base defined by the HO of *Globigerinoides diminuta* Bolli and the upper boundary is defined by the HO of *F. peripheroronda* (text-figs. 6, 7).

Additional events: HOs of *Fohsella praefohsi*, *Globorotaloides variabilis*, *Globigerinoides bulloideus*, *Menardella archaeomenardii*, *Hirsutella praescitula*, *Globigerina foliata*, *Globigerinoides mitra*, *Globigerina pseudociperoensis*, *Globigerinoides bispherica*, *Globigerinoides altiapertura*, *Praeorbulina sicana*, *Praeorbulina transitoria*, and *Praeorbulina glomerosa*.

Estimated local age: early middle 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 the zone is defined by the HO of *F. fohsi s.l.* which includes *Fohsella 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 the *Globorotalia merotumida*. The base of the zone is 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 the *Globoquadrina venezuelana*. The base of the zone is 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 subdehiscens*.

Remarks: This zone is approximately equivalent to the upper M13b to lower Pl2 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

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 *Globigerinoides obliqua* Interval zone

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

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

Remarks: This zone is approximately equivalent to the upper Pl2 - 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*, *Globoturborotalita decoraperta*, *Globigerinella praecalida*, *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*, *Globoturborotalita ciperoensis*, *Paragloborotalia kugleri*, *Catapsydrax dissimilis*, *C. stainforthi*, *Fohsella peripheroronda*, and *F. fohsi*.

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 φ 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 Martínez (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 *Globoquadrina 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 Sinú 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 south-north 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 Pliocene, 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 Sinú 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 SJFB 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 Carmenian 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; Bürgl 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 Petroleo (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
Subfamily CATAPSYDRACINAE Bolli, Loeblich and Tappan 1957
Genus *Catapsydrax* Bolli, Loeblich and Tappan 1957
Genus *Globigerinita* Brönnimann 1951

Subfamily GLOBIGERININAE Carpenter, Parker and Jones 1862
Genus *Globigerina* d'Orbigny 1826
Genus *Globigerinella* Cushman 1927
Genus *Globigerinoides* Cushman 1927
Genus *Globorotaloides* Bolli 1957
Genus *Globoturborotalita* Hofker 1976
Genus *Subbotina* Brotzen and Posarias 1961

Subfamily ORBULININAE Schultze 1854
Genus *Orbulina* d'Orbigny 1839
Genus *Praeorbulina* Olsson 1964

Subfamily SPHAEROIDINELLINAE 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 *Paragloborotalia* Cifelli 1982
Genus *Turborotalia* Cushman and Bermúdez 1949

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

Family TRUNCOROTALOIDIDAE Loeblich and Tappan 1961
Genus *Acarinina* Subbotina 1953
Genus *Igorina* Davidzon 1976
Genus *Morozovella* McGowran 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 CUSHMAN and BERMÚDEZ 1937: p. 25, pl. 3: figs. 4-6.

Catapsydrax dissimilis (Cushman and Bermúdez 1937) – BOLLI, LOEBLICH and TAPPAN 1957: p. 36, pl. 7: figs. 6a-c (re-illustrated holotype), 7a, b, 8a-c. – BLOW 1959: p. 203, pl. 12: figs. 88a-c, 89 and 90. – POSTUMA 1971: p. 256, 257. – KENNETT and SRINIVASAN 1983: p. 22, pl. 2: figs. 5-8. – BOLLI and SAUNDERS 1985: p. 186, fig. 17: 2a-c, and 3a-c. – PEARSON and CHAISSON 1997: p. 57, pl. 2: fig. 12. – (?) CHAISSON and D'HONDT 2000: p. 30, pl. 2: fig. 10 – Pearson et al. 2006: p. 77, pl. 5.3: figs.: 18-20 (illustrated holotype - SEM).

Globigerinita dissimilis (Cushman and Bermúdez 1937) – BERMÚDEZ 1961: p. 1262, pl. VII: figs 4a-c, 5a-c.

Globigerinita dissimilis (Cushman and Bermúdez) subsp. *dissimilis* CUSHMAN and BERMÚDEZ 1937 (*emend.)* – BLOW and BANNER 1962: p. 106, pl. XIV: fig. D.

Globigerinita dissimilis (Cushman and Bermúdez) subsp. *ciperoensis* BLOW and BANNER 1962: p. 107, pl. XIV: fig. A-C.

Catapsydrax stainforthi Bolli, Loeblich and Tappan 1957
Plate 4, 3 a-c, 4 a-c

Catapsydrax stainforthi BOLLI, LOEBLICH and TAPPAN 1957: p. 37, pl. 7: figs. 11a-c. – BLOW 1959: p. 204, pl. 14: figs. 91a-c, 92 and 93. – Postuma 1971: p. 258, 259. – KENNETT and SRINIVASAN 1983: p. 26, pl. 3: figs. 4-6.

Globigerinita stainforthi stainforthi (Bolli, Loeblich and Tappan 1957) – BLOW 1969: p. 131, pl. 25: figs. 8-10.

Genus *Globigerinita* Brönnimann 1951

Type Species. *Globigerinita naparimaensis* Brönnimann 1951

Globigerinita uvula (Ehrenberg 1861)

Pylodexia uvula EHRENBERG 1861: pp. 206, 207, 308 [description]; and Ehrenberg 1872: pl. 2: figs. 24 and 25 [illustrations].

Globigerina bradyi WIESNER 1931: p. 133.

?*Globigerina juvenilis* Bolli 1957. – BLOW 1969: p. 122, pl. 17: figs. 5, 6.

Globigerinita uvula (Ehremberg 1861) – KENNETT and SRINIVASAN 1983: p. 224, pl. 56: figs. 6-8. – Rögl 1985: p. 323, fig. 5: 26.

Globigerinita juvenilis (Bolli 1957)

Globigerina 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).

2 *Globigerinoides diminuta* Bolli, 1957. a) dorsal view, b) axial view, c) ventral view. Scale bar: 75 Fm; d) wall texture detail, scale bar: 20 Fm. Middle Miocene, *Globigerinoides primordius* zone - *Globigerinoides diminuta* subzone. Buenavista-1 Well. Plato Basin, LMV Sedimentary Province. Magdalena, Colombia. 9180ft - 9200ft Sample. (Repository: SC-ICP-PF-00013).

3 '*Globoturborotalita angustiumbilicata*'. a) ventral view. Scale bar: 50µm, b) wall texture detail, scale bar: 20µm. Late Oligocene to earliest early Miocene, *Globoturborotalita ciperoensis* zone. Carmen Formation (upper segment), Arroyo Alférez, Carmen-Zambrano Section, SJFB – Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-586 Sample. (Repository: SC-ICP-PF- 00077).

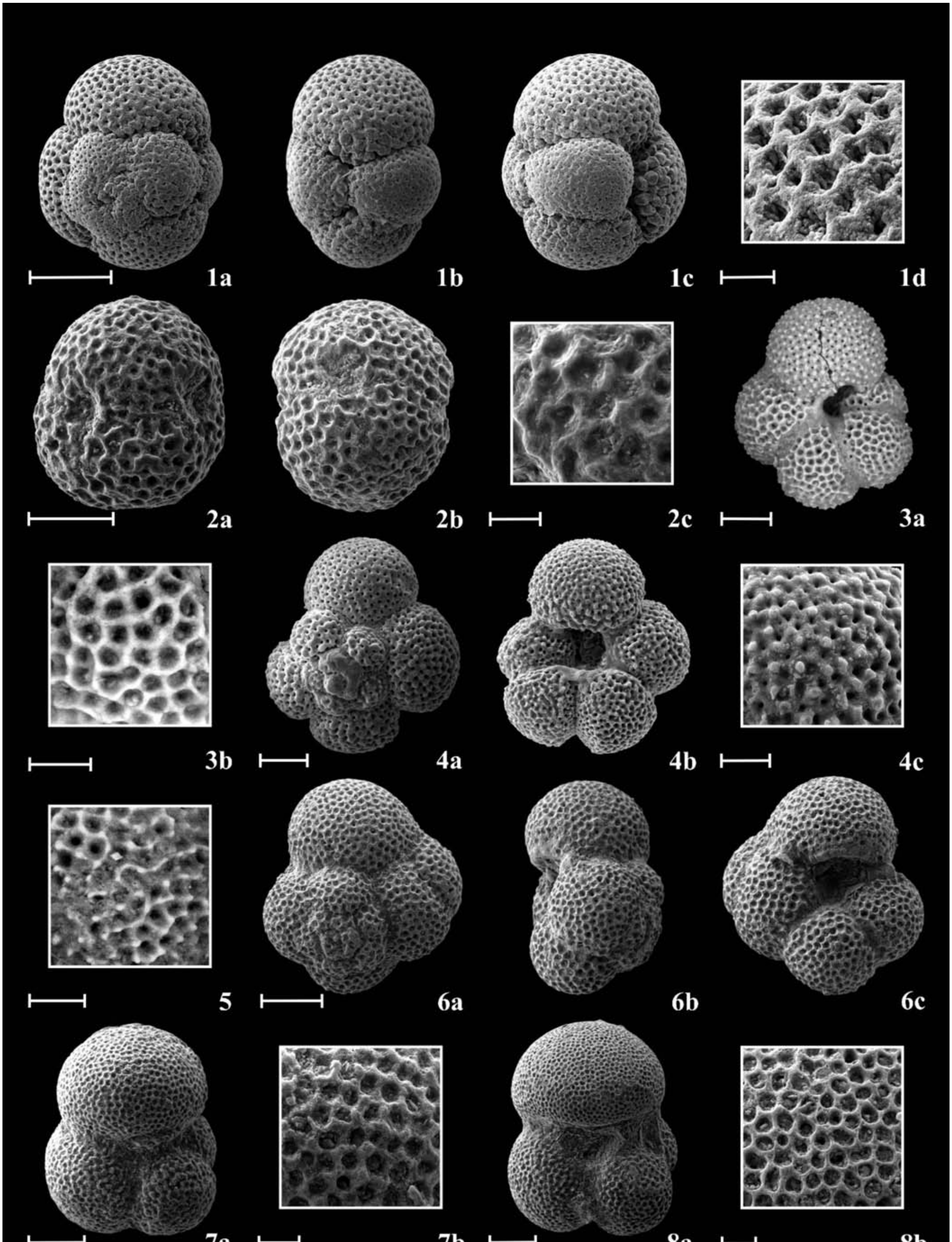
4 *Globoturborotalita ciperoensis* (Bolli, 1957). a) dorsal view Sp. 1, b) ventral view Sp. 2. Scale bar: 50 Fm; c) wall texture detail Sp. 2, scale bar: 20 Fm. Late Oligocene, *Paragloborotalia opima* zone. Carmen Formation (lower segment), Arroyo Alférez, Carmen-Zambrano Section, SJFB – Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-381 Sample. (Repository: SC-ICP-PF- 00042).

5 *Globoturborotalita ciperoensis* (Bolli, 1957). Wall texture detail (specimen from Plate V, figs. 7 a-c). Scale bar: 20 Fm. Late Oligocene, *Gloturborotalita ciperoensis* zone. Carmen Formation (upper segment), Arroyo Alférez, Carmen-Zambrano Section, SJFB – Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-557 Sample. (Repository: SC-ICP-PF-00078).

6 *Globoturborotalita ouachitaensis* (Howe and Wallace 1932). a) dorsal view, b) axial view, c) ventral view. Scale bar: 75µm. Late Eocene, *Subbotina yeguaensis* zone. Chengue Formation, Arroyo El Limón, SJFB – Sinú Sedimentary Province. Bolívar, Colombia. AL-021sltst Sample. (Repository: SC-ICP-PF- 00022).

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).


1a
1b
1c
1d
2a
2b
2c
3a
3b
4a
4b
4c
5
6a
6b
6c
7a
7b
8a
8b

[Not] *Globigerina juvenilis* Bolli 1957 – BERMÚDEZ 1961: p. 1187, pl. IV: figs. 4a, b.
[Not] *Globigerina juvenilis* Bolli 1957 – BLOW 1969: p. 122, pl. 17: figs. 5, 6.
Globigerinita glutinata (Egger 1893) – KENNETT and SRINIVASAN 1983 [*in part*]: p. 224, pl. 56: fig. 5.

Genus *Globigerina* d'Orbigny 1826
Type Species: *Globigerina bulloides* d'Orbigny 1826

Globigerina foliata Bolli 1957
Globigerina foliata Bolli 1957b: p. 111, pl. 24: figs. 1a-c. – BLOW 1959; p. 177, pl. 10: figs 42a-c. – BLOW 1969: p. 121, pl. 16: figs. 2-3.
[Not] *Globigerina foliata* Bolli 1957. – BERMÚDEZ 1961: p. 1182, pl. V: fig. 2.
Globigerina juvenilis Bolli 1957. – BERMÚDEZ 1961: p. 1187, pl. IV: fig. 4a, b.

Globigerina pseudociperoensis Blow 1969
Globigerina praebulloides Blow subsp. *pseudociperoensis* BLOW 1969: v. 1, p. 381, 382, pl. 17: figs. 8, 9. – GIBSON 1983: p. 369, pl. 1: figs. 7-9.

Remarks: A penultimate whorl with only four chambers (instead of five of *G. ciperoensis*) and a distinctive wall texture (resembles that of *Globigerina praebulloides*) characterize this species.

Genus *Globigerinella* Cushman 1927
Type Species: *Globigerina aequilateralis* Brady 1879

Globigerinella praecalida (Blow 1969)
Globigerina calida Parker subsp. *praecalida* BLOW 1969: p. 119, pl. 13: figs. 6, 7; pl. 14: fig. 3.

Genus *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, italics 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. *Globigerina conglobata* Brady 1879, *Globigera quadrilobata* d'Orbigny 1846, or *Globigera fistulosa* Schubert 1810), has been retained here.

The '*Globigerinoides*' word belongs to a substantivized adjective [*Globigerina* + -*oides* (Latin adjective suffix), which literally means '*having the form or appearance of Globigerina*'], and hence it has no gender. The species-group name endings of morphospecies grouped under the genus *Globigerinoides* could be in any grammatical gender form and, therefore, it is not necessary to change them to a masculine form employing the -*us*

PLATE 2
Globorotaliidae: *Fohsella* and *Paragloborotalia*. SEM images.

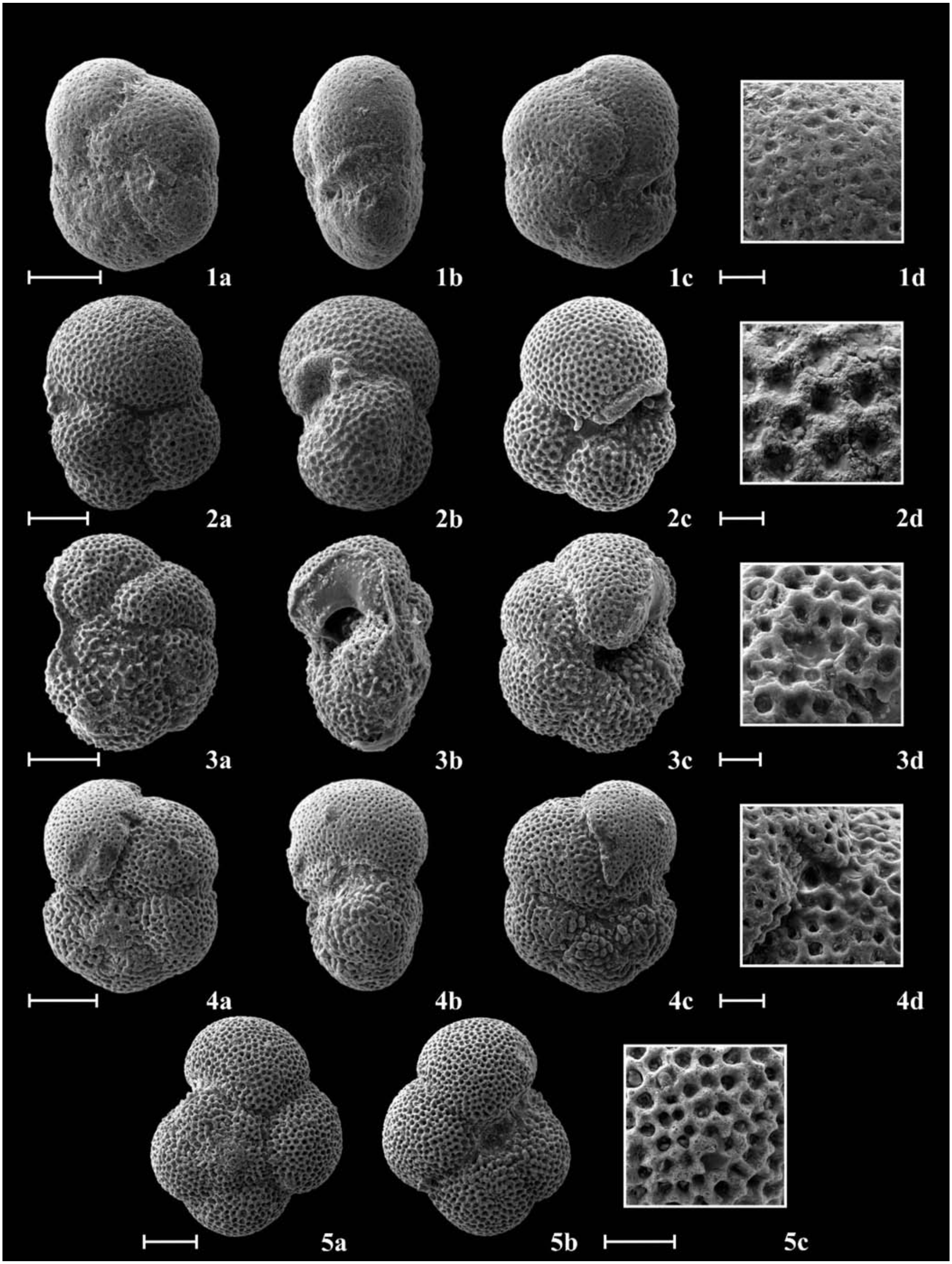
1 *Fohsella peripheroronda* (Blow and Banner 1966). a) dorsal view, b) axial view, c) ventral view. Scale bar: 100µm; d) wall texture detail, scale bar: 20µm. Middle Miocene, *Globigerinoides primordius* zone - *Globigerinoides diminuta* subzone. Buenavista-1 Well. Plato Basin, LMV Sedimentary Province. Magdalena, Colombia. 10240ft - 10260ft Sample. (Repository: SC-ICP-PF- 00007).

2 *Paragloborotalia griffinoides* 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 griffinoides* zone - *Clavigerinella colombiana* subzone. Chengue Formation, Arroyo El Limón, Carmen-Zambrano Section, SJFB - Sinú Sedimentary Province. Bolívar, Colombia. AL-006slst Sample. (Repository: SC-ICP-PF- 00030).

3 *Paragloborotalia kugleri* (Bolli 1957). a) dorsal view, b) axial view, c) ventral view. Scale bar: 50 Fm; d) wall texture detail, scale bar: 10 Fm. Early 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).

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 fohsi* zone - *Fohsella fohsi 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. Bolívar, Colombia. G05-CB-446 Sample. (Repository: SC-ICP-PF-00044).


1a
1b
1c
1d
2a
2b
2c
2d
3a
3b
3c
3d
4a
4b
4c
4d
5a
5b
5c

ending *when the type-species name ends in neuter form*. Furthermore, Cushman retained the neuter form of *Globigerina 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* Parker 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. 187, pl. 10: figs. 61a, b.
Globigerinoides altiaperturus Bolli 1957 – Postuma 1971: p. 284, 285. – Gibson 1983: p. 370, pl. 1: figs. 1, 2; pl. 4: figs. 7, 8.
?*Globigerinoides altiapertura* Bolli 1957 – Kennett and Srinivasan 1983: p. 54, pl. 11: figs. 4-6.

Globigerinoides bispherica Todd 1954

Globigerinoides bispherica Todd 1954 (In Brönnimann and Todd 1954): p. 681, pl. 1: figs. 1 a-c, and 4. – BOLLI 1957b: p. 114, pl. 27: figs. 1a, b.
Globigerinoides sicanus De Stefani 1950. – Bermúdez 1961 [*in part*]: 1240, pl. XI: fig. 12. – GIBSON 1983: p. 370, pl. 1: figs. 4, 5. – KENNETT and SRINIVASAN 1983: p. 62, pl. 13: figs. 4-6.
?*Praeorbulina sicana* (De Stefani 1950). – CHAISSON and D'HONDT 2000: p. 36, pl. 2: figs. 8, 9.

Globigerinoides bulloideus Crescenti 1966
Plate 4, 5a-c.

Globigerinoides bulloideus CRESCENTI 1966: p. 43, text fig. 9. – KENNETT and SRINIVASAN 1983: p. 60, pl. 12: figs. 7-9.

Globigerinoides diminuta Bolli 1957
Plate 1, 2a-c.

Globigerinoides diminuta Bolli 1957b: p. 114, pl. 25: figs. 11a-c. – Blow 1959: p. 191, pl. 13: figs. 66a, b. – Blow 1969: p. 126, pl. 20: fig. 4. – Postuma 1971: 288, 289.
Globigerinoides diminutus Bolli 1957 – Kennett and Srinivasan 1983: p. 74, pl. 16: figs. 4-6.

Globigerinoides mitra Todd 1957

Globigerinoides mitra Todd 1957: p. 302, pl. 78: figs. 3, 6. – BOLLI 1957b: p. 114, pl. 26: figs. 1a, b, 2a, b, 3a, b and 4. – BLOW 1959: p. 191, pl. 13: fig. 67. – BOLLI and SAUNDERS 1985: p. 194, fig. 21: 2a, b.

PLATE 3

Globorotaliidae: *Turborotalia*; Globoquadrinidae: *Globoquadrina*; Hantkeninidae: *Clavigerinella*; and Truncorotaloididae: *Acariina* and *Morozovella*. SEM images.

1 *Turborotalia ampliapertura* (Bolli 1957). a) dorsal view, b) axial view, c) ventral view. Scale bar: 100µm; d) wall texture detail, scale bar: 20µm. Early Oligocene, *Turborotalia ampliapertura* zone. Carmen Formation (lower segment), Carmén de Bolívar, Carmen-Zambrano Section, SJFB - Sinú Sedimentary Province. Bolívar, Colombia. HD-433 Sample. (Repository: SC-ICP (HD) - PF- 00009).

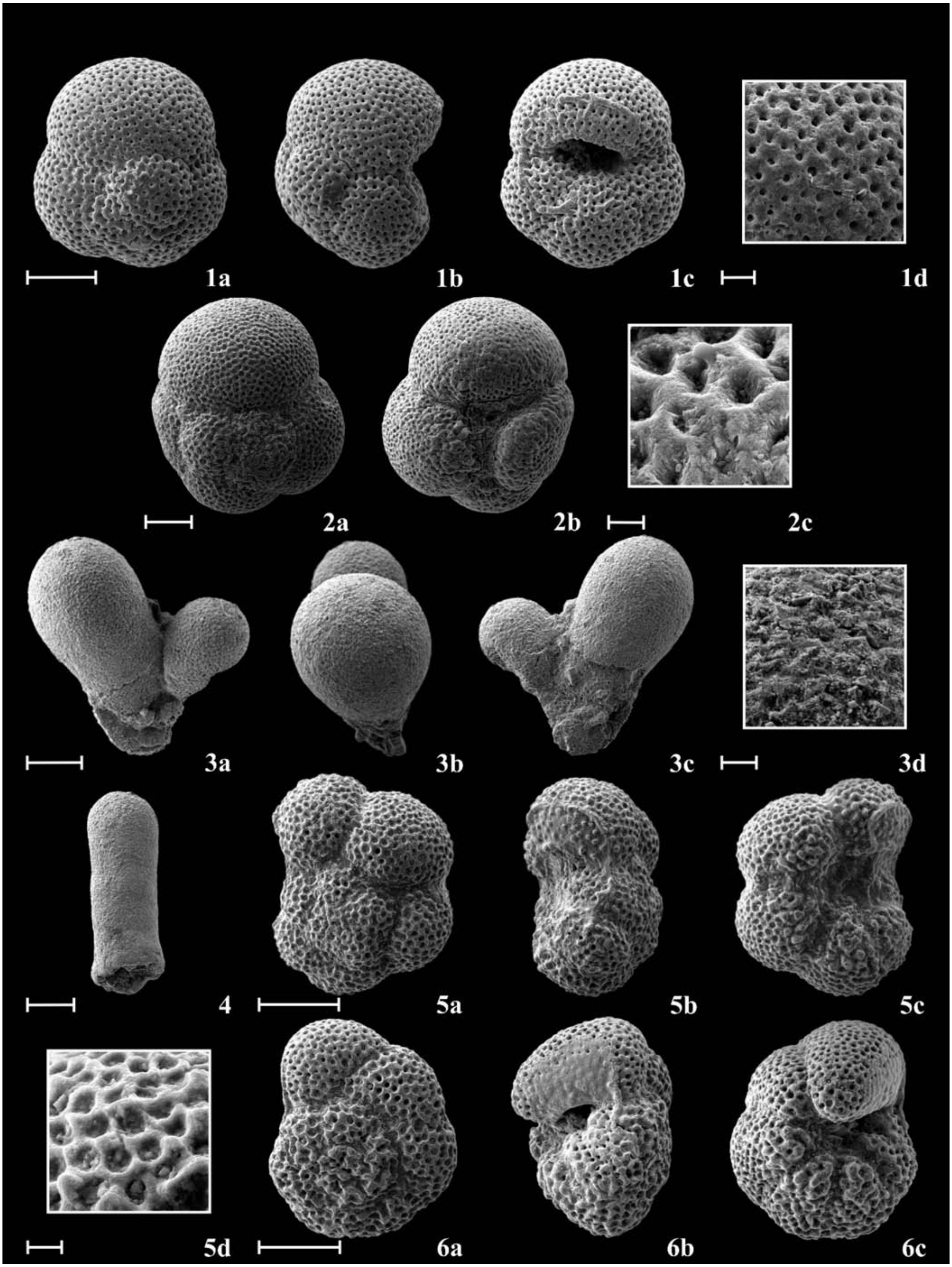
2 *Globoquadrina venezuelana* (Hedberg 1937). a) dorsal view, b) ventral view, scale bar: 100 Fm; c) wall texture detail, scale bar: 10 Fm. Middle Miocene, *Fohsella fohsi* zone - *Fohsella fohsi sensu lato* subzone. Tayrona-1 Well, LGB - Guajira Sedimentary Province. Guajira, Colombia. 12030ft Sample. (Repository: SC-ICP-PF- 00017).

3 *Clavigerinella eocanica* (Nuttall 1928) – *Clavigerinella colombiana* (Petters 1954) transitional specimen. a) dorsal view, b) axial view, c) ventral view. Scale bar: 100 Fm; d) recrystallized wall texture detail, scale bar: 10µm. Middle Eocene, *Paragloborotalia griffinoides* zone - *Clavigerinella colombiana* subzone. Chengue Formation, Arroyo Salvador, Carmen-Zambrano Section, SJFB - Sinú Sedimentary Province. San Juan Nepomuceno, Bolívar, Colombia. AS-139slst Sample. (Repository: SC-ICP-PF- 00004).

4 *Clavigerinella jarvisi* (Cushman 1930), chamber. Scale bar: 100 Fm. Middle Eocene, *Paragloborotalia griffinoides* zone - *Clavigerinella colombiana* subzone. Chengue Formation, Arroyo El Limón, Carmen-Zambrano Section, SJFB - Sinú Sedimentary Province. Bolívar, Colombia. AL-006slst Sample. (Repository: SC-ICP-PF- 00005).

5 *Acarinina pentacamerata* (Subbotina 1947). a) dorsal view, b) axial view, c) ventral view. Scale bar: 100 Fm; d) wall texture detail, scale bar: 20 Fm. Middle Eocene, *Paragloborotalia* griffinoides zone - *Clavigerinella colombiana* subzone. Chengue Formation, Arroyo El Limón, Carmen-Zambrano Section, SJFB - Sinú Sedimentary Province. Bolívar, Colombia. AL-025slst Sample. (Repository: SC-ICP-PF-00001).

6 *Igorina broedermanni* (Cushman and Bermúdez, 1949). a) dorsal view, b) axial view, c) ventral view. Scale bar: 100µm. Middle Eocene, *Paragloborotalia griffinoides* zone - *Clavigerinella colombiana* subzone. Chengue Formation, Arroyo El Limón, Carmen-Zambrano Section, SJFB - Sinú Sedimentary Province. Bolívar, Colombia. AL-025slst Sample. (Repository: SC-ICP-PF- 00001).


1a
1b
1c
1d
2a
2b
2c
3a
3b
3c
3d
4
5a
5b
5c
5d
6a
6b
6c

[Not] *Globigerinoides mitra* Todd 1957. – KENNETT and SRINIVASAN 1983: p. 76, pl. 16: figs. 7-9.
?Globicuniculus mitra (Todd 1957) – SAITO and THOMPSON 1976 (In: Saito, Thompson and Breger 1976): p. 287; figures in: Loeblich and Tappan 1988: pl. 528: figs. 1-3.

Globigerinoides obliqua Bolli 1957
Globigerinoides obliqua Bolli 1957b [*in part*]: p. 113, pl. 25: figs. 10a-c. – BLOW 1959: p. 191, pl. 11: figs. 68a, b.
Globigerinoides obliquus Bolli 1957. – BERMÚDEZ 1961: p. 1231, pl. X: figs. 3a-c. – KENNETT and SRINIVASAN 1983: p. 56, pl. 11: figs. 7-9.
?Globigerinoides obliquus Bolli 1957. – POSTUMA 1971: p. 296, 297.

Globigerinoides primordius Blow and Banner 1962
Plate 4, 6a-c

Globigerinoides quadrilobatus (d'Orbigny) subsp. *primordius* BLOW and BANNER 1962: p. 115, pl. IX: figs. Dd-Ff. – BLOW 1969: p. 127, pl. 20: figs. 1, 5 and 6. – POSTUMA 1971: p. 298, 299. – KENNETT and SRINIVASAN 1983: p. 54, pl. 11: figs. 1-3.

Globigerinoides subquadrata Brönnimann 1954
Globigerinoides subquadrata BRÖNNIMANN 1954 (In Brönnimann and Todd 1954): p. 680, pl. 1: figs. 8a-c.
Globigerinoides subquadratus Brönnimann 1954.– BLOW 1969: p. 129, pl. 21: fig. 5.
[Not] *Globigerinoides subquadratus* Brönnimann 1954. – BERMÚDEZ 1961: p. 1244, pl. XII, figs. 3a-c. – POSTUMA 1971: p. 306, 307. – KENNETT and SRINIVASAN 1983: p. 74, pl. 16: figs. 1-3.
?Globigerinoides rubra (d'Orbigny 1839). – BOLLI 1957b [*in part*]: p. 113, pl. 25: figs. 13a, b.
Globigerinoides ruber (d'Orbigny 1839) – BOLLI and SAUNDERS 1985 [*in part*]: p. 196, fig. 20: 6a-c (holotype of *G. subquadrata*).

Remarks: Both an *equatorial* and *axial* subquadrate profile, with very to moderately *depressed intercameral sutures*, a distinctive shallow umbilicus, and *only one* arcuate 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)
Globigerina triloba REUSS 1850: p. 374, pl. 447: fig. 11a-c.
Globigerinoides triloba triloba (Reuss 1850). – BOLLI 1957b: p. 112, pl. 25: figs. 2a-c. – BLOW 1959: p. 187, pl. 11: figs. 60a, b.
Globigerinoides triloba (Reuss 1850) – KENNETT and SRINIVASAN 1983: p. 62, pl. 13: figs. 1-3.
[Not] *Globigerinoides trilobus* (Reuss 1850) – BERMÚDEZ 1961: p. 1244, pl. XII: fig. 6.
Globigerinoides trilobus (Reuss 1850) – POSTUMA 1971: p. 308, 309.
Globigerinoides trilobus trilobus (Reuss 1850) – GIBSON 1983: p. 371, pl- 4: fig. 12.

Genus *Globorotaloides* Bolli 1957
Type Species: *Globorotaloides variabilis* Bolli 1957

Globorotaloides suteri Bolli 1957
Plate 4, 7a-c

Globorotaloides suteri BOLLI 1957b: p. 117, pl. 27: figs. 9a-c 10a-b 11a-b 12a-b and 13a-b. – BOLLI 1957c: p. 166, pl. 37: figs. 10a-c 11 12. – BLOW and BANNER 1962: p. 122, pl. XIII: figs. N-P. – KENNETT and SRINIVASAN 1983: p. 214, pl. 53: figs. 3-5.

PLATE 4

Globigerinidae: *Catapsydrax*, *Globigerioides* and *Globorotaloides*. Optical images.

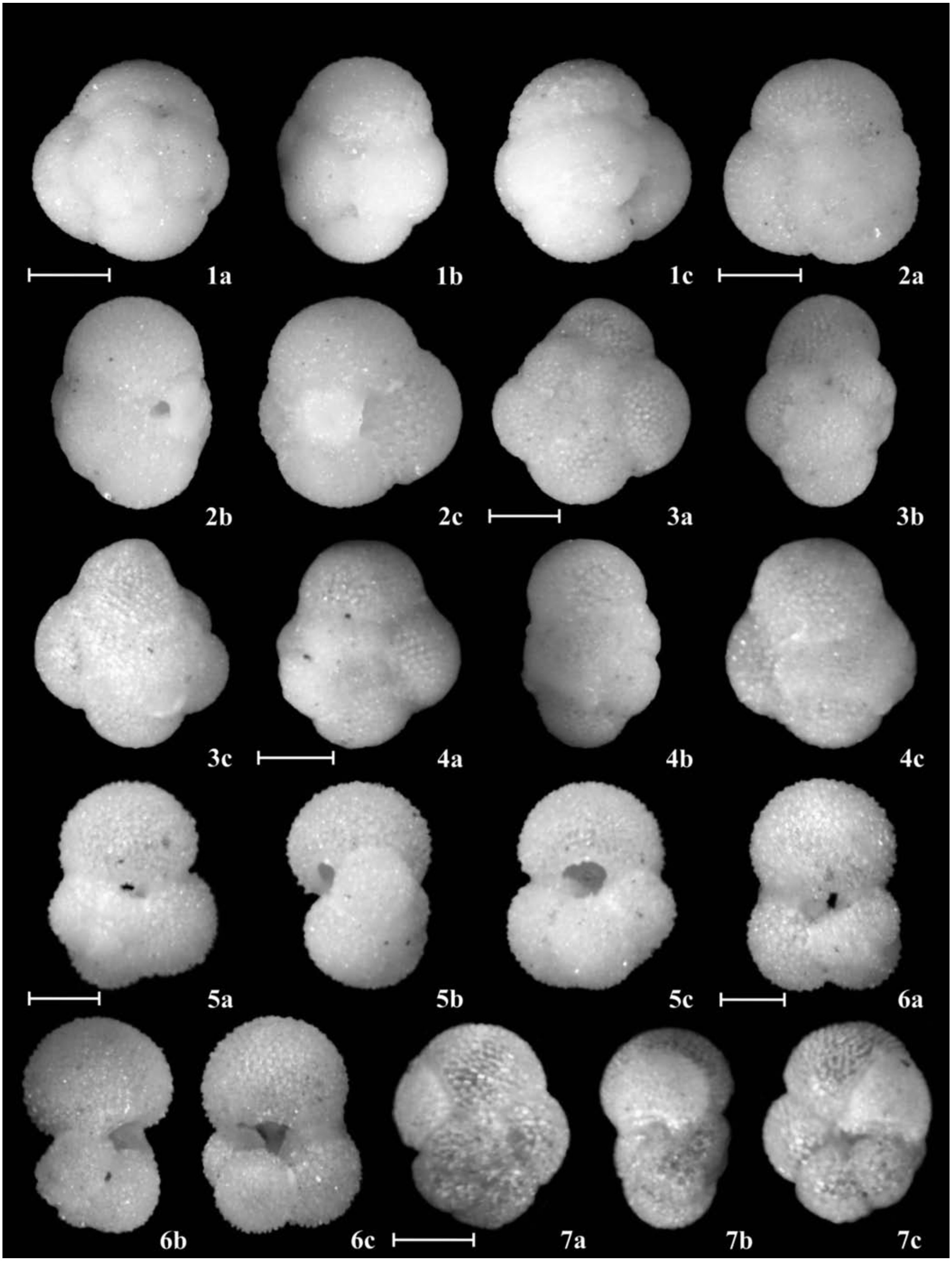
1,2 *Catapsydrax dissimilis* (Cushman and Bermúdez, 1937). a) dorsal view, b) axial view, c) ventral view. Scale bar: 150µm. Early Miocene, *Globoturborotalita ouachitaensis* zone - *Catapsydrax dissimilis* subzone. Carmen Formation (upper segment), Arroyo Alférez, Carmen-Zambrano Section, SJFB – Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-708 Sample. (Repository: SC-ICP-PF- 00064).

3,4 *Catapsydrax stainforthi* Bolli, Loeblich and Tappan, 1957. a) dorsal view, b) axial view, c) ventral view. Scale bar: 100 Fm. Early Miocene, *Globigerinoides primordius* zone - *Paragloborotalia kugleri* subzone. Carmen Formation (upper segment), Arroyo Alférez, Carmen-Zambrano Section, SJFB – Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-700 Sample. (Repository: SC-ICP-PF- 00065).

5 *Globigerinoides bulloideus* Crescenti, 1966. a) dorsal view, b) axial view, c) ventral view. Scale bar: 100 Fm. Early Miocene, *Globigerinoides primordius* zone - *Paragloborotalia kugleri* subzone. Carmen Formation (upper segment), Arroyo Alférez, Carmen-Zambrano Section, SJFB – Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-700 Sample. (Repository: SC-ICP-PF- 00071).

6 *Globigerinoides primordius* Blow and Banner, 1962. a) dorsal view, b) axial view, c) ventral view. Scale bar: 100 Fm. Early Miocene, *Globigerinoides primordius* zone - *Paragloborotalia kugleri* subzone. Carmen Formation, Arroyo Alférez, Carmen-Zambrano Section, SJFB – Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-700 Sample. (Repository: SC-ICP-PF- 00072).

7 *Globorotaloides suteri* Bolli, 1957. a) dorsal view, b) axial view, c) ventral view. Scale bar: 100 Fm. Latest Oligocene to earliest early Miocene, *Globoturborotalita ciperoensis* zone. Carmen Formation (upper segment), Arroyo Alférez, Carmen-Zambrano Section, SJFB – Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-586 Sample. (Repository: SC-ICP-PF- 00075).


1a
1b
1c
2a
2b
2c
3a
3b
3c
4a
4b
4c
5a
5b
5c
6a
6b
6c
7a
7b
7c

Catapsydrax unicavus Bolli, Loeblich and Tappan 1957. – PEARSON et al. 2006 [*in part*]: p. 77, pl. 5.3: fig. 9-11 (illustrated holotype of *G. suteri*- SEM).

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. XIII: figs. 3a, b. – KENNETT and SRINIVASAN 1983: p. 214, pl. 53: figs. 6-8.

Genus ***Globoturborotalita*** Hofker 1976
Type Species: *Globigerina rubescens* Hofker 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.*) *anguliosuturalis*'. Previously, Blow and Banner (1962) regarded *Globigerina officinalis* as the stem species of *Globigerina ouachitaensis ciperoensis* and *Globigerina angulisuturalis* through *G. ouachitaenis ouachitaensis* (Lineage D); later Blow (1969) considered his *Globigerina anguliofficinalis* species a "phylogenetically advanced [taxon] […] of the lineage which leads from *G. officinalis* to *G. angulisuturalis*", establishing it as an ancestral form that "gradually evolves into *G. anguliosuturalis*". Recently, taking *Globoturborotalita bassriverensis* Olsson and Hemleben, 2006 as the first species of the genus line, Pearson et al. (2006) established a phylogenetic relationship between it and *G. anguliofficinalis* through the *G. ouachitaensis* – *G. gnaucki* lineage. Although the phylogenetic relationships between '*ciperoensis*-group' species are not completely understood, a four-chambered species (*G. ouachitaensis*) appears to be the stem species for the radiation of this morphologic group throughout the late Eocene and early Oligocene (Pearson et al. 2006).

Primarily because of test-size and wall texture (ultra-structure) characteristics of *Globigerina ouachitaensis* and *Globigerina anguliofficinalis*, Pearson et al. (2006) have included them under *Globoturborotalita*. In keeping with the features of this 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 cancellate 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 anguliofficinalis (Blow 1969)
Globigerina anguliofficinalis BLOW 1969: p. 117 181, pl. 2, figs. 1-5.
Globigerina ciperoensis anguliofficinalis BLOW 1969.
Globoturborotalita anguliofficinalis (Blow 1969) – PEARSON et al. 2006: p. 120, pl. 6.2: figs. 1-7.

Globoturborotalita angulisuturalis (Bolli 1957)
Plate 5, 1a-c, 2a-c, 3a-c.

Globigerina ciperoensis angulisuturalis BOLLI 1957b: p. 109, pl. 22, figs. 11a-c. – BOLLI and SAUNDERS 1985: p. 182, fig. 13: 5-7.

PLATE 5
Globigerinidae: *Globoturborotalita.* Optical images.

1-3 *Globoturborotalita angulisuturalis* (Bolli 1957). a) dorsal view, b) axial view, c) ventral view. Scale bar: 100µm. Late Oligocene, *Gloturborotalita ciperoensis* zone. Carmen Formation (upper segment), Arroyo Alférez, Carmen-Zambrano Section, SJFB – Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-557 Sample. (Repository: SC-ICP-PF- 00076).

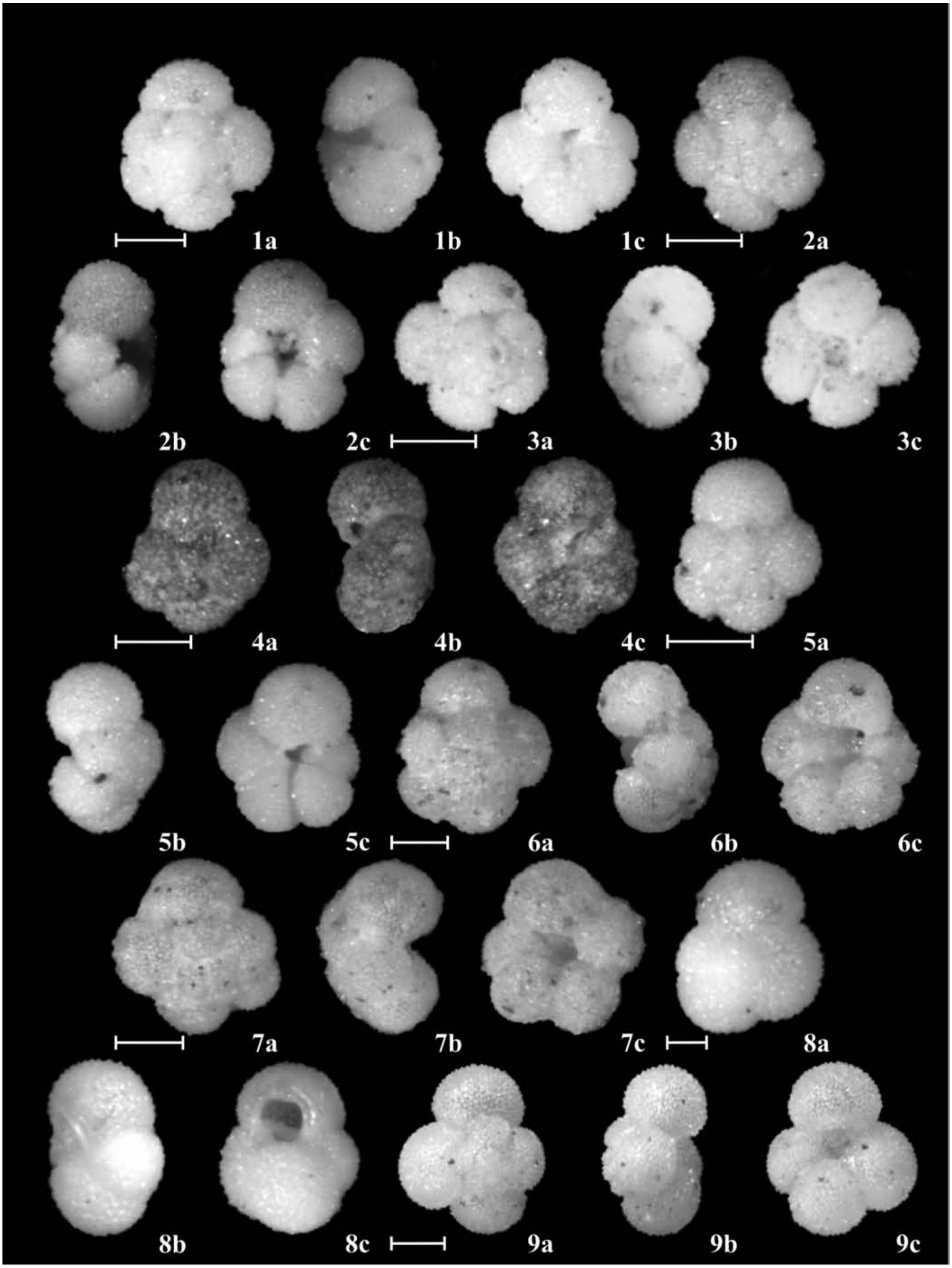
4 *'Globoturborotalita angustiumbilicata'*. a) dorsal view, b) axial view, c) ventral view. Scale bar: 100 Fm. Late Oligocene, *Gloturborotalita ciperoensis* zone. Carmen Formation (upper segment), Arroyo Alférez, Carmen-Zambrano Section, SJFB – Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-557 Sample. (Repository: SC-ICP-PF-00077).

5 '*Globoturborotalita angustiumbilicata*'. a) dorsal view, b) axial view, c) ventral view. Scale bar: 50µm. Late Oligocene to earliest early Miocene, *Globoturborotalita ciperoensis* zone. Carmen Formation (upper segment), Arroyo Alférez, Carmen-Zambrano Section, SJFB – Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-586 Sample. (Repository: SC-ICP-PF- 00077).

6,7 *Globoturborotalita ciperoensis* (Bolli, 1957). a) dorsal view, b) axial view, c) ventral view. Scale bar: 100 Fm. Late Oligocene, *Gloturborotalita ciperoensis* zone. Carmen Formation (upper segment), Arroyo Alférez, Carmen-Zambrano Section, SJFB – Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-557 Sample. (Repository: SC-ICP-PF- 00078).

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

9 *Globoturborotalita ouachitaensis* (Howe and Wallace 1932). a) dorsal view, b) axial view, c) ventral view. Scale bar: 100µm. Early Miocene, *Globigerinoides primordius* zone, *Paragloborotalia kugleri* subzone. Carmen Formation (upper segment), Arroyo Alférez, Carmen-Zambrano Section, SJFB – Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-600 Sample. (Repository: SC-ICP-PF-00079).


1a
1b
1c
2a
2b
2c
3a
3b
3c
4a
4b
4c
5a
5b
5c
6a
6b
6c
7a
7b
7c
8a
8b
8c
9a
9b
9c

Globigerina angulisuturalis Bolli 1957. – BLOW and BANNER 1962: p. 84, pl. IX, figs. Aa-Cc. – BLOW 1969: p. 118, pl. 1: figs. 4-6; pl. 12: 1-2. – POSTUMA 1971: p. 260, 261.
Globigerina (*Globigerina*) *angulisuturalis* Bolli 1957 – KENNETT 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
?Globigerina angustiumbilicata Bolli 1957. – BLOW 1959: p. 172, pl. 7: figs. 33a-c, 34. – BLOW and BANNER 1962: p. 85, pl. IX: figs. X-Z.
[Not] *Globigerina* (*Globigerina*) *angustiumbilicata* Bolli 1957 – KENNETT and SRINIVASAN 1983. p. 31, pl. 4: figs. 3-5.
[Not] *Tenuitellinata angustiumbilicata* (Bolli 1957). – LI 1987: p. 311, pl. 2: figs. 15 17-19; pl. 4: figs. 8-10.
?*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 angustiumbilicata* to be the type species of genus *Tenuitellinata*, pointing out differences between *G. angustiumbilicata* and the two remaining Bolli's subspecies of *Globigerina ciperoensis*. Under '*Globoturborotalita angustiumbilicata'* we have provisionally placed the homeomorphic specimens of *Tenuitellinata angustiumbilicata* (Bolli 1957b), characterized 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 ciperoensis BOLLI 1954 [*in part*]: v. 5, pt. 1, p. 1. figs. 1a, b. – BERMÚDEZ 1961: p. 1164, pl. II, figs. 1a-c, 2a-c. – POSTUMA 1971: p. 264, 265
Globigerina (*Globigerina*) *ciperoensis* Bolli 1954. – KENNETT and SRINIVASAN 1983: p. 28, pl. 4: figs. 6-8.
Globigerina ciperoensis Bolli subsp. *ciperoensis* BOLLI 1957: p. 109, pl. 22: figs. 10a, b. – BOLLI and SAUNDERS 1985: p. 182, fig. 13: 2-3.
Globigerina ouachitaensis Howe and Wallace subsp. *ciperoensis* (Bolli 1957) .– BLOW and BANNER 1962: p. 90, pl. IX: figs. E-G. – BLOW 1969: p. 122, pl. 17: figs. 7, 10, 11 (typical and atypical forms).

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

Globigerina druryi Akers subsp. *decoraperta* TAKAYANAGI and SAITO 1962: p. 85, pl. 28: figs. 10a-c.
Globigerina (*Zeaglobigerina*) *decoraperta* Takayanagi and Saito 1962 – KENNETT and SRINIVASAN: p. 48, pl. 9, figs. 4-6.

Globoturborotalita nepenthes (Todd 1957)
Globigerina nepenthes TODD 1957: p. 301, pl. 78. fig. 7. – Bolli 1957b: p. 111, pl. 24: figs. 2a-c. – BLOW 1959: p. 178, pl. 8: figs. 44, 45. – BLOW 1969: p. 122, pl. 14: fig. 5. – POSTUMA 1971: p. 266, 267 (transitional form). – BOLLI and SAUNDERS 1985: p. 201, fig. 25: 2-4.
Globigerina (*Zeaglobigerina*) *nepenthes* Todd 1956 – KENNETT and SRINIVASAN 1983: p. 48, pl. 9, figs. 1-3.
Sphaeroidinellopsis nepenthes (Todd 1956) – BERMÚDEZ 1961: p. 1277, pl. X: figs. 1a, b.
Globoturborotaliata nepenthes (Todd 1956) – CHAISSON and D'HONDT 2000: p. 33, pl. 1: fig. 16 [transitional specimen between *Globoturborotalita druyi* (Akers 1955) and *G. nepenthes* (Todd 1956)].

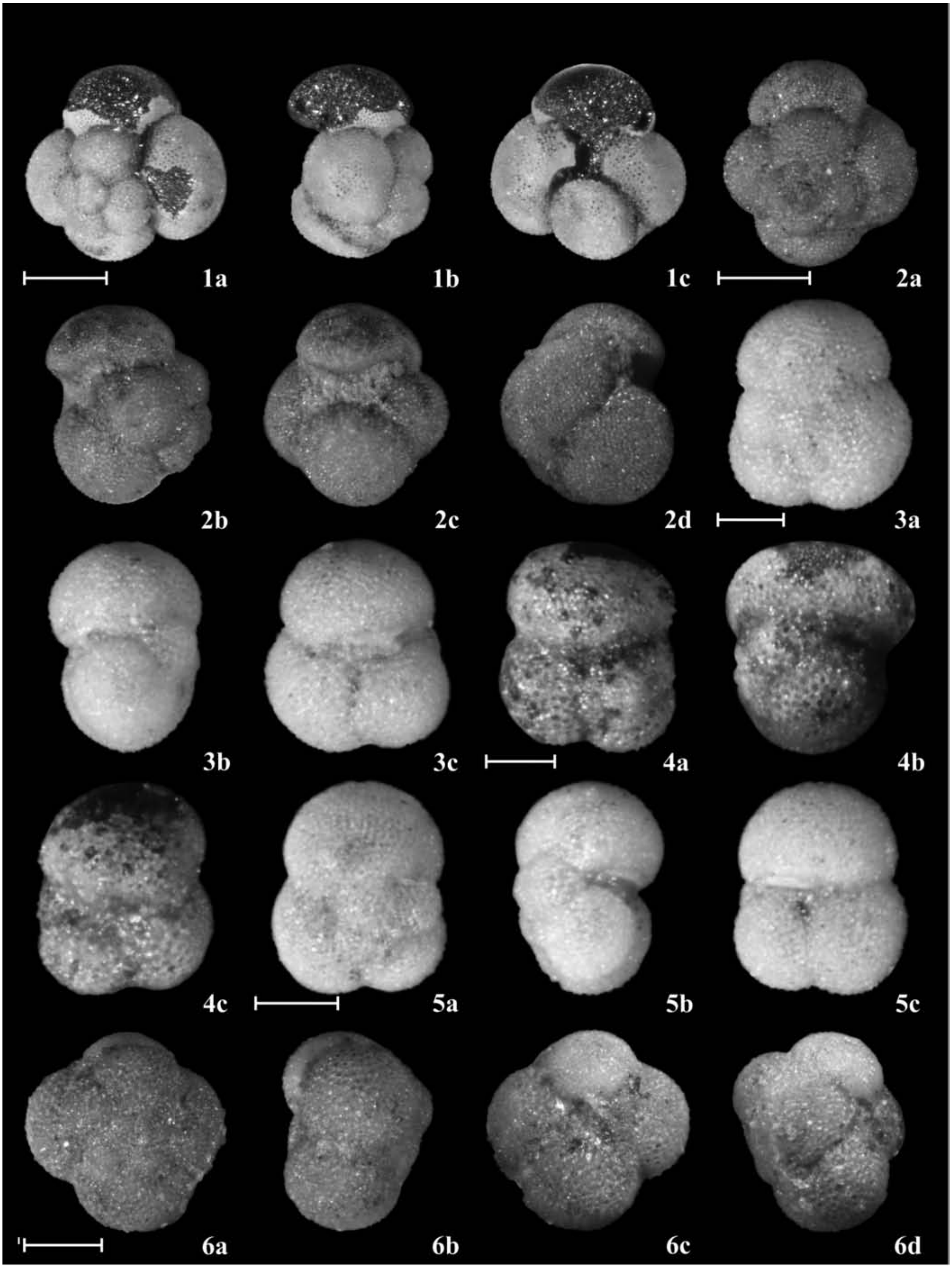
PLATE 6
Globigerinidae: *Subbotina.* Optical images.

1 *Subbotina gortanii* (Borsetti 1959). a) dorsal view, b) axial view, c) ventral view. Scale bar: 250µm. Late Oligocene, *Paragloborotalia opima* zone. Carmen Formation (Upper segment). Arroyo Alférez, Carmen - Zambrano Section, SJFB - Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-398 Sample. (Repository: SC-ICP-PF- 00087).

2 *Subbotina gortanii* (Borsetti 1959). a) dorsal view, b) axial view, c) ventral view, d) axial view. Scale bar: 250 Fm. Late Oligocene, *Paragloborotalia opima* zone. Carmen Formation (Upper segment). Arroyo Alférez, Carmen - Zambrano Section, SJFB - Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-372 Sample. (Repository: SC-ICP-PF-00087).

3-5 *Subbotina linaperta* (Finlay 1939), morphological variations. a) dorsal view, b) axial view, c) ventral view. Scale bar: 100µm. Late Eocene, *Subbotina yeguaensis* zone. San Jacinto Formation (Upper segment). Arroyo Alférez, Carmen - Zambrano Section, SJFB - Sinú Sedimentary Province. Bolívar, Colombia. Samples G05-CB-83 and G05-CB-131. (Repository: SC-ICP-PF- 00088).

6 *Subbotina senilis* (Bandy 1949). a) dorsal view, b) axial view, c) ventral view, d) axial view. Scale bar: 200 Fm. Late Oligocene, *Paragloborotalia opima* zone. Carmen Formation (Upper segment). Arroyo Alférez, Carmen - Zambrano Section, SJFB - Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-368 Sample. (Repository: SC-ICP-PF- 00089).


1a
1b
1c
2a
2b
2c
2d
3a
3b
3c
4a
4b
4c
5a
5b
5c
6a
6b
6c
6d

Globoturborotalita ouachitaensis (Howe and Wallace 1932)
Plate 1, 6a-c; Plate 5, 9a-c.

Globigerina ouachitaensis HOWE and WALLACE 1932: p. 74, pl. 10: fig. 7. – POSTUMA 1971: p. 152, 153.
Globigerina parva Bolli 1957 [*in part*] – BOLLI 1957c: p. 164, pl. 36: figs. 7a-c.
Globigerina ouachitaensis ouachitaensis Howe and Wallace 1932 – BLOW and BANNER 1962 [*in part*]: p. 90, pl. IX: figs. H-K.
Globoturborotaliata ouachitaensis (Howe and Wallace 1932). – PEARSON et al., 2006: p. 127, pl. 6.5: figs. 1-14.

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

Subbotina gortanii (Borsetti 1959)
Plate 6, 1a-c, 2a-d

Catapsydrax gortanii BORSETTI 1959: pp. 205 - 207, pl. 1: figs. 1a-d.
Globigerina turritilina Blow and Banner subsp. *turritilina* BLOW and BANNER 1962: p. 98, pl. XII: figs. D-G.
Globigerina gortanii gortanii (Borsetti 1959) – BLOW 1969: p. 122, pl. 17: figs. 1.
Globigerina gortanii (Borsetti 1959).
Subbotina gortanii (Borsetti 1959) – PEARSON et al. 2006 [*in part*]: p. 136, pl. 6.10: figs. 1-3 (illustrated holotype of *G. turritilina turritilina* - SEM), 4.

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 robust and by having a broader umbilicus and slightly more inflated chambers than *S. gortanii*.

Subbotina linaperta (Finlay 1939)
Plate 1, 7a, b; Plate 6, 3a-c, 4a-c, 5a-c.

Globigerina linaperta Finlay 1939: p. 125, pl. 13: figs. 54-57. – Bolli 1957a: p. 70, pl. 15: figs. 15-17 [considered by Pearson et al., 2006 as a *Subbotina patagonica* specimen]. – Bolli 1957c: p. 163, pl. 36, figs. 5a, b. – Bermúdez 1961[*in part*]: p. 1188, pl. IV, figs. 5a, b. – Jenkins 1985: p. 275, fig. 6: 2a-c [re-illustrated holotype].
Globigerina linaperta linaperta Finlay 1939– Blow and Banner 1962: p. 85, pl. XI, fig. H
Subbotina linaperta (Finlay 1939) – Pearson et al., 2006 [*in part*]: p. 144, pl. 6.14: figs. 1-8.

Remarks: Under *Subbotina linaperta* (Finlay 1939), only the following restricted morphological variation was considered: specimens with (1) a test with a sub-quadrate 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 aperture 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.

Globigerina ouachitaensis Howe and Wallace var. *senilis* Bandy 1949: p. 121, pl. 22: fig. 5a-c.
Subbotina jacksonensis (Bandy 1949) – Pearson et al. 2006 [*in part*]: p. 142, pl. 6.13: figs.4, 7 and 8 (illustrated holotype of *G. ouachitaensis senilis*- SEM).

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 ouachitaenis 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.

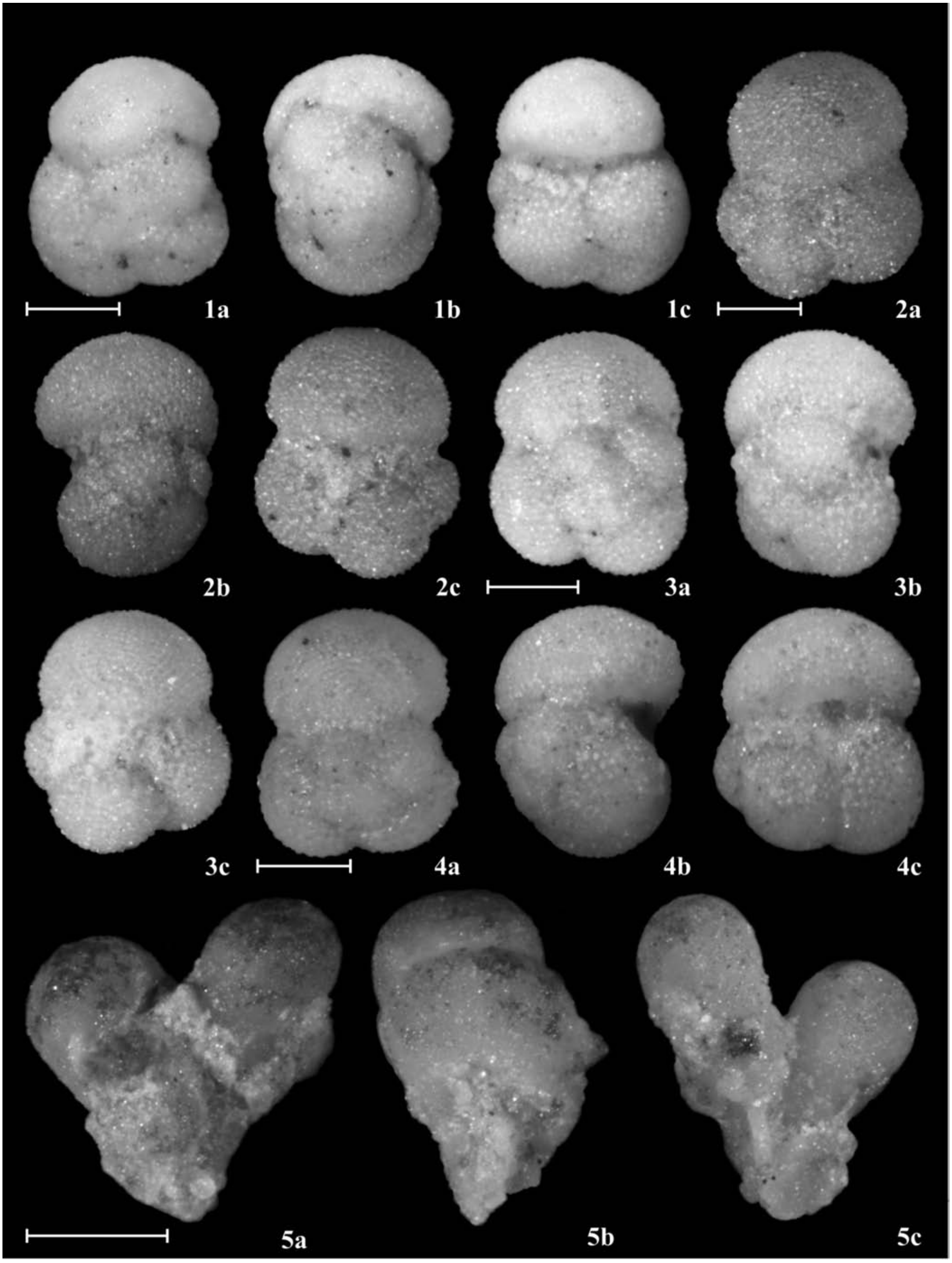
Globigerina yeguaensis Weinzierl and Applin 1929: p. 408, pl. 43: figs. 1a, b. – Bolli 1957c [*in part*]: p. 163, pl. 35: figs. 15a-c. – Bolli and Saunders 1985 [*in part*]: p. 180, 181, fig. 13: 23a, b.
[Not] *Globigerina yeguaensis* Weinzierl and Applin 1929 – Bermúdez 1961: p. 1208, pl. VI: figs. 5a, b.
[Not] *Globigerina yeguaensis* Weinzierl and Applin subsp. *yeguaensis* Weinzierl and Applin 1929 (*emend.*) – Blow and Banner 1962: p. 99, pl. XIII, figs. K-M.
?*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.
[Not] *Globigerina yeguaensis* Weinzierl and Applin 1929 – Berggren 1960: p. 73, pl. II: figs. 2a-c, 4a-c; pl. III: figs. 1a-c, 2a-c, 3a-c; pl. VIII: 3, 4, 5a-c.
?*Subbotina roesnaensis* Olsson and Berggren, 2006 [*in part*]: p. 148, pl. 6.16: fig. 8. (In: Pearson et al., 2006).

PLATE 7

Globigerinidae: *Subbotina*; Hantkeninidae: *Clavigerinella.* Optical images.

1-4 *Subbotina yeguaensis* (Weinzierl and Applin, 1929), morphological variations. a) dorsal view, b) axial view, c) ventral view. Scale bar: 150µm. Late Eocene and early Oligocene, *Subbotina yeguaensis* and *Turborotalia ampliapertura* zones. Carmen Formation (Lower segment). Arroyo Alférez, Carmen - Zambrano Section, SJFB - Sinú Sedimentary Province. Bolívar, Colombia. Samples G05-CB-285 and G05-CB-311. (Repository: SC-ICP-PF- 00090).

5 *Clavigerinella colombiana* (Petters, 1954). a) equatorial view, b) axial view, c) equatorial view. Scale bar: 250 Fm. Middle Eocene, *Paragloborotalia griffinoides* zone - *Clavigerinella colombiana* subzone. Chengue Formation. Arroyo Las Flechas, Serranía San Jacinto, SJFB - Sinú Sedimentary Province. Bolívar, Colombia. ALF-023slst Sample. (Repository: SC-ICP-PF- 00066).


1a
1b
1c
2a
2b
2c
3a
3b
3c
4a
4b
4c
5a
5b
5c

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

Genus *Orbulina* d'Orbigny 1839
Type Species: *Orbulina universa* d'Orbigny 1839

Orbulina bilobata d'Orbigny 1846
Orbulina bilobata d'Orbigny 1846: p. 164, pl. 9: figs. 11-14. – Bolli 1957b: p. 116, pl. 27: fig. 6. – Postuma 1971: p. 370, 371. – Kennett and Srinivasan 1983: p. 88, pl. 20: figs. 7-9.
Biorbulina bilobata (d'Orbigny 1846) – Blow 1959: p. 199, pl. 13: figs. 80, 81. – Bermúdez 1961: p. 1255, pl. XIX: figs. 20. – Blow 1969: p. 136, pl. 23: figs. 5, 6.
Orbulina universa d'Orbigny 1839 – Bolli and Saunders 1985 [*in part*]: p. 201, fig. 24: 1.

Orbulina suturalis Brönnimann 1951
Orbulina suturalis Brönnimmann 1951: p. 135, text-fig. 2: figs. 1, 2, 5-8, 10, text-fig. 3: figs. 3-8, 11, 13-16, 18, 20-22. text-fig. 4: figs. 2-4, 7-12, 15-16, 19-22. – BOLLI 1957: p. 115, pl. 27: fig. 4. – BLOW 1959: p. 200, pl. 13: figs. 82a-b. – POSTUMA 1971: p. 372, 373. – KENNETT and SRINIVASAN 1983: p. 86, pl. 20: figs. 1-3. – BOLLI and SAUNDERS 1985: p. 201, fig. 24: 3.

Genus *Praeorbulina* Olsson 1964
Type Species: *Globigerinoides glomerosa glomerosa* Blow 1956

Praeorbulina glomerosa (Blow 1956)
Globigerinoides glomerosa Blow subsp. *glomerosa* BLOW 1956: p. 65, text-fig. 1: 15-19; text-fig. 2: 1-2.
Porticulasphaera glomerosa glomerosa (Blow 1956). – BOLLI 1957b: p. 115, pl. 27: fig. 8. – BLOW 1959: p. 202, pl. 14: figs. 85a, b.
?*Globigerinoides glomerosus* Blow 1956. – BERMÚDEZ 1961 [*in part*]: p. 1229, pl. XI: fig. 7.
?*Globigerinoides glomerosus* var. *curva* Blow 1956. – BERMÚDEZ 1961: 1230, pl. XI: fig. 10.
Praeorbulina glomerosa glomerosa (Blow 1956). – BLOW 1969: p. 135, pl. 23: fig. 7. – POSTUMA 1971: p. 376, 377. – GIBSON 1983: p. 374, pl. 1: 3, 6. – KENNETT and SRINIVASAN 1983: p. 82, pl. 18: 5, 7.

Praeorbulina sicana (De Stefani 1950)
Globigerinoides conglobata (Brady 1879). – CUSHMAN and STAINFORTH 1945 [*in part*]: p. 68, pl. 13: fig. 6.
Globigerinoides sicana De Stefani 1950 (In De Stefani 1952): p. 9, fig. 6. Figured holotype in Blow 1969: pl. 3: figs. 10, 11.
Globigerinoides bispherica Todd 1954. – BLOW 1959: p. 189, pl. 11: figs. 64.
Globigerinoides sicanus De Stefani 1950. – BERMÚDEZ 1961 [*in part*]: 1240, pl. 12: fig. 1a, b. – BLOW 1969: p. 128, pl. 3: figs. 10, 11. – POSTUMA 1971: p. 304, 305.
[Not] *Globigerinoides sicanus* De Stefani 1950. – KENNETT and SRINIVASAN 1983: p. 62, pl. 13: figs. 4-6.
Praeorbulina sicana (De Stefani 1950). – BOLLI and SAUNDERS 1985: p. 199, fig. 24: 7a, b (re-drawn holotype).

Praeorbulina transitoria (Blow 1956)
Globigerinoides transitoria BLOW 1956: p. 65, 67, text-fig. 2: 12-13.

PLATE 8

Globoquadrinidae: *Dentoglobigerina* and *Globoquadrina*; Globorotaliidae: *Turborotalia.* Optical images.

1 *Dentoglobigerina pseudovenezuelana* (Blow and Banner, 1962). a) dorsal view, b) axial view, c) ventral view. Scale bar: 200µm. 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-00067).

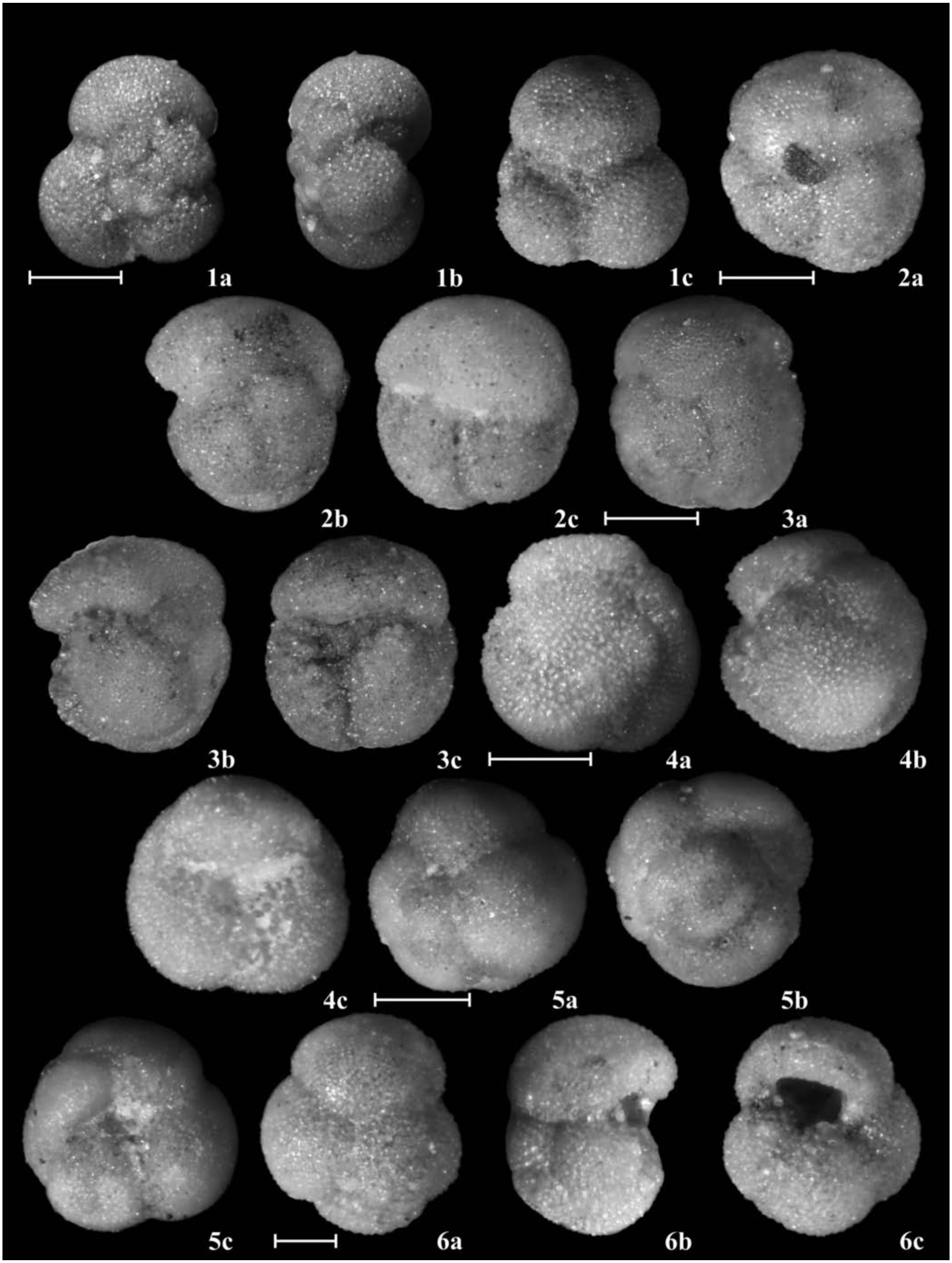
2 *Dentoglobigerina tapuriensis* (Blow and Banner 1962). a) dorsal view, b) axial view, c) ventral view. Scale bar: 200µm. Late Oligocene, *Globoturborotalita ciperoensis* zone. Carmen Formation (Upper segment). Arroyo Alférez, Carmen - Zambrano Section, SJFB - Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-564 Sample. (Repository: SC-ICP-PF- 00068).

3 *Dentoglobigerina tripartita* (Koch 1926). a) dorsal view, b) axial view, c) ventral view. Scale bar: 250 Fm. Late Oligocene, *Globoturborotalita ciperoensis* zone. Carmen Formation (Upper segment). Arroyo Alférez, Carmen - Zambrano Section, SJFB - Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-564 Sample. (Repository: SC-ICP-PF-00069).

4 *Globoquadrina venezuelana* (Hedberg 1937). a) dorsal view, b) axial view, c) ventral view. Scale bar: 200 Fm. Latest late Miocene to early Pliocene, *Globoquadrina venezuelana* zone. Buenavista-1 Well. Plato Basin, LMV Sedimentary Province. Magdalena, Colombia. 4500ft Sample. (Repository: SC-ICP-PF-00073).

5 *Globoquadrina venezuelana* (Hedberg 1937). a) dorsal view, b) axial view, c) ventral view. Scale bar: 150µm. Early Miocene, *Globoturborotalita ouachitaensis* zone - *Paragloborotalia kugleri* subzone. Carmen Formation (Upper segment). Arroyo Alférez, Carmen - Zambrano Section, SJFB - Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-700 Sample. (Repository: SC-ICP-PF- 00074).

6 *Turborotalia ampliapertura* (Bolli 1957). a) dorsal view, b) axial view, c) ventral view. Scale bar: 100 Fm. Late Eocene, *Subbotina yeguaensis* zone. Carmen Formation (Lower segment). Arroyo Alférez, Carmen - Zambrano Section, SJFB - Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-131 Sample. (Repository: SC-ICP-PF- 00092).


1a
1b
1c
2a
2b
2c
3a
3b
3c
4a
4b
4c
5a
5b
5c
6a
6b
6c

Porticulasphaera transitoria (Blow). – BOLLI 1957b: p. 115, pl. 27: fig. 3. – BLOW 1959: p. 202, pl. 14: figs. 87a-b.
?*Globigerinoides transitorius* Blow 1956. – BERMÚDEZ 1961 p. 1242, pl. XII: fig. 2.
Praeorbulina transitoria (Blow 1956). – POSTUMA 1971: p. 378, 379. – KENNETT and SRINIVASAN 1983: p. 84, pl. 19: figs. 6-8.

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

Sphaeroidinellopsis seminulina (Schwager 1866)
Globigerina seminulina SCHWAGER 1866: p. 256, pl. 7: fig. 112. – Postuma 1971: p. 274, 275.
Sphaeroidinellopsis seminulina (Schwager 1866). – BERMÚDEZ 1961: p. 1279, pl. IX, figs. 3a-c and 7a-c – (?) BLOW 1969: p. 139, pl. 30: fig. 7. – BOLLI and SAUNDERS 1985: p. 241, fig. 38: 6, 7a- b and 8-13.
Sphaeroidinellopsis seminulina seminulina (Schwager 1866). – GIBSON 1983: p. 375, pl. 2: figs. 10-12; pl. 5: fig. 7. – KENNETT and SRINIVASAN 1983: p. 206, pl. 57: figs. 6-8.

Sphaeroidinellopsis subdehiscens (Blow 1959)
Sphaeroidinella dehiscens PARKER and JONES subsp. *subdehiscens* BLOW 1959: p. 195, pl. 12: figs. 71a-c, 72.
Sphaeroidinella subdehiscens Blow 1959. – POSTUMA 1971: p. 388, 389.
Sphaeroidinellopsis subdehiscens subdehiscens (Blow 1959). – BLOW 1969: p. 140, pl. 30: figs. 1-3. – GIBSON 1983: p. 375, pl. 2: figs. 13-15.
Sphaeroidinellopsis subdehiscens (Blow 1969). – BERMÚDEZ 1961: p. 1275, pl. XIX, figs 32a-c.
Sphaeroidinellopsis seminulina seminulina (Schwager 1866). – KENNETT and SRINIVASAN 1983 [*in part*]: p. 206, pl. 57, figs. 6-8.
Sphaeroidinellopsis multiloba (LeRoy 1944). – BOLLI and SAUNDERS 1985 [*in part*]: p. 241, fig. 38: 14-17.

Genus *Dentoglobigerina* Blow 1979
Type Species: *Globigerina galavisi* Bermúdez 1961

Dentoglobigerina galavisi (Bermúdez 1961)
Globigerina galavisi BERMÚDEZ 1961: p. 1183, pl. IV, fig. 3. – BLOW 1969: p. 121, pl. 5: figs. 1-3 (re-illustrated holotype); pl. 16: figs. 4, 5.
Globigerina yeguaensis Weinzierl and Applin subsp. *yeguaensis* Weinzierl and Applin 1929 (*emend.*) – BLOW and BANNER 1962 [*in part*]: p. 99, pl. XIII, figs. K-M.
Globigerina yeguaensis Weinzierl and Applin 1929 [*in part*] – BOLLI and SAUNDERS 1985: p. 180, 181.
Dentoglobigerina galavisi (Bermúdez 1961). – LOEBLICH and TAPPAN 1988 [*images*]: pl. 527: figs. 8-11.
Dentoglobigerina galavisi (Bermúdez 1961). – PEARSON et al., 2006: p. 405, pl. 13.1: figs. 1-3 (illustrated holotype - SEM), 4-11, 13-15.

Dentoglobigerina globosa (Bolli 1957)
Globoquadrina altispira (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 altispira globosa (Bolli 1957). – KENNETT and u1983: p. 189, pl. 46: figs. 7-9.

Dentoglobigerina pseudovenezuelana (Blow and Banner 1962)
Plate 8, 1a-c

Globigerina venezuelana Hedberg 1937. – BOLLI 1957c [*in part*]: p. 164, pl. 35: figs. 16a-c and 17.
Globigerina yeguaensis Weinzierl and Applin subsp. *pseudovenezuelana* BLOW and BANNER 1962: p. 100, pl. XI: figs. J-L, N and O.
Dentoglobigerina pseudovenezuelana (Blow and Banner 1962) – BLOW 1969: p. 123, pl. 19: figs. 1, 2. – PEARSON et al. 2006: p. 407, pl. 13.2: figs. 1-3 (illustrated holotype - SEM).

PLATE 9

Globorotaliidae: *Fohsella*, *Globorotalia*, *Menardella*, *Neogloboquadrina.* Optical images.

1 Fohsella praefohsi (Blow and Banner 1966). a) dorsal view, b) axial view, c) ventral view. Scale bar: 150µm. Middle Miocene, *Fohsella fohsi* zone - *Fohsella peripheroronda* subzone. Buenavista-1 Well. Plato Basin, LMV Sedimentary Province. Magdalena, Colombia. 7220ft - 7230ft Sample. (Repository: SC-ICP-PF- 00070).

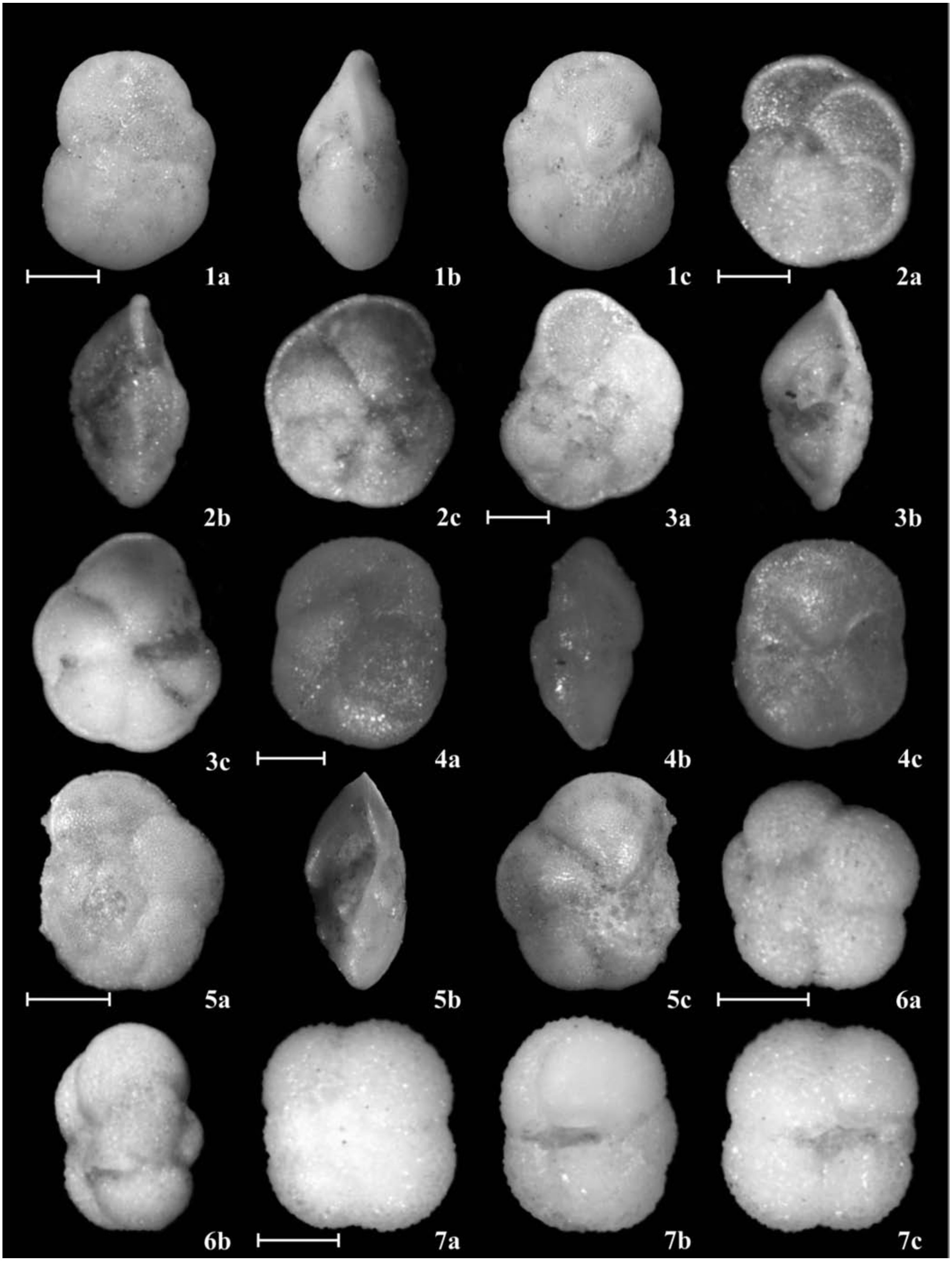
2,3 *Globorotalia merotumida* Blow and Banner 1965. a) dorsal view, b) axial view, c) ventral view. Scale bar: 100 Fm. Late Miocene, *Globorotalia merotumida* zone. Perdices Formation, Luruaco - Rotinet section. SFB, Sinú Sedimentary Province. Córdoba, Colombia. HD-1143 Sample. (Repository: SC-ICP (HD)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

4 *Hirsutella praescitula* (Blow 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. Buenavista-1 Well. Plato Basin, LMV 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, LMV 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, Sinú 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, Colombian Basin. Caribbean Sea, Colombia. 145.87m Sample. (Repository: SC-ICP (HD) - PF- 00031).


1a
1b
1c
2a
2b
2c
3a
3b
3c
4a
4b
4c
5a
5b
5c
6a
6b
7a
7b
7c

Dentoglobigerina tapuriensis (Blow and Banner 1962)
Plate 8, 2a-c.

Globigerina tripartita Koch subsp. *tapuriensis* BLOW and BANNER 1962: p. 97, pl. X: figs. H-K. – BLOW 1969: p. 124, pl. 16: figs. 7, 8.
Globigerina rohri Bolli 1957. – BERMÚDEZ 1961[*in part*]:p.1196, pl. IV: figs 8d and 8e, not 8a-c.
Dentoglobigerina tripartita (Koch 1926). – PEARSON et al. 2006 [*in part*]: p. 409, pl. 13.3: figs. 9-11, 14.

Dentoglobigerina tripartita (Koch 1926)
Plate 8, 3a-c.

Globigerina bulloides d'Orbigny var. *tripartita* KOCH 1926: p. 746, 747, text-fig. 21a, b. Re-illustrated holotype in BLOW and BANNER 1962: pl. X: figs. A-C.
Globigerina rohri BOLLI 1957b: p. 109, pl. 23: figs. 1a-c, 2a, b, 3a, b, 4a, b. – BOLLI 1957c: p.164, pl. 36: figs. 4a, b. – BERMÚDEZ 1961 [*in part*]: p. 1196, pl. IV: figs. 8b, 8c; not 8a, d and e.
Globoquadrina rohri (Bolli 1957) – BLOW 1959: p. 185, pl. 11: figs. 57a-c.
Globigerina tripartita Koch subsp. *tripartita* Koch 1962 (*emend.*) – BLOW and BANNER 1962: p. 96, pl. X: figs. D-F. – POSTUMA 1971: p. 276, 277.
Dentoglobigerina tripartita (Koch 1926) – PEARSON et al. 2006: p. 409, pl. 13.3: figs. 1-3 (re-illustrated holotype), 4-8, 12, 13, 15, 16.

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

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

Globigerina venezuelana HEDBERG 1937: p. 681, pl. 92: fig. 7a, b. – BOLLI 1957b: p. 110, pl. 23: figs. 6a-c, 7a, b, 8a, b. – POSTUMA 1971: p. 278, 279.
Globoquadrina venezuelana (Hedberg 1937). – BLOW 1959: p. 186, pl. 11: figs. 58a-c, 59. – BERMÚDEZ 1961: p. 1313, pl. XIII: figs. 9a, b. – KENNETT and SRINIVASAN 1983: p. 180, pl. 44: figs. 5-7. – PEARSON and CHAISSON 1997: p. 60, pl. 2: fig. 14.

Genus *Fohsella* Bandy 1972
(*nomen translatum*, ex subgenus)
Type Species: *Globorotalia* (*Globorotalia*) *praefohsi* Blow and Banner 1966
Globorotalia (*Fohsella*) *praefohsi* Blow and Banner 1966. – BANDY 1972

Fohsella fohsi (Cushman and Ellisor 1939)
Globorotalia fohsi CUSHMAN and ELLISOR 1939: p. 12, pl. 2: figs. 6a-c. – BERMÚDEZ 1961: p. 1288, pl. XIV: figs. 10a-c.
Globorotalia fohsi Cushman and Ellisor subsp. *fohsi* BOLLI 1950: p. 88, pl. 15, figs. 4a-c. – BOLLI 1957b [*in part*]: p. 119, pl. 28: figs. 10a-c. – BLOW 1959: p. 212, pl. 17: figs. 112a-c. – BOLLI and SAUNDERS 1985 [*in part*]: p. 213, fig. 26: 4a-c.
?*Globorotalia fohsi* Cushman and Ellisor 1939. – POSTUMA 1971: p. 322, 323.
Globorotalia (*Fohsella*) *fohsi* Cushman and Bermúdez 1939. – KENNETT and SRINIVASAN 1983: p. 100, pl. 23: figs. 1-3.

PLATE 10

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

1,2 *Paragloborotalia griffinoides* Olsson and Pearson, 2006. a) dorsal view, b) axial view, c) ventral view. Scale bar: 100 Fm. Earliest middle Eocene, *Acarinina pentacamerata* zone. Chengue Formation. Arroyo Salvador, SJFB - Sinú Sedimentary Province. San Juan Nepomuceno, Bolívar, Colombia. AS-146slst Sample. (Repository: SC-ICP-PF- 00082).

3 *Paragloborotalia kugleri* (Bolli 1957). a) dorsal view, b) axial view, c) ventral view. Scale bar: 100 Fm. Early Miocene, *Globigerinoides primordius* zone - *Paragloborotalia kugleri* subzone. Carmen Formation (upper segment), Arroyo Alférez, Carmen-Zambrano Section, SJFB - Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-700 Sample. (Repository: SC-ICP-PF- 00083).

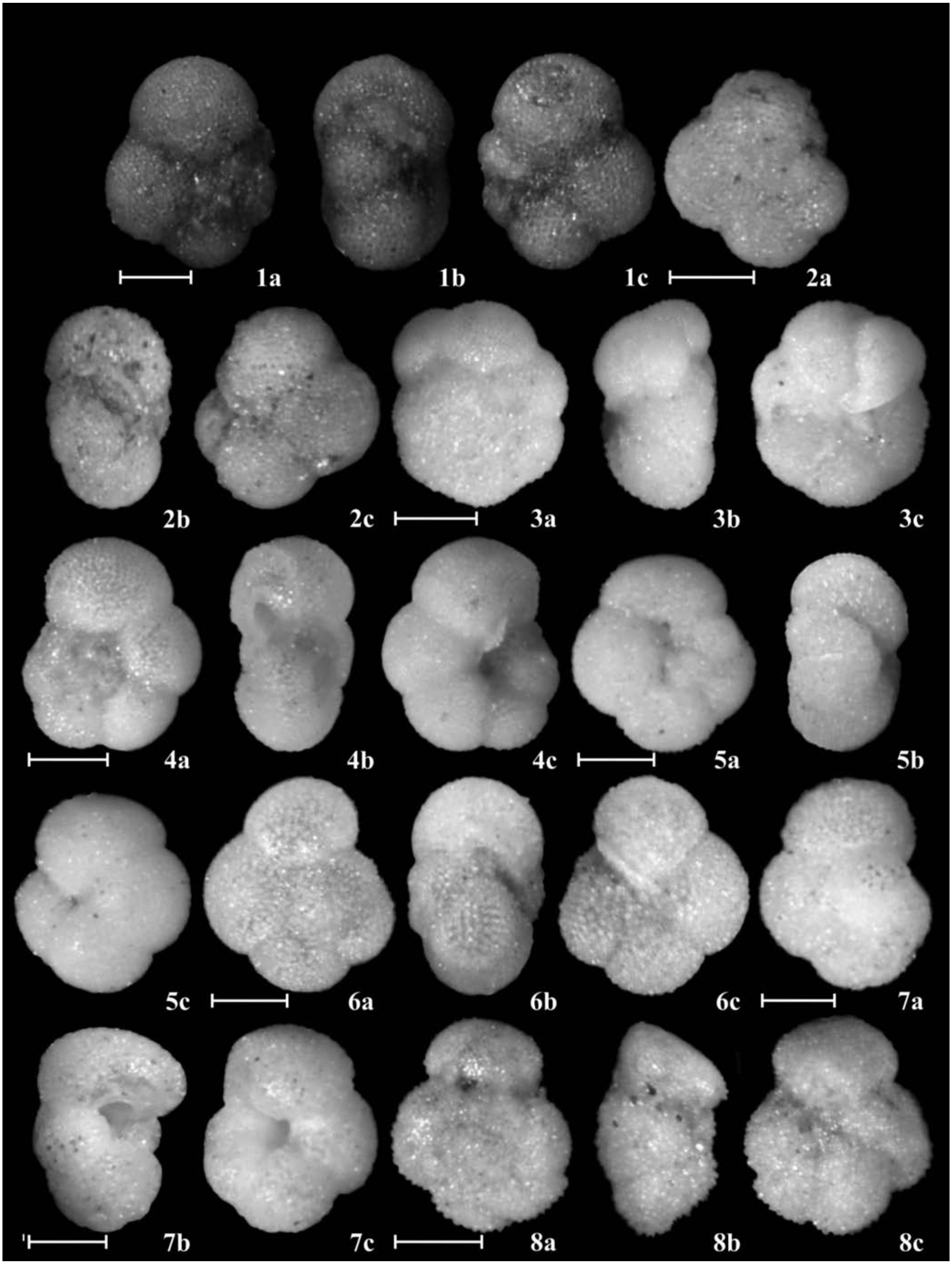
4 *Paragloborotalia mayeri* (Cushman and Ellisor 1939). a) dorsal view, b) axial view, c) ventral view. Scale bar: 100 Fm. Latest Oligocene to earliest early Miocene, *Globoturborotalita ciperoensis* zone. Carmen Formation (upper segment), Arroyo Alférez, Carmen-Zambrano Section, SJFB - Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-586 Sample. (Repository: SC-ICP-PF- 00084).

5 *Paragloborotalia nana* (Bolli 1957), transitional form to *P. opima* (?). a) dorsal view, b) axial view, c) ventral view. Scale bar: 100 Fm. Early Oligocene, *Turborotalia ampliapertura* zone. San Jacinto Formation, Arroyo Alférez, Carmen-Zambrano Section, SJFB - Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-186 Sample. (Repository: SC-ICP-PF- 00085).

6 *Paragloborotalia opima* transitional form to *P. nana* (?). a) dorsal view, b) axial view, c) ventral view. Scale bar: 100 Fm. Early Oligocene, *Turborotalia ampliapertura* zone. San Jacinto Formation, Arroyo Alférez, Carmen-Zambrano Section, SJFB - Sinú Sedimentary Province. Bolívar, Colombia. G05-CB-311 Sample. (Repository: SC-ICP-PF- 00086).

7 *Acarinina esnaensis* (LeRoy, 1953). a) dorsal view, b) axial view, c) ventral view. Scale bar: 100 Fm. Middle Eocene, *Acarinina pentacamerata* zone. Chengue Formation (lower segment), Arroyo Alférez, Carmen-Zambrano Section, SJFB - Sinú Sedimentary Province. Bolívar, Colombia. HD- 594 Sample. (Repository: SC-ICP (HD) - PF- 00023).

8 *Morozovella spinulosa* (Cushman, 1927). a) dorsal view, b) axial view, c) ventral view. Scale bar: 100 Fm. Middle Eocene, *Paragloborotalia griffinoides* zone - *Clavigerinella akersi* subzone. Chengue Formation, Arroyo Las Flechas, SJFB - Sinú Sedimentary Province. Bolívar, Colombia. ALF-054slst Sample. (Repository: SC-ICP-PF- 00091).


1a
1b
1c
2a
2b
2c
3a
3b
3c
4a
4b
4c
5a
5b
5c
6a
6b
6c
7a
7b
7c
8a
8b
8c

Fohsella fohsi (Cushman and Ellisor 1939). – CHAISSON and D'HONDT 2000: p. 30, pl. 2: figs. 1-3.

Fohsella lobata (Bermúdez 1949)
Globorotalia lobata BERMÚDEZ 1949: p. 286, pl. 22: figs. 15-17. – Postuma 1971: p. 328, 329.
Globorotalia fohsi lobata Bermúdez 1949. – BOLLI 1950: p. 88, pl. 15: figs. 7, 8a-c. – BOLLI 1957b:p. 119, pl. 28: figs. 13a-c, 14a-b. – BOLLI and SAUNDERS, 1985: p. 215, fig. 26: 9a, b, and 10a, b.
Globorotalia (*Fohsella*) *lobata* Bermúdez 1939. – KENNETT and SRINIVASAN 1983: p. 100, pl. 23: figs. 4-6.

Fohsella peripheroronda (Blow and Banner 1966)
Plate 2, 1a-d

Globorotalia fohsi barisanensis LeRoy 1939. – BOLLI 1950: p. 88, pl. 15, figs. 5, 6a-c. – BOLLI 1957b: p. 119, p. 28: figs. 8a-c. – BERMÚDEZ 1961: p. 1289, pl. XV: figs. 8a, b.
?*Globorotalia fohsi barisanensis* LeRoy 1939. – BLOW 1959: p. 212, pl. 17: figs. 110, 111a-c (*Fohsella peripheroronda* – *Fohsella peripheroacuta* transition?).
Globorotalia (*Fohsella*) *peripheroronda* KENNETT and SRINIVASAN 1983: p. 96, pl. 22: figs. 1-3.
Globorotalia (*Turborotalia*) *peripheroronda* BLOW and BANNER 1966: p. 294, pl. 1: fig. 1a-c; pl. 2: figs. 1-3. – POSTUMA 1971: p. 348, 349. – GIBSON 1983: p. 372. pl. 5: figs. 5, 6.
?*Globorotalia* (*Turborotalia*) *peripheroronda* BLOW and BANNER 1966 á form – BLOW 1969. p. 156, pl. 36: fig. 7.
Globorotalia fohsi peripheroronda Blow and Banner 1966. – BOLLI and SAUNDERS 1985: p. 213, fig. 29: 14a-c.

Fohsella praefohsi (Blow and Banner 1966)
Plate 9, 1a-c.

Globorotalia fohsi Cushman and Ellisor subsp. *fohsi* Bolli 1950. – BOLLI 1957b [*in part*]: p. 119, pl. 28: figs. 9a-c.
Globorotalia fohsi Cushman and Ellisor 1939 – *Globorotalia fohsi lobata* Bermúdez 1949 transitional specimen. – BOLLI 1957b: p. 119, pl. 28: figs. 12a, b.
Globorotalia fohsi lobata Bermúdez 1949. – BLOW 1959: p. 213, pl. 16: figs. 113a-c.
Globorotalia (*Globorotalia*) *praefohsi* BLOW and BANNER 1966: p. 295, 296, pl. 1, figs. 3a-c, 4a-c.
Globorotalia (*Fohsella*) *praefohsi* Blow and Banner 1966. – KENNETT and SRINIVASAN 1983: p. 98, pl. 22: figs. 7-9.
Globorotalia fohsi praefohsi Blow and Banner 1966. – BOLLI and SAUNDERS 1985: p. 213, fig. 26: 11a, b.
Fohsella praefohsi (Blow and Banner 1966) – CHAISSON and D'HONDT 2000: p. 31, pl. 2: fig. 4, 5.

Fohsella robusta (Bolli 1950)
Globorotalia fohsi Cushman and Bermúdez subsp. *robusta* BOLLI 1950: v. 1, pts. 3 - 4, p. 84, 89, pl. 15: fig. 3. – BOLLI 1957b:p. 119, pl. 28: figs. 16a-c.
Globorotalia (*Fohsella*) *robusta* Bolli 1950. – KENNETT and SRINIVASAN 1983: p. 102, pl. 23: figs. 7-9.
Globorotalia fohsi robusta Bolli 1950 . – BOLLI and SAUNDERS 1985: p. 215, fig. 29: 7a, b.

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

Globorotalia merotumida Blow and Banner 1965
Plate 9, 2a-c, 3a-c.

Globorotalia (*Globorotalia*) *merotumida* BLOW and BANNER 1965: p. 1352, 1353, text-fig. 1a-c. – BLOW 1969: p. 166, pl. 9: figs. 4-6 (re-illustrated holotype). – GIBSON 1983: p. 372, pl. 6: figs. 1-8, 13 (?) – KENNETT and SRINIVASAN 1983: p. 154, pl. 37: figs. 4-6.

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. praescitul*a - *M. archaeomenardii*]

Globorotalia scitula (Brady) subsp. *praescitula* BLOW 1959: p. 221, pl. 19: figs. 128a-c. – GIBSON 1983: p. 373, pl. 5: figs. 1, 2.
Globorotalia (*Turborotalia*) *praescitula* Blow 1959. – BLOW 1969: p. 158, pl. 39: fig. 9.
Globorotalia (*Globoconella*) *praesictula* Blow 1959 – KENNETT and SRINIVASAN 1983: p. 108, pl. 25: figs. 4-6.

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

Menardella archeomenardii (Bolli 1957)
Plate 9, 4a-c. [Transitional form *H. praescitul*a - *M. archaeomenardii*]

Globorotalia archeomenardii BOLLI 1957b: p. 119, pl. 28: figs. 11a-c. – POSTUMA 1971: p. 316, 317. – PEARSON and CHAISSON 1997: p. 61, pl. 2: fig. 18.
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 praemenardii CUSHMAN and STAINFORTH 1945: p. 70, pl. 13, fig. 14a-c. – BOLLI 1957b: p. 120, pl. 29: figs. 4a-c. – POSTUMA 1951: p. 352, 353. – PEARSON and CHAISSON 1997: p. 61, pl. 2: fig. 19.
[Not] *Globorotalia praemenardii* Cushman and Stainforth 1945 – BERMÚDEZ 1961: p. 1298, pl. XV, figs. 7a-b.
Globorotalia (*Globorotalia*) *praemenardii praemenardii* Cushman and Stainforthi 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, Frerichs and Vincent 1967
Type Species: *Globigerina dutertrei* d'Orbigny 1839

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

Globorotalia acostaensis Blow 1959: p. 208, pl. 17: figs. 106a-c, 107.
Globorotalia (*Turborotalia*) *acostaensis acostaensis* Blow 1959 – Blow 1969: p. 146, pl. 9: figs. 13-15 (re-illustrated holotype).
Globorotalia acostaensis acostaensis Blow 1959 – Bolli and Saunders 1985: p. 210, fig. 27: 11, fig. 28: 16-17, 19-21.
Neogloboquadrina acostaensis (Blow 1959) – Kennett and Srinivasan 1983: p. 196, pl. 48: figs. 1-3. – Chaisson and D'Hondt, 2000: p. 35, pl. 1: figs. 11, 12.

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

Aristerospira pachyderma Ehrenberg 1861: p. 386, pl. 1: fig. 4.
Globigerina pachyderma (Ehrenberg 1872) – PARKER 1962: p. 224, pl. 1: figs. 26-35, pl. 2: figs. 1-6.

Globorotalia (*Turborotalia*) *pachyderma* (Ehremberg 1872). – BANDY 1972: p. 294-296, pl. 1: figs. 1a-b, 2a-d and 3a-b; pl. 2: figs. 4a; pl. 3: figs. 1 a-b, 2a-b, 3a-b; pl.4: figs. 2, 3a-b, 4a-b.
Neogloboquadrina pachyderma (Ehremberg 1872) – KENNETT and SRINIVASAN 1983: p. 192, pl. 47: figs. 6-8. – CHAISSON and D'HONDT 2000: p. 36, pl. 1: fig. 13.

Genus *Paragloborotalia* Cifelli 1982
Type Species: *Globorotalia opima opima* Bolli 1957

Paragloborotalia griffinoides Olsson and Pearson 2006
Plate 2, 2a-d; Plate 10: 1a-c, 2a-c

Globorotalia bolivariana (Petters 1954) – BOLLI 1957c: p. 169, pl. 37: figs. 14a-c, 15a-c, 16. – POSTUMA 1971: p. 175, 176.
'Hastigerina' cf. *Hastigerina bolivariana* (Bolli 1957) – TOUMARKINE and LUTERBACHER 1985: p. 127, fig. 27: 5a-c, 6a-c, and 8, 9.
Paragloborotalia griffinoides OLSSON and PEARSON 2006: p. 85, fig. 5.7: 1-19 (In: Pearson et al. 2006).

Paragloborotalia kugleri (Bolli 1957)
Plate 2, 3a-d; Plate 10: 3a-c.

Globorotalia kugleri BOLLI 1957b: p. 118, pl. 28: figs. 5a-c. – POSTUMA 1971: p. 324, 325. – BOLLI and SAUNDERS 1985 [*in part*]: p. 203, fig. 26: 2, 4, 5; not 3a-c.
Globorotalia (*Turborotalia*) *kugleri* Bolli 1957 – BLOW 1969: p. 152, pl. 10: 1-3 (re-illustrated holotype); pl. 38: figs 1-4.
Globorotalia (*Fohsella*) *kugleri* Bolli 1957 – KENNETT and SRINIVASAN 1983 [*in part*]: p. 94, pl. 21: figs. 3-5.
Paragloborotalia kugleri (Bolli 1957) – PEARSON and CHAISSON 1997: p. 63, pl. 2: fig. 17.

Paragloborotalia mayeri (Cushman and Ellisor 1939)
Plate 2, 4a-d; Plate 10, 4a-c.

Globorotalia mayeri CUSHMAN and ELLISOR 1939: p. 11, pl. 2: figs. 4a-c. – BOLLI 1957b: p. 118, pl. 28: figs. 4a-c. – POSTUMA 1971: p. 332, 333. – BOLLI and SAUNDERS 1985: p. 203, fig. 26: 32 - 36.
Turborotalia mayeri (Cushman and Ellisor 1939) – BERMÚDEZ 1961: p. 1325, pl. XVIII: fig 7a-c.
Globorotalia (*Jenkinsella*) *mayeri* Cushman and Ellisor 1939. – KENNETT and SRINIVASAN 1983. p. 174, pl. 43: figs. 4-6.
Globorotalia (*Turborotalia*) *mayeri* Cushman and Ellisor 1939. – BLOW 1969: p. 153, pl. 3, figs. 7-9 (re-illustrated holotype).
?*Paragloborotalia mayeri* (Cushman and Ellisor 1939). – PEARSON and CHAISSON 1997: p. 63, pl. 2: fig. 20.
Paragloborotalia mayeri (Cushman and Ellisor 1939). – CHAISSON and D'HONDT, 2000: p. 36, pl. 1: fig. 14, 15.

Paragloborotalia nana (Bolli 1957)
Plate 10, 5a-c.

Globorotalia opima Bolli subsp. *nana* BOLLI 1957b: p. 118, pl. 28: figs. 3a-c. – BOLLI and SAUNDERS 1985: p. 202, fig. 26: 15 and 17-20.
Globorotalia (*Turborotalia*) *opima nana* Bolli 1957. – BLOW and BANNER 1962: p. 119, pl. XIII: figs. Q-S. – BLOW 1969: p. 154, pl. 39: fig. 1, 2. – POSTUMA 1971: p. 340, 341.
"Globorotalia" nana Bolli 1957. – KENNETT and SRINIVASAN 1983: p. 106, pl. 24: 3-5.
Paragloborotalia nana (Bolli 1957). – PEARSON et al. 2006: p. 86, pl. 5.8: 1-3 (illustrated holotype - SEM), 4-10.

Paragloborotalia opima (Bolli 1957)
Plate 2, 5a-c

Globorotalia opima Bolli subsp. *opima* BOLLI 1957b: p. 117, pl. 28: figs. 1a-c, 2. – CIFELLI 1982: (figures in: Loeblich and Tappan 1988, pl. 519: figs. 5, 6). – POSTUMA 1971: p. 344, 345. – BOLLI and SAUNDERS 1985: p. 202, fig. 26: 24-29.
Globorotalia (*Turborotalia*) *opima opima* Bolli 1957. – BLOW 1969: p. 155, pl. 39: fig. 3.
Paragloborotalia opima (Bolli 1957) – CIFELLI 1982: p. 114, pl. 2: figs. 1 and 2. – PEARSON et al. 2006: p. 86, pl. 5.8: 11, 13-15 (illustrated holotype - SEM), 16. (into *P. nana* description).

Genus *Turborotalia* Cushman and Bermúdez 1949
Type Species: *Globorotalia centralis* Cushman and Bermúdez 1937

Turborotalia ampliapertura (Bolli 1957)
Plate 3, 1a-d; Plate 8, 6a-c

Globigerina ampliapertura BOLLI 1957b [*in part*]: p. 180, pt. 22: figs. 5a, b, and 6a-c. – BOLLI 1957c: p. 164, pl. 36, figs. 8a-c. – BLOW 1969: p. 117, pl. 12: figs. 6, 9, 10. – POSTUMA 1971: p. 142, 143. – BOLLI and SAUNDERS 1985: p. 182, fig. 14: 1a-c, 2a, b, and 3a, b.
[Not] *Globigerina ampliapertura* Bolli 1957. – BERMÚDEZ 1961: p. 1155, pl. III: figs. 8a-c.
Globigerina ampliapertura ampliapertura Bolli 1957 – BLOW and BANNER 1962: p. 83, pl. XI: figs. A-D.
Turborotalia ampliapertura (Bolli 1957) – PEARSON et al. 2006 [*in part*]: p. 440, pl. 15.2: figs. 1-3(illustrated holotype - SEM), 4-8, 16-19.

Turborotalia euapertura (Jenkins 1960)
Globigerina ampliapertura BOLLI 1957b [*in part*]: p. 180, pt. 22, figs. 4a, b.
Globigerina euapertura JENKINS 1960: p. 351, pl. 1: figs. 8a-c. – GIBSON 1983: p. 369, pl. 4: fig. 15. – JENKINS 1985: p. 274, fig. 6: 18a-c.
Globigerina ampliapertura Bolli subsp. *euapertura* (Jenkins 1960) – BLOW and BANNER 1962: p. 84, pl. XI: figs. E-G.
Globigerina prasaepis Blow 1969: p. 123, 184, pl. 10: figs. 13; pl. 18: 3-7.

Genus *Clavigerinella* Bolli, Loeblich and Tappan 1957
Type Species: *Clavigerinella akersi* Bolli, Loeblich and Tappan 1957

Clavigerinella akersi Bolli, Loeblich and Tappan 1957
Clavigerinella akersi BOLLI, LOEBLICH and TAPPAN 1957: p. 30, pl.3: figs. 5a, b. – BOLLI 1957c: p. 161, pl. 35: fig. 4. – BERMÚDEZ 1961: p. 1219, pl. XIX: fig. 8a, b. – LOEBLICH and TAPPAN 1964: p. C665, pl. 531: 10a, b. – POSTUMA 1971: p. 132, 133. – TOUMARKINE and LUTERBACHER 1985: p. 119, figs. 22: 11-14. – PEARSON et al. 2006: p. 219, pl. 8.1: figs. 11-13 (illustrated holotype - SEM), 14-19.

Clavigerinella colombiana (Petters 1954)
Plate 3, 3a-d; Plate 7, 5a-c

Hastigerinella colombiana PETTERS 1954: p. 40, pl. 8: figs. 10a, b.
Clavigerinella sp. aff. *Clavigerinella akersi* Bolli, Loeblich and Tappan 1957 – BOLLI 1957c: p. 161, pl. 35: fig. 3a, b. (? transitional form between *Clavigerinela eocanica* and *Clavigerinella colombiana*).
Clavigerinella colombiana (Petters) – TOUMARKINE and LUTERBACHER 1985: p. 121, fig. 22: 16-18. – PEARSON et al. 2006: p. 220, pl. 8.2: figs. 1-2 (illustrated holotype - SEM), 3-5.

Clavigerinella jarvisi (Cushman 1930)
Plate 3, 4

Hastigerinella jarvisi Cushman 1930: p. 18, pl. 3: fig. 8.
Clavigerinella jarvisi (Cushman 1930) – BOLLI 1957c: p. 162, pl. 35: figs. 5-6. – PEARSON et al. 2006: p. 220, pl. 8.2: figs. 6-9, 10 (illustrated holotype - SEM).
[Not] *Clavigerinella jarvisi* (Cushman 1930) – POSTUMA 1971: p. 132, 133.
Clavigerinella eocanica jarvisi (Cushman 1930) – TOUMARKINE and LUTERBACHER 1985: p. 121, fig. 22: 8 and 9.

Genus *Acarinina* Subbotina 1953
Type Species: *Acarinina acarinata* Subbotina 1953

Acarinina aspensis (Colom 1954)
Globigerina aspensis Colom 1954: p. 151, pl. 3, fig. 1-35. – BERMÚDEZ 1961: p. 1157, pl. I: figs. 2a-c.
Globorotalia aspensis (Colom 1954). – BOLLI 1957c: p. 166, pl. 37: figs. 18a-c. – POSTUMA 1971: p. 174, 175.
Acarinina aspensis (Colom 1954) – PERSON et al. 2006: p. 273, pl. 9.4: figs. 1-16.

Acarinina bullbrooki (Bolli 1957)
Globorotalia bullbrooki Bolli 1957c: p. 167, pl. 38, figs. 4a-c and 5a-c. – POSTUMA 1971: p. 180, 181.
Acarinina bullbrooki (Bolli 1957) – TOUMARKINE and LUTERBACHER 1985: p. 130, fig. 29: 5-10. – PEARSON et al. 2006: p. 274, pl. 9.6: figs. 1-3 (illustrated holotype - SEM), 4-15.

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 1960: p. 92, pl. V: figs. 3a-c, pl. Vl: figs. 1a-c, pl. X: figs. 3a-c.
Globigerina colomi BERMÚDEZ 1961: p. 1167, pl. II: figs. 6a-c.
Acarinina esnaensis (LeRoy 1953) – PEARSON et al. 2006: p. 285, pl. 9.11: figs. 1-3 (illustrated holotype - SEM), 4-9.

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

Globorotalia pentacamerata SUBBOTINA 1947 [*in part*]: p. 128, pl. 7: figs. 12-17.
Acarinina pentacamerata (Subbotina 1947) – TOUMARKINE and LUTERBACHER 1985: p. 116, fig. 17: 5a-c. – PEARSON et al. 2006: p. 295, pl. 9.14: figs. 1-4.

Genus *Igorina* Davidzon 1976
Type Species: *Acarinina tadjikistanensis* Bykova 1953

Igorina broedermanni (Cushman and Bermúdez 1949)
Plate 3, 6a-c

Globorotalia (*Truncorotalia*) *broedermanni* CUSHMAN and BERMÚDEZ 1949: p. 40, pl. 7: figs. 22-24. – Bolli 1957a: p. 80, pl. 19: fig. 13-15. – BOLLI 1957c: p.167, pl. 37: figs. 13a-c (?).
Globorotalia broedermanni Cushman and Bermúdez 1949. – POSTUMA 1971: p. 178, 179.
Pseudogloborotalia broedermanni (Cushman and Bermúdez 1949) – BERMÚDEZ 1961: p. 1340, pl. XVI: figs. 6a-c.
Acarinina broedermanni (Cushman and Bermúdez 1976) – TOUMARKINE and Luterbacher 1985: p. 130, fig. 29: 15-17, 19, 20 a-c (?).
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* McGowran 1968
Type Species: *Pulvinulina velascoensis* Cushman 1925

Morozovella spinulosa (Cushman 1927)
Plate 10, 8a-c

Globorotalia spinulosa CUSHMAN 1927: p. 114, pl. 23, fig. 4 a-c. – BOLLI 1957c: p. 168, pl. 38: figs. 6a-c, 7a-c. – POSTUMA 1971: p. 212, 213.
"Globorotalia (*Globorotalia*) *spinulosa* Cushman 1927*"* – BLOW 1969: p. 172, pl. 50: figs. 2-5.
Pseudogloborotalia spinulosa (Cushman 1927). – BERMÚDEZ 1961: p. 1347, pl. XVII: figs. 2a, b.
Morozovella spinulosa (Cushman 1927). – TOUMARKINE and LUTERBACHER 1985: p. 130, fig. 30: 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).
[Not] *Morozovelloides coronata* (Blow 1979) – PEARSON et al. 2006: p. 335, pl. 10.2: figs. 1-16.

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

Truncorotaloides rohri Brönnimann and Bermúdez 1953
Truncorotaloides rohri BRÖNNIMANN and BERMÚDEZ 1953: p. 818. pl. 87: figs. 7-9. – BOLLI, LOEBLICH and TAPPAN 1957: p. 42, pl. 10: figs. 5a-c (re-illustrated holotype). – BERMÚDEZ 1961: p. 1352, pl. XVII, figs. 3a, b; pl. 20: figs. 10a-c. – BLOW 1969: p. 174, pl. 50: figs. 6-8. – POSTUMA 1971: p. 232, 233. – TOUMARKINE and LUTERBACHER 1985: p. 134, fig. 32: 9a-c; fig. 33: 12-18.
?*Truncorotaloides rohri* Brönnimann and Bermúdez 1953 – BOLLI 1957c: p. 170, pl. 39: figs. 8-12.
Acarinina rohri (Brönnimann and Bermúdez 1953) – PEARSON et al. 2006: p. 311, pl. 9.20: figs. 1-3 (illustrated holotype - SEM), 4-15.

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. Reyment, 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

BERGGREN, W. A., 1960. Some planktonic foraminifera from Lower Eocene (Ypresian) of Denmark and northwestern Germany. *Stockholm University Contributions to Geology*, 3: 42-108.

BERGGREN, W. A., KENT, D. V., SWISHER C. C. III. and AUBRY, M-P., 1995. A revised Cenozoic geochronology and chronostratigraphy. *Society for Sedimentary Geology (SEPM) Special Publication*, 54:129-212.

BERGGREN, W. A. and PEARSON, P. N., 2005. A revised tropical and subtropical Paleogene planktonic foraminiferal zonation. *Journal of Foraminiferal Research,* 35(4):279-298.

BERMÚDEZ, P. J., 1961. Contribución al estudio de las Globigerinidea de la región Caribe-Antillana. *Congreso Geológico Venezolano, Tomo 3, Mem. III,* 1116-1393. Caracas: Ministerio de Minas e Hidrocarburos, Publicación Especial No. 3.

BLOW, W. H., 1959. Age, Correlation, and Biostratigraphy of the Upper Tocuyo (San Lorenzo) and Pozon Formation, Eastern Falcon, Venezuela). *Bulletin of American Paleontology*, 39(178): 67-251.

———, 1969. Late Middle Eocene to recent planktonic foraminiferal biostratigraphy. In: Brönniman, P. and Renz, R. R., Eds., *Proceedings of the First International Conference on Planktonic Microfossils*, *Geneva, 1967*, 199-422. .

———, 1979. *The Cainozoic Globigerinida, a study of the morphology, taxonomy, evolutionary relationships and the stratigraphical distribution of some globigerinida.* Leiden, E. J. Brill, 1413 pp.

BLOW, W. H., and BANNER, F. T., 1962. The Mid-Tertiary (Upper Eocene to Aquitanian) Globigerinaceae. In: Eames, F. E., Banner, F. T., Blow, W. H., Clarke, W. J. and Cox, L. R., Eds. *Fundamentals of mid-Tertiary stratigraphical correlation,* 61-151.. Cambridge. Cambridge University Press.

BOLLI, H. M., 1957a. The genera *Globigerina* and *Globorotalia* in the Paleocene-Lower Eocene Lizard Springs Formation of Trinidad, B.W.I. In: Loeblich, A. R., Tappan, H., Beckmann, J. P., Bolli, H. M., Gallitelli, E. M. and Troelsen, J. C., Eds. *Studies in foraminifera,* 61-81. Washington. Smithsonian Institution. U.S. Natural Museum Bulletin 215..

———, 1957b. Planktonic foraminifera from the Oligocene-Miocene Cipero and Lengua formations of Trinidad, B.W.I. In: Loeblich, A. R., Tappan, H., Beckmann, J. P., Bolli, H. M., Gallitelli, E. M. and Troelsen, J. C., Eds. *Studies in foraminifera,* 97-123*.* Washington. Smithsonian Institution. .S. Natural Museum Bulletin 215.

———, 1957c. Planktonic foraminifera from the Eocene Navet and San Fernando formations of Trinidad, B.W.I. In: Loeblich, A. R., Tappan, H., Beckmann, J. P., Bolli, H. M., Gallitelli, E. M. and Troelsen, J. C., Eds. *Studies in foraminifera,* 35-39*.* Washington. Smithsonian Institution. U.S. Natural Museum Bulletin 215.

———, 1959a. Planktonic foraminifera as index fossils in Trinidad, West Indies and their value for worldwide stratigraphic correlation. *Eclogae Geologica Helvetica*, 52(2):541-552.

———, 1959b. Planktonic foraminifera from the Cretaceous of Trinidad. *Bulletin of American Paleontology*, 39:258-177.

BOLLI, H. M., LOEBLICH, A. R. and TAPPAN, H., 1957. Planktonic Foraminiferal Families Hantkeninidae, Orbulinidae, Globorotaliidae and Globotruncanidae. In: Loeblich, A. R., Tappan, H., Beckmann, J. P., Bolli, H. M., Gallitelli, E. M. and Troelsen, J. C., Eds. *Studies in foraminifera,* 3-50. Washington. Smithsonian Institution. U.S. Natural Museum Bulletin 215..

BOLLI, H.M. and SAUNDERS, J.B., 1985. Oligocene to Holocene low latitude planktic foraminifera. In: Bolli, H. M., Saunders, J. B. and Perch-Nielsen, K., Eds., *Plankton stratigraphy, Volume 1,* 155-262. Cambridge: Cambridge University Press.

BOLLI, H.M., SAUNDERS, J.B. and PERCH-NIELSEN, K., 1985., Eds. *Plankton stratigraphy. Volume 1*. Cambridge: Cambridge University Press, 595 pp..

BÜRGL, H., 1962. "Notas explicativas a la bioestratigrafía del Terciario marino de Colombia." Bogota: Internal Report Ecopetrol, 23pp.

———, 1965. The Oligo-Miocene boundary in the marine Tertiary of Colombia. In: Saunders, J. B., Ed., *Transactions of the Fourth Caribbean Geological Conference*, 158. Trinidad

BURKE, K., 1988. Tectonic evolution of the Caribbean. *Annual Review of Earth and Planetary Sciences*, 16:201-230.

BOURDINE, B. W., 1974. "Neogene biostratigraphy and paleoenvironments, Lower Magdalena Basin, Colombia." PhD dissertation, Louisiana State University, 265pp.

CARDONA, A., 2003. "Correlações entre fragmentos do embasamento Pre-Mesozóico da terminação septentrional dos Andes colombianos, con base em dados isotópicos e geocronológicos." Disertatação de Mestrado, Instituto de Geociências, Universidao de São Paulo, Brasil. 143pp.

CASE, J. E., SHAGAM, R. and GIEGENGACK, R. F., 1990. Geology of the Northern Andes: an overview. In: Dengo, G. and Case, J. E., Eds., *The geology of North America, part H. The Caribbean region*, 177-120. Boulder: Geological Society of America.

CEDIEL, F., SHAW, R. P. and CÁCERES, C., 2003. Tectonic assembly of the northern Andean Block. In: Bartolini, C., Buffler, R. T. and Blickwede, J., Eds., *The circum-Gulf of Mexico and the Caribbean: Hydrocarbon habitats, basin formation, and plate tectonics,* 815-848. Tulsa: American Association of Petroleum Geologists, Memoir 79.

CHAISSON, W. P. and D'HONDT, S. L., 2000. Neogene planktonic foraminifer biostratigraphy at site 999, Western Caribbean Sea. In: Leckie, R. M., Sigurdsson, H., Acton, G. D., Draper, G., Eds, *Proceedings of the Ocean Drilling Program, scientific results*, *165,* 19-56. College Station, Texas: IODP.

CORDANI, H. G., CARDONA, A., JIMÉNEZ, D. M., LIU, D. and NUTMAN, A. P., 2005. Geochronology of Proterozoic basement inliers in The Colombian Andes: tectonic history of remnants of a fragmented Grenville Belt. In: Vaughan, A. P. M., Leat, P. T. and Pankhurst R. J., Eds., *Terrane processes at the margins of Gondwana,* 329-349. London: Geological Society. Special Publications, 246:329-349.

COATES, A. G., AUBRY, M-P., BERGGREN, W. A., COLLINS, L. S. and KUNK, M., 2003. Early Neogene history of the Central America arc from Bocas del Toro, western Panama. *Geological Society of America Bulletin*, 115(3):271-287.

COATES, A. G., COLLINS, L. S., AUBRY, M-P. and BERGGREN, W. A., 2004. The geology of the Darien, Panama, and the late Miocene-Pliocene collision of the Panama arc with northwestern South America. *Geological Society of America Bulletin*, 116(11-12):1327-1344.

COOPER, R. A., CRAMPTON, J. S., RAINE, J. I., GRADSTEIN, F. M., MORGANS, H. E., SADLER P. M., STRONG C. P., WAGHORN, D. and WILSON G. J., 2001. Quantitative biostratigraphy of the Taranaki Basin, New Zealand: A deterministic and probabilistic approach. *Bulletin of the American Association of Petroleum Geologists,* 85(8):1469-1498.

CORREDOR, F., SHAW, J. H. and VILLAMIL, T., 2003. Complex imbricate systems in the southern Caribbean Basin, offshore northern Colombia: Advanced structural and stratigraphic analysis, and implications for regional oil exploration. In: *Memoirs VIII Simposio Bolivariano "Exploración Petrolera en Cuencas Subandinas",* 45-56, Cartagena, Colombia.

CUARTAS, C. H., 2006. "Modelo bioestratigráfico para el Cenozoico de un sector del Caribe Colombiano." M.Sc. thesis, Departamento de Geología, Universidad EAFIT, Medellín, 104 pp.

CUSHMAN, J. A. and RENZ, H. H., 1941. New Oligo-Miocene Foraminifera from Venezuela. *Cushman Laboratory for Foraminifera Research Contributions*, 17:1-27.

———, 1946. The foraminiferal fauna of the Lizard Springs Formation of Trinidad, B.W.I. *Cushman Laboratory for Foraminifera Research Special Publication*, 18:1-48.

———, 1948. The foraminiferal fauna of the Oligocene St. Croix Formation of Trinidad, B.W.I. *Cushman Laboratory for Foraminifera Research Special Publication*, 22:1-46.

CUSHMAN, J. A. and STAINFORTH, R. M., 1945. The foraminifera of the Cipero Marl Formation of Trinidad, B.W.I. *Cushman Laoratory for Foraminifera Research Special Publication*, 14:1-75.

DUGGLEBY, R. G. and WARD, L. C., 1991. Analysis of physiological data characterized by two regimes separated by an abrupt transition. *Physiological Zoology*, 64: 885-889.

DUQUE-CARO, H., 1968. Observaciones generales a la bioestratigrafía y geología regional en los departamentos de Bolívar y Córdoba. *Boletín de Geología de la Universidad Industrial de Santander*, 24:71-87.

———, 1972a. Ciclos tectónicos y sedimentarios de Colombia y sus relaciones con la paleoecología. *Boletín Geológico*, 19(3):1-23.

———, 1972b. Relaciones entre la bioestratigrafía y la cronoestratigrafía en el llamado Geosinclinal de Bolivar. *Boletín Geológico*, 19(3):25-68.

———, 1975. Los foraminíferos planctónicos y el Terciario de Colombia. *Revista Española de Micropaleontología*, 7(3):403-427.

———, 1979. Major structural elements and evolution of northwestern Colombia. In: Watkins, J. S., Montadert, L. and Dickerson, P. W., Eds., *Geological and geophysical investigations of continental margins,* 329-351.. Tulsa: American Association of Petroleum Geologists, Memoir 29.

———, 1990. Neogene stratigraphy, paleoceanoraphy and paleobiogeography in northwest South America and evolution of the Panama Seaway. *Palaeogeography, Palaeoclimatology, Palaeoecology* 77:203-234.

———, 1991. “Contribution to the geology of the Pacific and the Caribbean coastal areas of the northwestern Colombia and South America.” Dissertation PhD, Princeton University, 132pp.

DUQUE-CARO, H. and REYES, R., 1999. “Biostratigraphy study integrating seismic data of the Guajira Region (onshore and offshore)”. Bogota: Ecopetrol Internal Report, 130pp.

ELLIS and MESSINA CATALOGUE OF FORAMINIFERA, 1942-2006. Micropaleontology Project, Inc. New York.

FIORINI, F. and JARAMILLO, C., 2006. Paleobathymetric and paleoenvironmental reconstruction of the Oligocene and Miocene deposits of southern Caribbean (Carmen de Bolívar, Colombia) based on benthonic foraminifera. In: *Abstracts: FORAMS2006*.

FLINCH, J. F., 2003. Structural evolution of the Sinu-Lower Magdalena Area (Northern Colombia). In: Bartolini, C., Buffler, R. T. and Blickwede, J., Eds., *The circum-Gulf of Mexico and the Caribbean: Hydrocarbon habitats, basin formation, and plate tectonics*, 776-796. Tulsa: American Association of Petroleum Geologists, Memoir 79.

FOOTE, M., 2000. Origination and extinction components of taxonomic diversity: General problems. *Paleobiology*, 26 (4):74-102.

GIBBONS, J. D. and CHAKRABORTI, S., 1992. *Nonparametric statistical inference*. New York: Marcel Dekker Ed, 680pp.

GIBSON, T. G., 1983. Key Foraminifera from Upper Oligocene to Lower Pleistocene strata of the Central Atlantic Coastal Plain. In: Ray, C. E., Ed. *Geology and Paleontology of the Lee Creek Mine, North Carolina, I.,* 355-452. Washington, Smithsonian Institution Press. Smithsonian Contribution to Paleontology 53.

GRADSTEIN, F. M., 1985. Stratigraphy and the fossil record. In: Gradstein, F. M., Agterberg, F. P., Brower, J. C. and Schwarzacher, W., Eds., *Quantitative stratigraphy,* 17-39. Brussels: Reidel Publ. Co. & UNESCO.

GRADSTEIN, F. M. and AGTERBERG, F. P., 2003. *Tools for biostratigraphic zonation and correlation.* Available at: www.rasc.uio.no

IACCARINO, S., 1985. Mediterranean Miocene and Pliocene planktic foraminifera. In: Bolli, H. M., Saunders, J. B. and Perch-Nielsen, K., Eds., *Plankton stratigraphy,* 283-315. Cambridge: Cambridge University Press.

ICP-ECOPETROL., 2000. “Evaluación integrada del Valle Inferior del Magdalena. División de exploración y producción, Vicepresidencia Adjunta de Exploración, Gerencia de Estudios Regionales. “ Internal Report, Piedecuesta, 367pp.

INTERNATIONAL COMMISSION ON ZOOLOGICAL NOMENCLATURE (ICZN), 1999. *International Code of Zoological Nomenclature*. 4th edition. London: The Natural History Museum. Also, www.iczn.org/iczn/index.jsp.

JAMES, K., 2005. A simple synthesis of Caribbean geology. *Caribbean Journal of Earth Science*, 39:69-82.

JARAMILLO, M., 1999. “Aplicación del método bioestratigráfico cuantitativo de Correlación Gráfica en el Terciario de la cuenca del Valle Inferior del Magdalena.” MSc trabajo de grado Universidad EAFIT, Medellín, 51pp.

JENKINS, D. J., 1985. Southern mid-latitude Paleocene to Holocene planktic foraminifera. In: Bolli, H. M., Saunders, J. B. and Perch-Nielsen, K., Eds., *Plankton stratigraphy,* 263-282. Cambridge: Cambridge University Press..

KELLOGG, J., TOTO, E. and CERON, J., 2005. Structure and tectonics of the Sinú – San Jacinto accretionary prism in northern Colombia**.** In: *Memoirs X Congreso Colombiano de Geología, Bogotá, Colombia*, 104.

KEMPLE, W. G., SADLER, P. M. and STRAUSS, D. J., 1995. *Extending graphic correlation to many dimensions: Stratigraphic correlation as constraints to optimization,* 65-82. Tulsa: Society for Sedimentary Geology (SEPM) Special Publication 53.

KENNETT, J. P. and SRINIVASAN, M. S., 1983. *Neogene planktonic foraminifera*. Stroudsburg: Hutchinson Ross Publishing Company, 265pp.

KROONEMBERG, S. 1982. A Grenvillian Granulite Belt in the Colombian Andes and its relation to the Guiana Shield. *Geologie en Mijnbow*, 61:325-333.

KUCERA, M. and KENNETT, J. P., 2000. Biochronology and evolutionary implications of Late Neogene California margin planktonic foraminiferal events. *Marine Micropaleontology*, 40: 67-81.

LOEBLICH, A. L., Jr. and TAPPAN, H., 1964. *Sarcodina, chiefly “Thecamebas” and Foraminifera.* Lawrence: Geological Society of America and University of Kansas Press. Treatise of Invertebrade Paleontology, Part C, Protista 2, 900 pp.

LOEBLICH, A.R., Jr. and TAPPAN, H. N., 1988. *Foraminiferal genera and their classification.* New York: Van Nostrand Reinhold, 970 pp.

MARTÍNEZ, J. I., 1995. Biostratigraphic re-assessment of the Cenozoic Lower Magdalena Valley, Colombia. In: *Memoirs V Congreso Colombiano del Petróleo, Bogotá*, 1-8.

MARTÍNEZ, J. I. and LÓPEZ, E., 2005. El sistema fluvial del Magdalena durante el Plioceno – Cuaternario: Contexto tectónico y escenario paleoclimático. In: Restrepo, J. D., Ed., *Los sedimentos del Río Magdalena: Reflejo de la crisis ambiental,* 101-112. Medellin: Fondo Editorial Universidad EAFIT.

OLSSON, R. K., HEMLEBEN, C., BERGGREN, W. A. and HUBER, B. T., Eds., 1999. *Atlas of Paleocene planktonic foraminifera*. Washingto, D.C.: Smithsonian Contributions to Paleobiology, 85, 252 pp.

PARKER, F. L., 1962. Planktonic foraminiferal species in Pacific sediments. *Micropaleontolgy*, 8(2): 219-254

PEARSON, P. N., 1998. Speciation and extinction asymmetries in paleontological phylogenies: evidence for evolutionary progress?. *Paleobiology*, 24(3):305-335.

PEARSON, P. N. and CHAISSON, W. P., 1997. Late Paleocene to Middle Miocene planktonic foraminifer biostratigraphy of the Ceara Rise. In: Shackleton, N. J., Curry, W. B., Richter, C. and Bralower, T. J., Eds, *Proceedings of the Ocean Drilling Program, Scientific Results*, *154*, 33-68. College Station: IODP.

PEARSON, P. N., OLSSON, R. K., HUBER, B. T., HEMBELEN, C. and BERGGREN, W. A., 2006. *Atlas of Eocene planktonic foraminifera*. Cushman Foundation for Foraminiferal Research, Special paper 41.

PETTERS, V. and SARMIENTO, R., 1956. Oligocene and Lower Miocene biostratigraphy of the Carmen-Zambrano area, Colombia. *Micropaleontology*, 2(1):7-35.

PINDELL, J. L., CANDE, S. C., PITMAN, W. C., ROWLEY, D., DEWEY, J., LABRECQUE, J. and HAXBY, W., 1988. A plate-kinematic framework for models of Caribbean evolution. *Tectonophysics*, 155:121-138.

PINDELL, J. L. and BARRET, S. F., 1990. Geologic evolution of the Caribbean region: A plate-tectonic perspective. In: Dengo, G., Case, J. E., Eds., *The Geology of North America, Part H. The Caribbean region,* 405-432. Boulder: Geological Society of America, Special Publication.

POSTUMA, J. A., 1971. *Manual of planktonic foraminifera*. Amsterdam: Elsevier Publishing Company, 420 p.

R DEVELOPMENT CORE TEAM., 2005. R: *A language and environment for statistical computing*. Vienna: R Foundation for Statistical Computing, http:\\www.R-project.org.

RENZ, H. H., 1948. *Stratigraphy and fauna of the Agua Salada Group, State of Falcón, Venezuela*. Geological Society of America, Memoir 32, 219pp.

RESTREPO, J. C., MIRANDA, J. and RESTREPO, J. D., 2005. El Río Magdalena: Contexto global, suramericano y nacional. In: Restrepo, J. D., Ed., *Los sedimentos del Río Magdalena: Reflejo de la crisis ambiental,* 53-76. Medellin: Fondo Editorial Universidad EAFIT.

RÖGL, F., 1985. Late Oligocene and Miocene planktic foraminifera of the Central Paratethys. In: Bolli, H. M., Saunders, J. B. and Perch-Nielsen, K., Eds., *Plankton stratigraphy,* 315-328. Cambridge: Cambridge University Press.

ROTH, J. M., DROXLER, A. W. and KAMEO, K., 2000. The Caribbean carbonate crash at the Middle to Late Miocene transition: linkage to the establishment of the modern global ocean conveyor. In: Leckie, R. M., Sigurdsson, H., Acton, G. D. and Draper, G., Eds., *Proceedings of the Ocean Drilling Program, Scientific Results*, *165*:249-273. College Station: IODP

SADLER, P. M., 2003. *Constrained optimization approaches to the paleobiologic correlation and seriation problems: A user's guide and reference manual to the CONOP program family, Version 6.5*, Riverside: University of California Riverside.

SPENCER-CERVATO, C., THIERSTEIN, H. R., LAZARUS, D. B. and BECKMANN, J. P., 1994. How synchronous are Neogene marine plankton events? *Paleoceanography*, 9:739-763.

STAINFORTH, R. M., 1965. Mid-Tertiary diastrophism in northern South America. In: Saunders, J. B., Ed., *Transactions of the Fourth Caribbean Geological Conference*, 159-174. Trinidad

———, 1969. Ages of Upper Tertiary and Quaternary formations in Venezuela. Asociación Venezolana de Geología, Minería y Petróleo. *Boletín Informativo*, 12:75-90.

STONE, B., 1968. Planktonic foraminiferal zonation in the Carmen-Zambrano area, Colombia. *Micropaleontology*, 14(3):363-364.

TOTO, E. A. and KELLOGG, J. N., 1992. Structure of the Sinú-San Jacinto fold belt – An active accretionary prism in northern Colombia. *Journal of South America Earth Sciences*, 5(2):211-222.

TOUMARKINE, M. and LOUTERBACHER, H., 1985. Paleocene and Eocene planktic foraminifera. In: Bolli, H. M., Saunders, J. B. and Perch-Nielsen, K., Eds., *Plankton stratigraphy*, 87-154. Cambridge: Cambridge University Press/

YEAGER, D. P. and ULTSCH, G. R., 1989. Physiological regulation and conformation: a BASIC program for the determination of critical points. *Physiological Zoology*, 62: 888-907.

APPENDICES 1-4 online at www.micropress.org

APPENDIX 1
Highest (Last) and Lowest (First) documented occurrence of some planktonic foraminifera in the analyzed wells. HO = Highest Occurrence, LO = Lowest Occurrence. Species list contains names of types species.

APPENDIX 2
Relative position of events and their 5% relaxed fit intervals (minimum and maximum potential positions) found by constrained optimization in scenarios 1 and 2.

APPENDIX 3
Phi index (φ) from 58 stronger events, calculated in 70 tested wells, including those 26 used in performing CONOP9. Nominated with letters (from A to Z) those wells used in constrained optimization. Number of wells where an event is recorded, mean value and standard deviation of Phi index (φ) are also presented. Order of events corresponds to the order given in Table 1.

APPENDIX 4
Literature age assignment of some of the potential zonal markers of the proposed sequence. Order of events corresponds to the order given in Table 1.

Manuscript received April 19, 2007
Manuscript accepted September 29, 2007

SUPPLEMENT 1

The Phi Index, developed by J. E. Arenas, Bioestratigraphy Team, Colombian Petroleum Institute, ICP-ECOPETROL, km.7 vía Piedecuesta, Santander, Colombia; email: jearnasm@unal.edu.co, jarenasm@yahoo.co.uk; telephone: 57-7-6847143

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 $\{n_1, n_2, n_3, \ldots n_k\}$ the set of events recorded in a given stratigraphic succession. Suppose that n is the event to be evaluated and n_i is another event from the same set. The *Phi index* for n_a event is defined as:

$$\varphi = \sum_{i=1}^{k} C_{\alpha i} \Big/ \sum_{i=1}^{k} W_{\alpha i} = \sum_{i=1}^{k} \left[A_{\alpha i} * W_{\alpha i} \right] \Big/ \sum_{i=1}^{k} \left[A_{\alpha i ideal} * W_{\alpha i} \right] \quad (1)$$

where $A_{\alpha i}$ and $A_{\alpha i \ ideal}$ are the '*categorization*' *function* evaluated in $m_{\alpha i}$ condition, for studied and ideal sequences respectively, and $W_{\alpha i}$ is the *Weight function* evaluated in the absolute difference between n_α position and n_i position in a reference sequence (*e. i.* Δ_{Events}).

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

$$m_{\alpha i} \begin{cases} >0 & \text{if } n_i \text{ position is above } n_a \text{ position, } \forall\, n_i > n_a, \text{ or} \\ & \text{if } n_i \text{ position is below } n_a \text{ position, } \forall\, n_i < n_a \\ <0 & \text{if } n_i \text{ position is below } n_a \text{ position, } \forall\, n_i > n_a \\ & \text{if } n_i \text{ position is above } n_a \text{ position, } \forall\, n_i < n_a \\ =0 & \text{if } n_i \text{ position is above } n_a \text{ position, } \forall\, n_i < n_a \\ & \text{when } n_i \text{ and } n_a \text{ positions have been recorded in same level.} \end{cases} \quad (2)$$

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_i and n_α behavior observed in stratigraphic succession fits the expected behaviour found in the ideal sequence ($m_{\alpha i} > 0$); 2) *Wrong* when this behavior is not the expected, ($m_{\alpha i} < 0$); and 3) *Right sensu lato,* when there is the same probability that this behaviour could be right or wrong ($m_{\alpha i} = 0$). For this work, we have employed the following values:

$$A_{\alpha i} \begin{cases} = 1.0, & \text{when it is right } \textit{sensu stricto } (m_{\alpha i} > 0), \\ = 0.0, & \text{when it is wrong} (m_{\alpha i} < 0), \text{ or} \\ = 0.5, & \text{when it is right sensu lato} (m_{\alpha i} = 0). \end{cases} \quad (3)$$

Δ_{Events}*:* Parameter that establishes the absolute difference between the n_α and n_i position in the *ideal sequence of events.*

$$\Delta_{Events} = \left[\left| n_i - n_\alpha \right| \right] \in \left[1, n_{k-1} \right] \quad (4)$$

However, given that for any $A_{\alpha i}$ set for specific target event *(n_α),* the more outstanding $A_{\alpha i}$ values are those that indicate the relationship between the n_i events more close to n_α event[1]; it has considered suitable penalize for departure between n_i position in relation to n position in the ideal sequence of events *(e. i.* Δ_{Events}*)* employing the *Weight function:*

$$W = e^{\alpha x}, \beta < 0 and x = (A_{Events-1}) \quad (5)$$

where β is the parameter that restricts the function concavity:

$$\hat{a} = \varsigma^{-1} Ln\ p\varsigma(-1) \quad (6)$$

with η = *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:

$$p = \frac{e^k}{e^{k+1}} \approx 0.36788, \forall k \in \mathbb{Z} \quad (7)$$

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 φ for given n_α: 1) define the ideal sequence of events; 2) indicate η value and to calculate β *(equation 6);* 3)calculate the *Weight function* for all possible x ($\Delta_{Events-1}$) values *(equations 4 and 5);* 4) indicate the relative position that take $\{n_i\}$, including n_α, in the analyzed section (in strict stratigraphic order); 5) arrange the n_i events set (recorded in stratigraphic succesion) in accordance with the order that these same n_i events have in the ideal sequence; 6) calculate $m_{\alpha i}$ and $A_{\alpha i}$ *(equations 2 and 3),* and to ascribe the specific Δ_{Events} values and their respective W values for each n_i - n_a pair; and 7) calculate $C_{\alpha i}$, $\Sigma W_{\alpha i}$ and ΣC_i. The following matrix illustrates the process for calculating the φ index for n_α into a n_i events set:

$$\begin{array}{cccccc} \text{ni} & m_{\alpha i} & A_{\alpha i} & A_{Events_{\alpha i}} & W_{\alpha i} & C_{\alpha i} \\ n_1 & m_{\alpha 1} & A_{\alpha 1} & \left| n_1 - n_a \right| & W_{\alpha 1} & C_{\alpha 1} \\ n_2 & m_{\alpha 2} & A_{\alpha 2} & \left| n_2 - n_a \right| & W_{\alpha 2} & C_{\alpha 2} \\ n_3 & m_{\alpha 3} & A_{\alpha 3} & \left| n_3 - n_a \right| & W_{\alpha 3} & C_{\alpha 3} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ n_k & m_{\alpha k} & A_{\alpha \kappa} & \left| n_k - n_a \right| & W_{\alpha k} & C_{\alpha k} \\ & & & & \sum_{i=1}^{k} W_{\alpha i} & \sum_{i=1}^{k} C_{\alpha i} \end{array}$$

Example. Suppose a *sedimentary stratigraphic section,* which the biostratigraphic distribution of certain taxa has been studied (text-fig. 1 5a), 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 sucession compared to an ideal sequence of events (tex-fig. 15b). Let's also assume that the *ideal sequence* has 20 LO events (text-fig. 15b), the η value is 19 and β 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. 15c), and the $m_{\alpha i}$ $A_{\alpha i}$ and Δ_{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 $n_\alpha = n_{10}$. Both events are recorded in the same position in the stratigraphic succesion, therefore the $m_{\alpha i}$ (in this case, m_{10-14}) condition is 0 (text-fig. 15a, c and e-*M matrix);* and the *categorization function* (A_{10-14}) is 0.5 *(equation 3,* text-fig. 15e-*A matrix).* Given that Δ_{Events} value between n_{14} and n_{10} is 4, its respective *W* value is 0.54 (*Weight function* evaluated for $x = 3$ (Δ_{Events}–1); text-fig. 15d and e-Δ*E and W matrices).* Lastly, $C_{\alpha i}$ 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_{18}, n_{20}}), allowing to calculate that φ for n_{10} *as 0.44 (equation 1;* text-fig. 15e-*W and C matrices* and f).

The lowest φ 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 occurences 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_{18}) and J (n_{20}) above it, and events W (n_{13}), N (n_{14}), and D (n_{10}) below it.

The φ Index values could help to detect: *a)* an unexpected biological behaviour *(e.g.* N taxon maybe could have taken refuge into region, text-fig. 1 5a, 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 = {$A_{(h+2)1}$, $A_{(h+2)2}$, $A_{(h+2)(h+1)}$, $A_{(h+2)(h+3)}$, $A_{(h+2)(h+10)}$}, 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 *mimimun* and the *maximum* values (respectively) in an open interval where the $n_{(h+2)}$ (n_α) position should be, fulfilled with its behaviour into ideal sequence.