



# Paleoenvironmental reconstruction for the lower Pliocene Arroyo Piedras section (Tubará – Colombia): Implications for the Magdalena River – paleodelta's dynamic

C.E. Molinares<sup>a</sup>, J.I. Martinez<sup>b</sup>, F. Fiorini<sup>c</sup>, J. Escobar<sup>d,e</sup>, C. Jaramillo<sup>e,\*</sup>

<sup>a</sup> ECOPETROL S.A., Calle 37 # 8-43, Piso 7, Bogotá, Colombia

<sup>b</sup> Departamento de Geología, Área de Ciencias del Mar, Universidad Eafit, A.A. 3300 Medellín, Colombia

<sup>c</sup> The Petroleum Institute, Abu Dhabi, United Arab Emirates

<sup>d</sup> Departamento de Ciencias Biológicas y Ambientales, Universidad de Bogotá Jorge Tadeo Lozano, Colombia

<sup>e</sup> STRI, Smithsonian Tropical Research Institute, CTPA, P.O. Box 0843, 03092 Balboa, Ancon, Panama

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## ABSTRACT

The Magdalena river transports one of the largest load of sediments per basin area in the world. Its delta position has changed several times over the Neogene. The Arroyo Piedras Section (169 m) in northern Colombia, contains part of the record of the Late Miocene to Early Pliocene evolution of the Magdalena paleodelta. The section was described and sampled for sedimentological and micropaleontological analyses. Based on lithofacies and benthic foraminifera content, the section was divided in three segments, and the upper segment was dated as Early Pliocene using planktonic foraminifera. The lower segment suggests siliciclastic sedimentation in a proximal prodelta/delta plain transitional environment. The intermediate segment suggests sedimentation in a lagoon and/or coastal swamp environment, whereas the upper segment is interpreted as the result of a transgression and subsequent deposition at the foreshore/upper shoreface environment, with a considerable decrease of terrigenous input. The decrease of sediment delivery to the delta produced by permanent El Niño-like conditions coupled with autocyclic processes could explain the transgressive pattern observed in the Arroyo de Piedras section during the Early Pliocene.

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## 1. Introduction

The Magdalena delta develops on the continental margin of the Colombian Caribbean Sea and it is located at the convergence of the South American and the Caribbean tectonic plates (Ercilla et al., 2000, 2002). The Magdalena River is 1612 km long and drains a basin of 257,438 km<sup>2</sup> (Restrepo and Kjerfve, 2000a, 2000b). This river transports more sediment in suspension ( $144 \times 10^6$  t yr<sup>-1</sup>) than the Orinoco and Parana Rivers, despite its moderate basin rainfall regimen (2050 mm yr<sup>-1</sup>), much smaller water discharge (7200 m<sup>3</sup> s<sup>-1</sup>) and drainage area (Milliman and Meade, 1983; Restrepo and Kjerfve, 2000a).

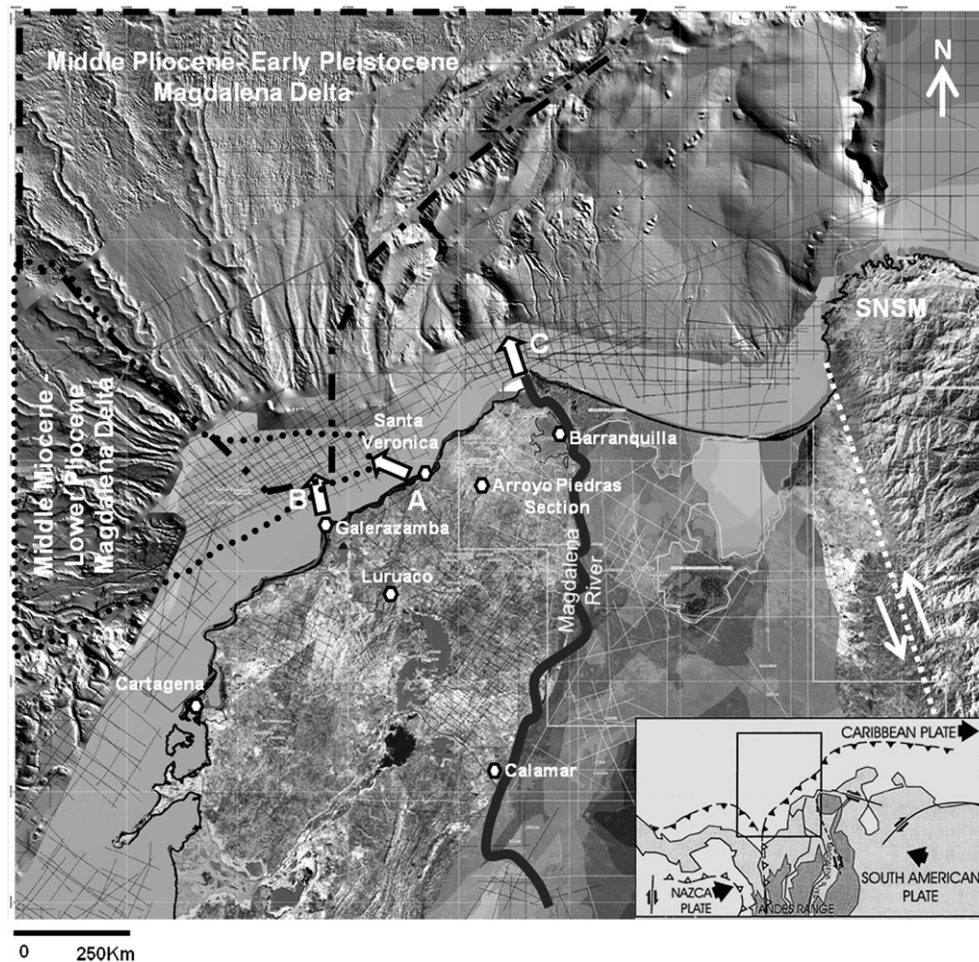
The Magdalena delta-river is a wave-dominated system that has a fan bulge shape (Vermette et al., 1992) and covers an area of

$5.3 \times 10^3$  km<sup>2</sup> (Reading and Richards, 1994). It has a volume of  $1.8 \times 10^5$  km<sup>3</sup> and its sediments extend deeper than 4000 m in the Colombia Basin (Kolla et al., 1984). The Magdalena delta system apparently changed its course during the Pliocene (e.g. Bordine, 1974; Kolla et al., 1984; Pince et al., 2003). This migration apparently coincided in part, with three regional events: (1) a rapid sea-level fall (e.g. Miller et al., 2005) (2) an increase rate of Andean uplift (e.g. Mora et al., 2008), and (3) a permanent El Niño-like paleoceanographic conditions (e.g. Wara et al., 2005; Ravelo et al., 2006; Fedorov et al., 2006).

Paleocurrent data measured at the Arroyo Piedras creek for the Upper Miocene and Lower Pliocene interval (Bordine, 1974), a thicker Pliocene sequence located southwest of the modern Magdalena delta (Kolla et al., 1984), and southeast-northwest paleochannels observed on offshore seismic images (Fig. 1), suggest that the Magdalena River transported sediments north-westward and its discharge was possibly located in front of Santa Veronica Beach (Fig. 1; e.g. Carvajal, 1990). Probably during the middle Pliocene, the drainage system changed toward the north (e.g. Hoorn et al., 1995; Pince et al., 2003). The Magdalena paleo-

\* Corresponding author.

E-mail addresses: [cmolinares@ecopetrol.com.co](mailto:cmolinares@ecopetrol.com.co) (C.E. Molinares), [jmartin@eafit.edu.co](mailto:jmartin@eafit.edu.co) (J.I. Martinez), [ffiorini@pi.ac.ae](mailto:ffiorini@pi.ac.ae) (F. Fiorini), [Jaimeh.escobar@utadeo.edu.co](mailto:Jaimeh.escobar@utadeo.edu.co) (J. Escobar), [jaramillo@si.edu](mailto:jaramillo@si.edu) (C. Jaramillo).



**Fig. 1.** Location Map of the Magdalena delta-river. The image is a combination of Multibeam Scan Sounding offshore images (MBES) and Radar onshore images from the northern Magdalena River basin. During the Early Pliocene, some paleogeographic models (i.e. Bordine, 1974; Pince et al., 2003) suggest that the Magdalena River paleodrainage probably changed from discharging sediments in front of the Santa Veronica beach (A), to a northwest – southeast paleodrainage direction, delivering sediments around Galerazamba area (B). Note the location of the present Magdalena River mouth (C) and the Sierra Nevada de Santa Marta (SNSM). Images: Ecopetrol S.A.'s courtesy.

River mouth would have migrated to an ancient major channel near Calamar, thus flowing northwestward near Luruaco and discharging into the Caribbean Sea near Galerazamba (Fig. 1; Bordine, 1974; Molina et al., 1986).

If the scenario described above is correct, the Magdalena paleo-river migration from Santa Veronica to Calamar would have significantly reduce the supply of sediments to Tubará (Fig. 1) thus, producing significant paleoenvironmental changes. In order to prove this idea we analyzed (i.e. lithology and micropaleontology) the Arroyo de Piedras section, located in the Tubará region and originally described by Redmond (1953). We aim to provide: (1) a paleoenvironmental reconstruction based on benthonic foraminifera assemblages, (2) a review of the Arroyo de Piedras section dates based on planktonic foraminifera content and (3) a review of the possible controls on Tubará region accumulations and its relation with the dynamics of the Magdalena River paleodelta system during the Early Pliocene.

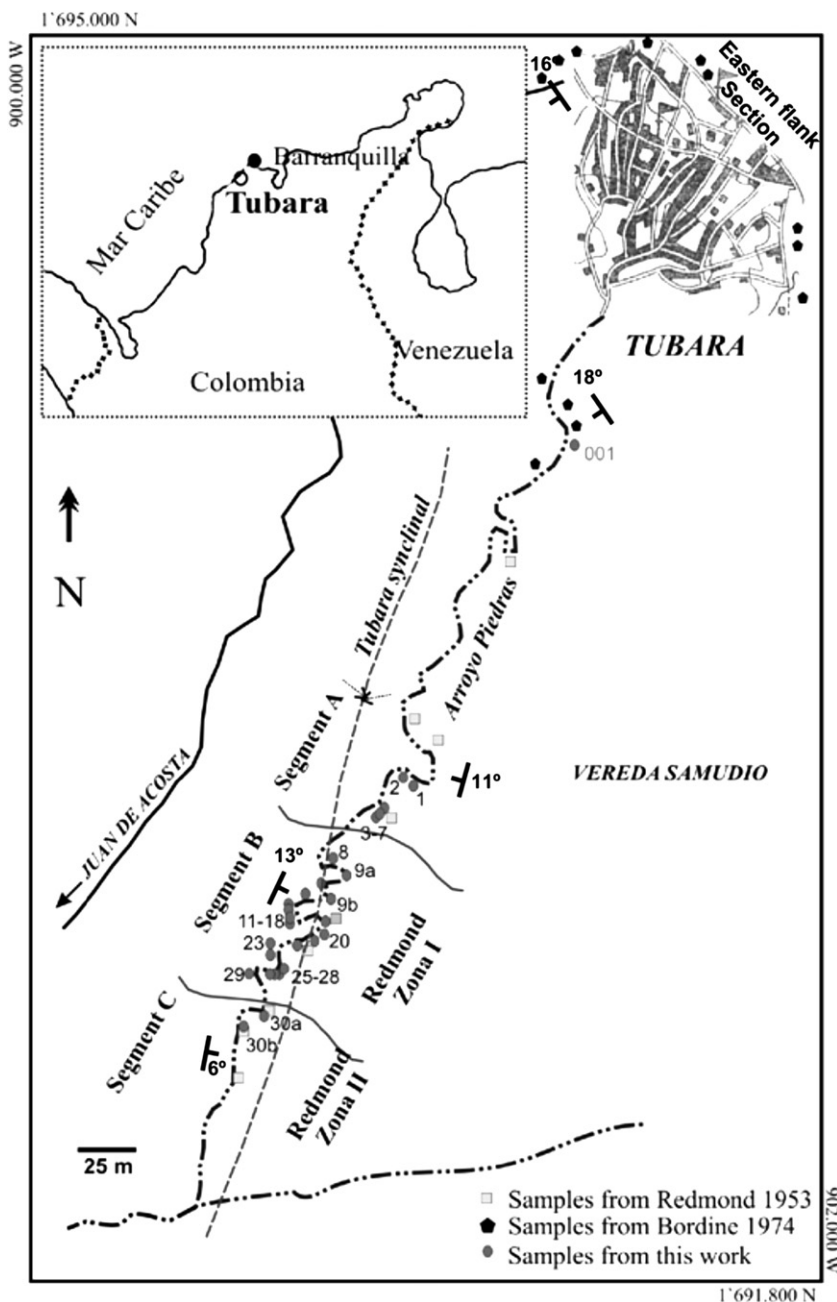
## 2. Regional setting

The onshore plains, between Cartagena and the present Magdalena River mouth (Fig. 1), are composed of a thick, and pervasive, Pliocene–Quaternary terrigenous succession, which resulted from migrations of the Magdalena River (Verette et al., 1992). The

Magdalena delta-river sediments (Fig. 1) produced a lobular geometry evident from both bathymetry (e.g. Shepard, 1973; Carvajal, 1990; Pirmez et al., 1990) and multibeam echo sounding images (Ercilla et al., 2000, 2002; Romero-Otero et al., 2009). The paleodelta sediments accumulated in the Tubará region and the lobular geometry observed in offshore (Ercilla et al., 2000, 2002; Romero-Otero et al., 2009) must be older than lower to middle Pleistocene, evidenced by the coralline limestones of the La Popa Formation and equivalents units that sporadically crop out between Barranquilla and Cartagena (Bordine, 1974). The La Popa Formation restricts the age of the paleodelta, as coral reef development would be impossible with the presence of deltaic sediments (Fig. 1).

The Arroyo Piedras creek (10°52'31.20"N; 74°58'37.96"W), located ~25 km southwest of Barranquilla City (Fig. 2), is one of the most studied stratigraphic sections in northern Colombia (e.g. Anderson, 1926, 1927a, 1927b, 1929; Redmond, 1953; Van den Bold, 1966; Bordine, 1974; Duque-Caro, 1972a, 1972b, 1976), because it contains the record of the Middle Miocene to Early Pliocene evolution of the Magdalena paleodelta (Bordine, 1974).

Foraminifera assemblages from the Arroyo Piedras section were first analyzed by Redmond (1953), who reported some normal neritic benthonic foraminifera species apparently diagnostic of a Caribbean Sea – Pacific Ocean seaway connection. However,



**Fig. 2.** Arroyo Piedras creek (Tubará, northern Colombia). The map illustrates the samples collected in this work, compared to those from previous works (i.e. Redmond, 1953; Bordine, 1974). Segment B and C correspond to Zones I and II of Redmond (1953), respectively.

Bordine (1974; Fig. 2) studied some samples collected in surrounding outcrops and interpreted the interval as a regressive successions, from outer shelf to coarse-grain marginal marine environments, where it was apparently impossible to differentiate to which oceanographic province the Foraminifera taxa belonged to.

Redmond subdivided this section in two sets; bottom (II) and an upper (I). According to the same author, these two sets would correspond with horizons O–S, previously described by Anderson (1929), which might be Late Miocene in age, based on foraminifera (Redmond, 1953) and ostracods assemblages (Van den Bold, 1966).

Then, Bordine (1974) studied two sections in the same region: The Arroyo Piedras section and the eastern flank syncline section.

The Arroyo Piedras or the lower section, it was the same section described by Redmond (1953) and Van den Bold (1966); where Bordine reported the presence of *Globorotalia nepenthes*. According to Bordine (1974) this species date the section Late Miocene–Early Pliocene in age. The other section studied by Bordine is located on the eastern flank of the syncline of Tubara and occupy a position stratigraphically higher and it might correspond to the middle Pliocene (Fig. 2).

Duque-Caro (1975) pointed out that the section of Tubara (Horizons O–S) studied by Redmond (1953) contains a planktonic fauna, which enables it to fit between the N16–N18 (Blow, 1969) and it could be Late Miocene–Early Pliocene in age.

In resume, the Arroyo Piedras Section apparently corresponds to the O to S horizons reported by Anderson (1927a, 1927b, 1929).



and partially to the upper part of the so-called informal lithostratigraphic unit, “Tubará Formation”. The two intervals (Zones II and I) described by Redmond (1953) and Van den Bold (1966) might be Upper Miocene and lower Pliocene, where the eastern flank of the syncline section described by Bordine (1974), could be middle Pliocene (Fig. 3; for a detailed discussion see Porta, 1974, 2003).

### 3. Material and methods

Around 165 m of the stratigraphic section exposed along the Arroyo Piedras Creek were studied by using an integrated sedimentological and micropaleontological approach. Thirty-five samples were collected along the Arroyo Piedras Creek. About 50 g for each sample were disaggregated in water, washed through a 63 µm sieve, and dried at 60 °C. The dried residues were examined for microfossils and then split, in order to obtain samples with at least 300 foraminiferal specimens. Both, planktonic or benthonic foraminifera were identified at the species level when possible, and counted (Table 1). Scanning electron photomicrographs (SEM) and some optical images from the most representative species occurring in the section in the Fig. 4a and b. The relative abundances of the most common benthonic foraminifera species are represented in the Fig. 5.

Taxonomic identification is mainly based on comparisons with benthonic foraminifera publications from the Caribbean region (e.g. Cushman and Renz, 1941; Renz, 1948; Stainforth, 1948; Bermudez, 1949; Phleger and Parker, 1951; Redmond, 1953; Smith, 1964; Boltovskoy and Gualançay, 1975; Poag, 1981; Bolli et al., 1984; Kohl, 1985; Casell and Sen Gupta, 1989; Collins, 1993; Parada-

Ruffinatti, 1996; Javaux and Scott, 2003). Generic assignments are based on Loeblich and Tappan (1987).

In addition, samples with 300 or more specimens (Table 2) were used to perform a Cluster Analysis (Fig. 6), using the UPGMA (unweighted pair group average, Sneath and Sokal, 1973) and Euclidean distance. Cluster analyses were executed with the MVSP® software (<http://www.kovcomp.co.uk/>), with the purpose of identifying foraminifera assemblages of paleoecological significance and investigate the stratigraphic distribution of these assemblages along the Arroyo Piedras Section.

Finally, paleoenvironmental interpretations were supported by comparing fossil benthonic foraminifera assemblages with their modern analogs from the Caribbean and Gulf of Mexico areas (e.g. Phleger and Parker, 1951; Culver and Buzas, 1982; Poag, 1981; Javaux and Scott, 2003 and references therein), and also from worldwide ecological information (Murray, 1991).

### 4. Stratigraphic succession

The Arroyo Piedras section was divided in three stratigraphic segments (A–C), separated by the dominance of sandstones or mudstones (Fig. 5). Fourteen lithofacies assemblages were identified throughout the section.

#### 4.1. Segment A

The Segment A, between 0 and 51.8 m (Fig. 5), contains four lithofacies. Lithofacies A1 is characterized by a rhythmic succession of fine to medium-grained fossiliferous lithoarenite sandstones, usually well calibrated and cemented. This interval contains layers

Ma	Age	Zones	Sections					Lithostratigraphy		
		Berggren et al 1995	Blow 1969					Bueno 1970	Bürgli et al; 1955	Anderson 1929
1	Gelasian	PL 6	N 20	Arroyo Saco	Usiacuri	Pto. Colombia	Arroyo Piedras	Saco Fm.	Tubara-Saco-Juan de Acosta-Chorrera Beds	S R Q P O M N Tubara Group
2										
3										
4										
5										
6	Pliocene	PL 5	N 19	Arroyo Saco	Usiacuri	Pto. Colombia	Arroyo Piedras	Tubara Fm.	Tubara-Saco-Juan de Acosta-Chorrera Beds	S R Q P O M N Tubara Group
7		PL 4								
8		PL 3								
9	Zanclean	PL 2	N 18	Arroyo Saco	Usiacuri	Pto. Colombia	Arroyo Piedras	Tubara Fm.	Tubara-Saco-Juan de Acosta-Chorrera Beds	S R Q P O M N Tubara Group
10		PL 1								
11		PL 1								
12	Messinian	M 14	N 17	Arroyo Saco	Usiacuri	Pto. Colombia	Arroyo Piedras	Piojo Formation	Piojo Formation	S R Q P O M N Tubara Group
13		b								
14		M 13								
15	Late Miocene	a	N 16	Arroyo Saco	Usiacuri	Pto. Colombia	Arroyo Piedras	Piojo Formation	Piojo Formation	S R Q P O M N Tubara Group
16		M 12								
17		M 11								
18	Tortonian	M 10	N 15	Arroyo Saco	Usiacuri	Pto. Colombia	Arroyo Piedras	Piojo Formation	Piojo Formation	S R Q P O M N Tubara Group
19		M 9								
20		M 8								
21	Serravallian	M 7	N 10	Arroyo Saco	Usiacuri	Pto. Colombia	Arroyo Piedras	Piojo Formation	Piojo Formation	S R Q P O M N Tubara Group
22		M 7								
23		M 7								
24	Langhian	M 7	N 10	Arroyo Saco	Usiacuri	Pto. Colombia	Arroyo Piedras	Piojo Formation	Piojo Formation	S R Q P O M N Tubara Group
25		M 7								
26		M 7								
27	Middle Miocene	M 7	N 10	Arroyo Saco	Usiacuri	Pto. Colombia	Arroyo Piedras	Piojo Formation	Piojo Formation	S R Q P O M N Tubara Group
28		M 7								
29		M 7								
30	Langhian	M 7	N 10	Arroyo Saco	Usiacuri	Pto. Colombia	Arroyo Piedras	Piojo Formation	Piojo Formation	S R Q P O M N Tubara Group
31		M 7								
32		M 7								

**Fig. 3.** Stratigraphic position of the Arroyo Piedras Section respect to other “Tubará Formation” localities. The “Tubará Formation” is an informal lithostratigraphic unit. For a detailed discussion about the stratigraphic position and boundaries of the “Tubará Formation” see Porta (1974, 2003). The Arroyo Piedras section age was based on planktonic foraminifera assemblages described by Bordine (1974), Duque-Caro (1975), and this work (Modified from Porta, 2003).

**Table 1**  
Benthonic foraminifera identified from Arroyo Piedras creek. Original names between brackets are marked. Asterisk represents species previously reported by Redmond (1953).

<i>Ammonia parkinsoniana</i> (d'Orbigny) [= <i>Rosalina parkinsoniana</i> ]	* <i>Hanzawaia concentrica</i> (Cushman) [= <i>Truncatulina concentrica</i> ]
<i>Ammonia tepida</i> (Linné) [= <i>Rotalia beccarii</i> (Linné) var. <i>tepida</i> Cushman]	* <i>Hanzawaia deprimus</i> (Phleger & Parker) [= <i>Cibicides deprimus</i> ]
* <i>Amphistegina lessoni</i> d'Orbigny	* <i>Oolina hexagona</i> (Williamson) [= <i>Entosolenia squamosa</i> (Williamson) var. <i>hexagona</i> Williamson]
* <i>Angulogerina colombiana</i> Redmond	* <i>Oolina colombiana</i> Redmond
* <i>Angulogerina</i> cf.	* <i>Massilina crenata</i> (Karrer) [= <i>Spiroloculina crenata</i> ]
<i>A. jamaicensis</i> Cushman & Todd	<i>Miliollinella fichteliana</i> (d'Orbigny) [= <i>Triloculina fichteliana</i> ]
<i>Angulogerina</i> cf. <i>A. hexagona</i> Williamson	<i>Miliollinella</i> sp. A
<i>Angulogerina</i> sp. A	<i>Nonion</i> sp. A
* <i>Asterigerina carinata</i> d'Orbigny	* <i>Nonionella atlantica</i> Cushman
* <i>Bolivina bicostata</i> (Cushman) [= <i>B. costata</i> (Cushman) var. <i>bicostata</i> Cushman]	* <i>Nonionoides grateloupii</i> (d'Orbigny) [= <i>Nonionina grateloupii</i> ]
<i>Bolivina</i> cf. <i>B. caudriae</i> Cushman & Renz	* <i>Pararotalia sarmientoi</i> (Redmond) [= <i>Rotalia sarmientoi</i> ]
<i>Bolivina</i> cf. <i>B. acerosa</i> Cushman	* <i>Planorbulina mediterraneensis</i> d'Orbigny
* <i>Bolivina tortuosa</i> (Brady) var. <i>lissa</i> Redmond	* <i>Quinqueloculina lamarckiana</i> d'Orbigny
<i>Bolivina floridana</i> Cushman	<i>Quinqueloculina</i> cf.
* <i>Bulimina striata</i> (d'Orbigny) var. <i>mexicana</i> Cushman	<i>Q. panamensis</i> Cushman
* <i>Buliminella elegantissima</i> (d'Orbigny) [= <i>Bulimina elegantissima</i> ]	<i>Quinqueloculina seminulum</i> (Stache) [= <i>Alveolina seminulum</i> ]
<i>Buliminella morgani</i> Andersen	<i>Quinqueloculina</i> sp. A
* <i>Cancris sagra</i> (d'Orbigny) [= <i>Rotalia sagra</i> ]	* <i>Rectobolivina hancocki</i> (Cushman & McCulloch) [= <i>Bifarina hancocki</i> ]
* <i>Cassidulina caribaeana</i> Redmond	* <i>Rectobolivina pacifica</i> (Cushman & McCulloch) [= <i>Bifarina pacifica</i> ]
<i>Cibicides rugosa</i> Phleger & Parker	* <i>Reusella bordata</i> Redmond
<i>Cibicides</i> cf. <i>C. sinistralis</i>	<i>Reusella atlantica</i> (Reuss) [= <i>Reusella spinulosa</i> (Reuss) var. <i>atlantica</i> Cushman]
Coryell & Rivero	* <i>Siphonina pulchra</i> Cushman
<i>Cibicides perforatus</i> Coryell & Rivero	<i>Textularia</i> cf. <i>T. lancea</i> Lalicker & McCulloch
* <i>Compressigerina coartata</i> (Palmer) [= <i>Uvigerina coartata</i> ]	<i>Textularia</i> cf. <i>T. truncata</i> Höglund
<i>Criboelphidium poeyanum</i> (d'Orbigny) [= <i>Polystomella poeyana</i> ]	<i>Textularia lateralis</i> Lalicker
<i>Cymbaloporeta</i> sp. A	<i>Textularia</i> aff. <i>T. lateralis</i> Lalicker
<i>Cymbaloporeta</i> sp. B	<i>Textularia</i> cf. <i>T. secasensis</i>
<i>Cymbaloporeta tobagoensis</i> (Bronnimann) [= <i>Cymbalopora tobagoensis</i> ]	Lalicker & McCulloch
* <i>Cymbaloporeta bradyi</i> (d'Orbigny) [= <i>Cymbalopora poeyi</i> (d'Orbigny) var. <i>bradyi</i> Cushman]	<i>Textularia</i> cf. <i>T. vola</i> Lalicker & McCulloch
* <i>Discorbis terquemi</i> van Bellen	<i>Textularia</i> cf. <i>T. scrupula</i> Lalicker & McCulloch
* <i>Discorbis floridensis</i> Cushman	<i>Triloculina tricarinata</i> d'Orbigny
* <i>Dyocibicides biserialis</i> Cushman & Valentine	<i>Triloculina antillarum</i> (d'Orbigny) [= <i>Spiroloculina antillarum</i> ]
* <i>Elphidium tubaraense</i> (Kleinpell) [= <i>Elphidium granti</i> (Kleinpell) var. <i>tubaraense</i> Redmond]	* <i>Uvigerina isidroensis</i> Cushman & Renz
* <i>Eponides repandus</i> Fichtel & Moll	* <i>Valvulinera olssoni</i> Redmond
* <i>Eponides antillarum</i> Galloway & Hemingway	
* <i>Fissurina atlantica</i> (Redmond) [= <i>Entosolenia atlantica</i> ]	
<i>Fissurina</i> sp. A	
<i>Guttulina</i> sp. A	

which are 15–25 cm thick, and are characterized by a continuous tabular geometry. The fossiliferous lithoarenite sandstone layers present erosional bases and a coarsening-upward pattern. Fragments of fossil mollusks, up to 3 cm in length, also are common. Ripple-wave cross lamination and unidirectional current ripples at the top of each layer are commonly present.

Lithofacies A2 is characterized by medium-grained to conglomeratic muddy fossiliferous lithoarenite sandstones that occur in layers 5–60 cm thick interbedded with coarsening-upward, sandy mudstones to muddy sandstones arranged in layers 3–20 cm thick. Frequently the mudstones present sandstone-siltstone laminae and interbedded lenticular layers of very fine-grained fossiliferous quartz sandstones, normally ranging in thickness from 1 to 8 mm. Lithofacies A3 is characterized by well calibrated medium-grained quartz sandstones which are 6 m thick. The facies succession tends to become fine upwards, with some preserved structures such as cross-bedding trough stratification with granules and pebbles at the base of troughs. Lithofacies A3 is characterized by plane-parallel gray mudstones and thin lenses of very fine-grained quartz sandstones at the top of each layer.

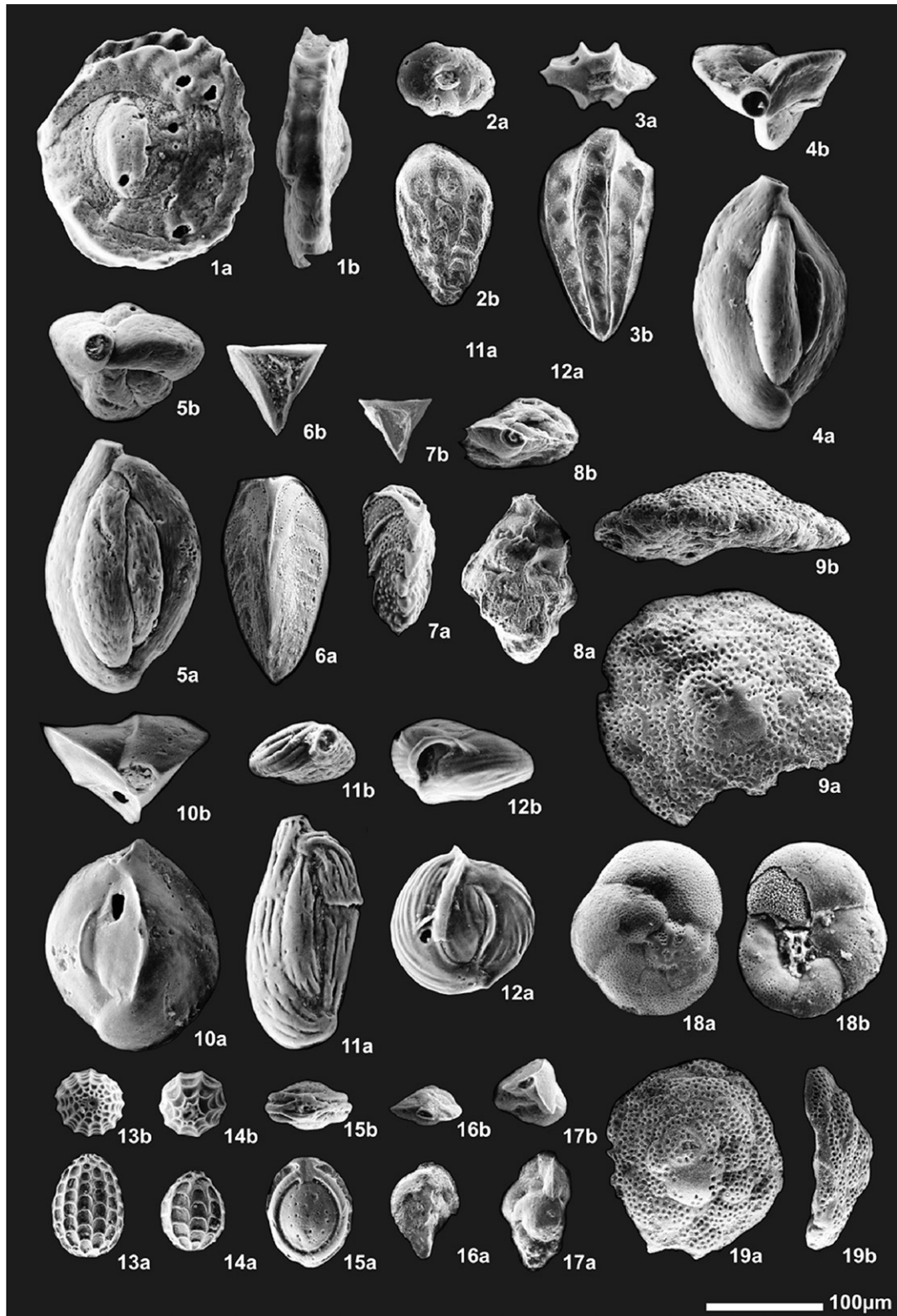
#### 4.2. Segment B

The Segment B, between 51.8 and 95.8 m, is less sandy than Segment A (Fig. 5). Six lithofacies were identified in this segment.

Lithofacies B1 contains a series of light-gray mudstones, with non-continuous plane-parallel lamination and/or unidirectional current ripples. Lithofacies B2 is characterized by fossiliferous sandstone levels with wave-cross lamination and lenticular bedding stratification, whereas lithofacies B3 is characterized by light-gray mudstones overlain by dark-gray carbonaceous mudstones, which frequently contain large fossil leaf fragments, mangroves roots and *Ophiomorpha* ichnofacies. Lithofacies B4 contains bioturbated, very fine-grained lithoarenite sandstones and siltstones, whereas lithofacies B5 is characterized by massive graded beds of conglomeratic fossiliferous lithoarenites, with abundant fragments of poorly selected fossil mollusks, which decrease in size and proportion toward the top. Lithofacies B6 is characterized by medium to coarse-grained lithoarenites, with low-angle plane-parallel cross-bedding stratification, lenticular geometry and erosive contacts on the base of strata. Complex fluid-escape structures are also frequent.

#### 4.3. Segment C

The uppermost segment, between 95.8 and 169 m, contains four lithofacies (Fig. 5). Segment C is characterized by the occurrence of muddy lithoarenites that grade to light-gray sandy siltstones. Lithofacies C1 is characterized by occurrences of light-gray mudstones, ending in an unconformity erosive surface, whereas lithofacies C2 is characterized by well-selected, bioturbated, well



**Fig. 4.** a. Foraminifera species identified in the Arroyo Piedras Section (1) *Massilina crenata* (Karrer), sample 26 (2) *Bolivina floridana* Cushman, sample 28 (3) *Bolivina interjuncta* var *bicostata* (Cushman), sample 30a (4) *Quinqueloculina lamarckiana* d'Orbigny, sample 27 (5) *Quinqueloculina seminula* (Linnaeus), sample 26 (6) *Reusella Bordata* Redmond, sample 30b (7) *Reusella atlantica* (Cushman), sample 26 (8) *Compressigerina coartata* (Palmer), sample 30b (9) *Cymbaloporeta tobagoensis* (Bronnimann), sample 30a (10) *Triloculina tricarinata* d'Orbigny, sample 26 (11) *Triloculina antillarum* (d'Orbigny), sample 26 (12) *Miliolinella fichteliana* (d'Orbigny), sample 23 (13) *Oolina hexagona* (Williamson), sample 27 (14) *Oolina colombiana* (Redmond), sample 27 (15) *Fissurina colombiana* (Redmond), sample 03 (16) *Bolivina tortuosa* (Brady) var *lissa* Redmond, sample 03 (17) *Angulogerina colombiana* Redmond, sample 20 (18) *Valvulineria olssoni* Redmond, sample 27 (19) *Cymbaloporeta bradyi* (Cushman), sample 30a. b. Foraminifera species identified in the Arroyo Piedras Section (1) *Globigerinoides sacculifer* (Brady), sample 30b (2) *Globigerinoides immaturus* (Le Roy), sample 30b (3) *Globigerinoides obliqua* (Bolli), sample 29 (4) *Globigerinoides rubra* (d'Orbigny), sample 30a (5) *Truncorotalia cf. crassaformis* (Galloway & Wissler), sample 29 (6) *Globorotalia conomiozea* (Kennett) cf. *subconomiozea* Bandy, sample 8 (7) *Nonionella atlantica* Cushman, sample 20 (8) *Nonion* sp., sample 03 (9) *Amphistegina lessoni* d'Orbigny, sample 30b (10) *Nonionoides grateloupii* (d'Orbigny), sample 01 (11) *Hanzawaia deprimus* (Phleger & Parker), sample 30a (12) *Hanzawaia concentrica* (Cushman) (13) *Asterigerina carinata* d'Orbigny, sample 30b (14) *Ammonia parkinsoniana* (d'Orbigny), sample 29 (15) *Ammonia tepida* (Cushman), sample 24 (16) *Pararotalia sarmientoi* (Redmond), sample 06 (17) *Elphidium tuberaensis* (Redmond), sample 29 (18) *Criboelphidium poeyanum* (d'Orbigny), sample 28.

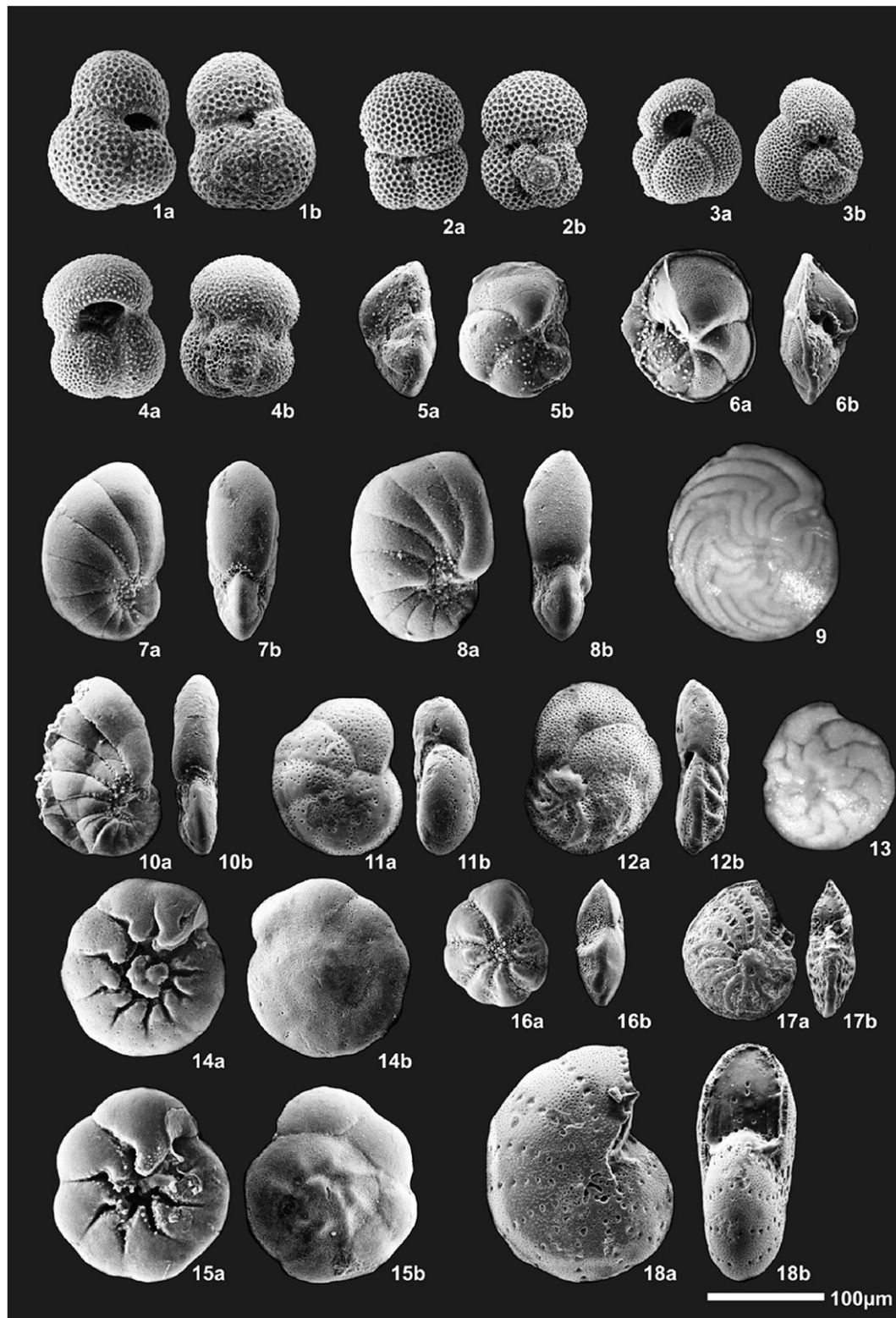


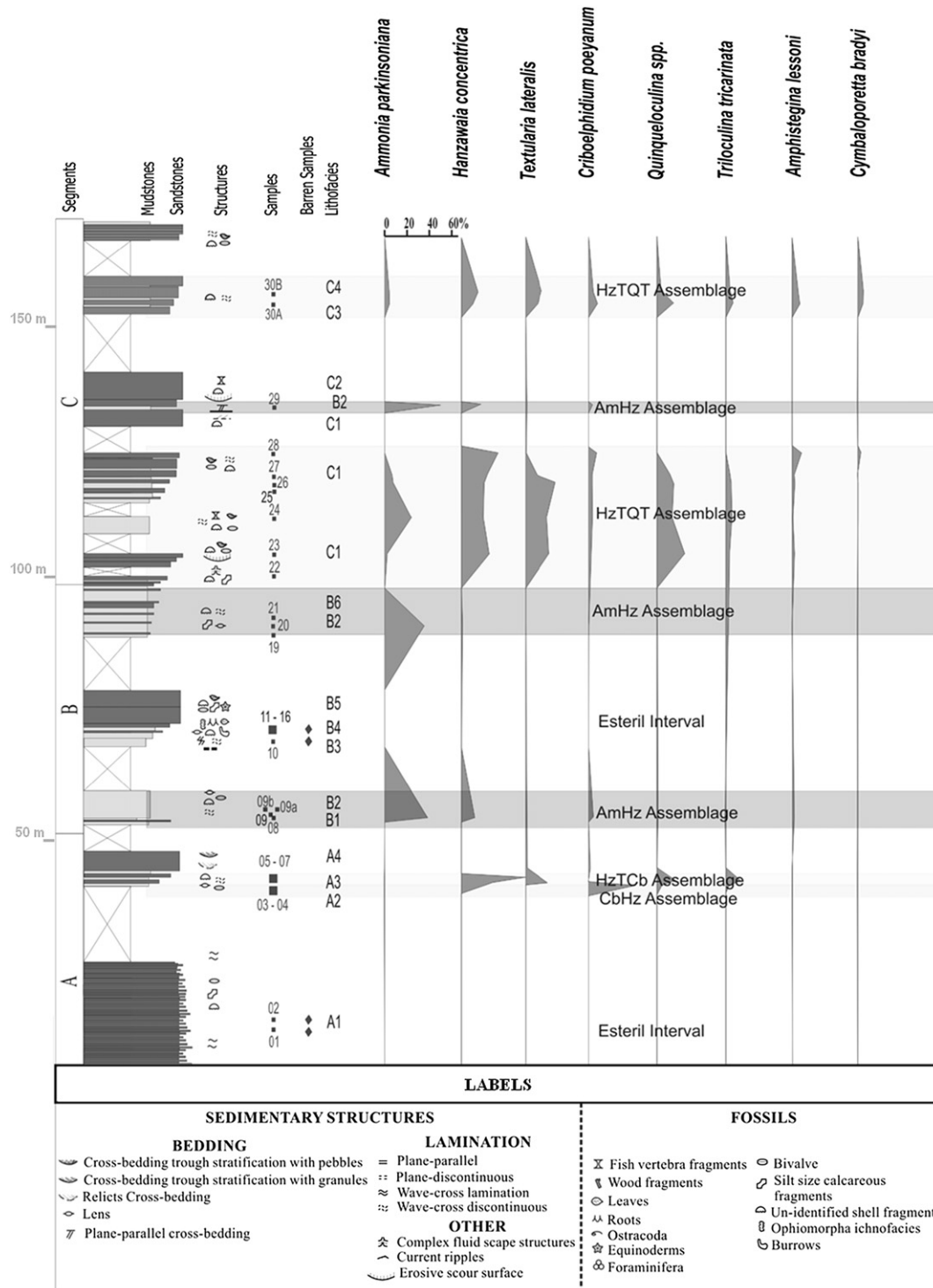
Fig. 4. (continued).

sorted medium-grained quartz sandstones, with very continuous low-angle plane-parallel bedding. Lithofacies C3 is characterized by fine-grained gray lithoarenitic sandstones, with wave-ripple cross lamination, whereas lithofacies C4 contains well-selected and cemented sandstones, with a coarsening-upward pattern where beds are thicker and more continuous.

### 5. Benthonic foraminifera assemblages

Twenty-one, out of the processed 35 samples, contained foraminifera. Sixty-eight species of benthonic foraminifera were identified (Table 1). Segment A was barren, but not the overlying segments where four foraminifera assemblages were identified and





**Fig. 5.** Arroyo Piedras section (Tubará, northern Colombia). Lithofacies, benthonic foraminifera assemblages, and relative (%) abundances of the most dominant species. See the text for details on Segments A–C and their foraminifera assemblages.

found associated to a particularly lithofacies following the Cluster analysis (Fig. 5). These assemblages are:

#### 5.1. *Criboelphidium*–*Hanzawaia* (CbHz) assemblage

This assemblage was found in muddy fossiliferous lithoarenites, in layers 5–60 cm thick, always associated with lithofacies A3 (Figs. 4 and 5). *Criboelphidium*–*Hanzawaia* (CbHz) assemblage is characterized by benthonic foraminifera mostly belonging to

the species *Criboelphidium poeyanum* (41%) and *Hanzawaia concentrica* (14%). In lower percentage abundance, *Quinqueloculina* spp. (6%) and *Triloculina tricarinata* (3%) are also present (Sample 03, Fig. 5).

#### 5.2. *Hanzawaia*–*Textularia*–*Criboelphidium* (HzTCb) assemblage

The *Hanzawaia*–*Textularia*–*Criboelphidium* (HzTCb) assemblage is characterized by the dominance of *H. concentrica* (72%), and by



**Table 2**

Percentages of benthonic foraminifera in samples with 300 or more specimens used to perform the Cluster analysis.

Species	Samples											
	3	6	8	20	23	24	26	27	28	29	30a	30b
<i>Ammonia parkinsoniana</i>	0.01	0.01	0.38	0.36	0.02	0.23	0.09	0.08	0.06	0.5	0.05	0.05
<i>Ammonia tepida</i>	—	—	0.01	0.01	—	0.02	—	0.01	0.01	—	—	—
<i>Amphistegina lessoni</i>	—	—	0.01	—	0.01	—	0.01	0.01	0.09	—	0.06	0.04
<i>Angulogerina colombiana</i>	0.01	0.01	0.01	—	0.01	—	—	—	0.01	—	—	—
<i>Angulogerina</i> cf. <i>A. jamaicensis</i>	0.04	0.01	—	0.05	—	0.01	—	0.03	0.01	0.03	0.00	0.00
<i>Angulogerina</i> sp. A	0.04	—	—	0.05	—	—	—	—	—	—	—	—
<i>Asterigerina carinata</i>	—	—	—	—	—	—	—	—	—	—	0.01	—
<i>Bolivina bicostata</i>	—	0.01	—	—	—	—	—	—	—	—	—	—
<i>Bulimina</i> spp.	—	0.01	0.02	—	—	—	—	—	—	0.01	—	—
<i>Bulimina striata</i> var. <i>mexicana</i>	—	—	—	—	—	—	—	—	—	—	—	—
<i>Buliminella elegantissima</i>	—	—	0.01	—	—	—	—	—	—	—	—	—
<i>Cassidulina caribbeana</i>	0.01	—	—	0.01	—	—	0.01	—	—	—	—	—
<i>Cibicides</i> cf. <i>C. sinistralis</i>	—	0.01	0.01	—	—	—	0.01	0.02	—	—	0.01	—
<i>Cibicides perforatus</i>	—	0.01	0.01	0.03	0.01	0.01	—	0.02	0.13	—	—	0.02
<i>Compressigerina coartata</i>	—	—	—	—	—	—	—	—	—	—	—	0.01
<i>Criboelphidium poeyanum</i>	0.41	0.02	0.05	—	0.02	0.03	0.03	0.05	0.07	0.03	0.08	0.05
<i>Cymbaloporetta tobagoensis</i>	—	—	—	—	—	—	—	—	—	—	0.01	—
<i>Cymbaloporetta bradyi</i>	—	—	—	—	—	—	—	—	0.01	—	0.04	0.04
<i>Discorbis terquemi</i>	0.07	0.01	0.02	0.1	0.01	0.02	0.02	0.03	0.01	—	0.02	0.01
<i>Discorbis floridensis</i>	—	—	—	—	—	0.01	0.01	0.04	—	—	—	—
<i>Dyocibicides biserialis</i>	—	—	—	—	—	—	—	—	—	—	0.01	—
<i>Eponides repandus</i>	—	0.01	0.04	0.02	0.04	0.01	—	—	0.03	0.04	0.05	0.03
<i>Eponides parantillarum</i>	—	—	0.01	—	—	—	0.01	0.01	0.01	0.02	—	—
<i>Fissurina atlantica</i>	0.04	0.01	0.01	0.01	—	—	—	—	—	—	—	—
<i>Hanzawaia concentrica</i>	0.14	0.72	0.22	0.11	0.24	0.19	0.3	0.33	0.4	0.27	0.19	0.24
<i>Hanzawaia deprimus</i>	—	0.02	—	—	—	0.03	0.01	—	0.01	0.01	0.02	0.02
<i>Haplofragmoides</i> spp.	—	0.01	—	—	—	—	—	—	—	—	—	—
<i>Massilina crenata</i>	—	—	—	—	—	—	—	—	0.01	—	—	0.01
<i>Miliollinella fichteliana</i>	—	—	—	—	—	—	0.01	0.01	0.01	—	—	0.01
<i>Miliollinella</i> sp. A	—	—	—	—	—	—	0.01	0.01	—	—	—	—
<i>Nonion</i> sp. A	0.01	—	—	—	—	—	—	—	—	—	—	—
<i>Nonionella atlantica</i>	0.02	—	0.03	0.06	0.05	0.02	—	0.01	0.04	—	—	0.01
<i>Pararotalia sarmientoi</i>	0.08	0.07	—	—	—	—	—	—	—	—	—	—
<i>Planorbulina mediterraneensis</i>	—	—	—	—	0.02	0.01	0.01	—	0.03	—	0.01	—
<i>Planulina</i> spp.	0.01	0.01	—	—	—	—	—	—	—	—	—	—
<i>Quinqueloculina lamarkiana</i>	—	—	—	—	—	0.01	0.01	0.02	—	—	—	—
<i>Quinqueloculina seminulum</i>	0.06	—	—	0.02	0.12	0.08	0.13	0.09	—	0.02	0.05	0.03
<i>Quinqueloculina</i> sp. A	—	—	—	—	0.11	0.01	—	—	—	—	0.09	0.02
<i>Quinqueloculina</i> spp.	—	—	0.01	—	—	0.02	0.01	—	—	—	—	0.01
<i>Rectobolivina hancocki</i>	—	—	0.01	0.03	0.01	—	0.01	—	0.01	—	—	—
<i>Rectobolivina pacifica</i>	—	—	—	—	—	—	—	—	—	—	—	—
<i>Reusella bordata</i>	—	—	0.1	—	—	—	—	—	0.02	—	0.1	0.12
<i>Reusella atlantica</i>	—	0.02	—	0.01	0.01	0.02	0.01	0.03	0.00	0.03	—	—
<i>Siphonina pulchra</i>	—	0.01	—	—	—	—	—	—	—	—	—	—
<i>Spirillina</i> spp.	—	—	—	—	—	—	—	—	—	—	—	0.01
<i>Textularia</i> cf. <i>T. truncata</i>	0.01	—	—	—	0.02	—	—	—	—	—	—	—
<i>Textularia lateralis</i>	0.01	0.02	0.01	0.07	0.21	0.19	0.24	0.1	0.01	0.01	0.12	0.16
<i>Textularia</i> aff. <i>T. lateralis</i>	—	—	—	—	—	—	0.01	—	—	—	0.01	0.01
<i>Textularia</i> cf. <i>T. secasensis</i>	—	—	—	—	0.01	—	—	—	—	—	0.01	—
<i>Textularia</i> cf. <i>T. vola</i>	—	—	—	—	—	—	—	—	—	—	0.01	—
<i>Textularia</i> cf. <i>T. scrupula</i>	—	—	—	—	—	—	—	—	—	—	—	—
<i>Triloculina tricarinata</i>	0.03	—	—	0.01	0.03	0.06	0.05	0.04	—	—	0.07	0.06
<i>Uvigerina isidroensis</i>	—	0.02	0.02	—	0.01	0.01	0.01	—	0.01	—	0.01	—
<i>Valvulinera olsoni</i>	—	—	0.01	—	—	—	—	—	—	—	—	0.01

low percentage abundances (2%) of *Textularia* aff. *Textularia lateralis* and *Criboelphidium poeyanum* (Sample 06, Fig. 5). This assemblage occurs at the top of lithofacies A3 and resembles the previous assemblage, though the HzTCb assemblage is marked by the dominance of *H. concentrica*.

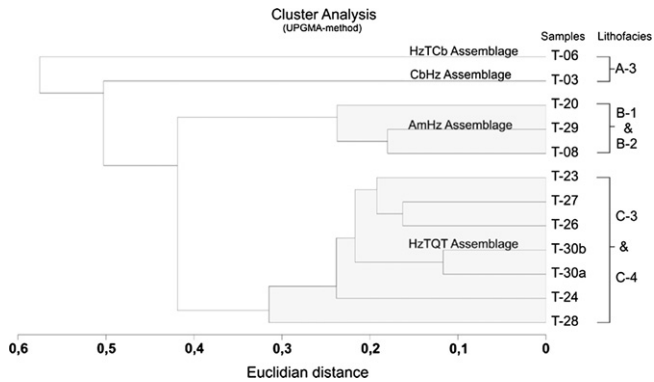
### 5.3. *Ammonia*–*Hanzawaia* (AmHz) assemblage

The middle part of the Arroyo Piedras stratigraphic section (i.e. Segment B) is characterized by the *Ammonia*–*Hanzawaia* assemblage (Samples from 8 to 21), which presents a low diversity, high percentage abundance of *Ammonia parkinsoniana* (35–50%), and a smaller percentage abundance of *H. concentrica* (10–20%) and

*C. poeyanum* (2–5%). AmHz assemblage was reported from mudstones described as lithofacies B1 and lithofacies B2, characterized by mudstones rich in organic matter (Fig. 5).

### 5.4. *Hanzawaia*–*Textularia*–*Quinqueloculina*–*Triloculina* (HzTQT) assemblage

The benthonic foraminifera assemblage *Hanzawaia*–*Textularia*–*Quinqueloculina*–*Triloculina* was recognized on intervals described as lithofacies C3 and C4 (Fig. 5). The association is mainly characterized by *H. concentrica* (20–40%), *Textularia* aff. *T. lateralis* (10–25%), *Quinqueloculina* spp. (9–15%) and *T. tricarinata* (3–5%). In this segment, overlying a conspicuous surface, *A. parkinsoniana*



**Fig. 6.** Cluster Analysis for the benthonic foraminifera assemblages identified in the Arroyo Piedras section (Tubará, northern Colombia). Note the relationship between the different foraminiferal assemblages with some particular lithofacies. See the text for details.

percentage abundance normally decreases at the expense of *Amphistegina lessoni*.

## 6. Paleoenvironmental interpretation

Based on lithofacies and benthonic foraminifera assemblages, the Arroyo Piedras section is interpreted to be the result of deposition on marginal marine environments which changed to normal marine conditions (Fig. 5). The Arroyo Piedras section corresponds to a succession of fluvial-dominated delta affected by transgression; the shallow marine to brackish marginal marine environments would correspond to the progradational delta phase (Segments from A to B), and the upper part (Segment C), would correspond to transgressive deposits accumulated over a transgressive surface (e.g. Bhattacharya and Walker, 1992).

### 6.1. Segment A

The Segment A is interpreted as the result of accumulation on a proximal prodelta/deltaic plain environment (Fig. 5). The lower part of Segment A is characterized by a rhythmic succession and a continuous tabular geometry of sandstone layers with erosional bases and a coarsening-upward pattern (lithofacies A1), which are commonly associated with mouth bars or proximal prodelta environments (e.g. Bhattacharya and Walker, 1992).

Associated with this lithofacies, the *Criboelphidium*–*Hanzawaia* (CbHz) assemblage was found. *Criboelphidium* or the non-keeled *Elphidium* species are regarded as infaunal morphotypes, generally associated with variable salinity conditions on inner shelves, mangroves and/or coastal swamps (Murray, 1991). *C. poeyanum* is a species associated with inner shelf, brackish, and coastal lagoon environments from Tobago, St. Lucia, Venezuela, Puerto Rico, Cuba, Belize, Panama, and mangroves from Bahamas and Florida (e.g. Javaux and Scott, 2003). Similarly, *H. concentrica* has been reported from coastal environments and swamps from Belize, and also is frequently associated with coral reefs from outer to inner shelf in Trinidad & Tobago and Venezuela (e.g. Javaux and Scott, 2003).

Other species that occur in lower percentage abundance in this interval such as *Triloculina tricarina* and *Quinqueloculina seminulum* have also been reported in hypersaline environments related to recent swamps and semi-protected coastal lagoons from Bahamas, Bermuda, and Florida (e.g. Javaux and Scott, 2003). At the top of lithofacies A3, the *Hanzawaia*–*Textularia*–*Criboelphidium* (HzTCb) assemblage records possibly a change to more normal saline conditions and a decrease in the influence of terrigenous sediments

from distributary channels. The HzTCb assemblage is marked by the dominance (72%) of *H. concentrica*. *Hanzawaia* are frequently considered as an epifaunal morphotype that prefers large organic matter concentrations, harder substrates and normal saline conditions (Murray, 1991).

The upper part of Segment A was possibly accumulated by distributary channels on a delta plain (Fig. 5). The distributary channels are evidenced by some fluvial-related sedimentary structures; e.g. interbedded lenticular layers of very fine-grained sandstones (lithofacies A2), and layers that tend to become fine-upward, with some preserved structures such as cross-bedding trough stratification bearing granules and pebbles at their bases (lithofacies A3). This interpretation is also supported by the low recovery of benthonic foraminifera.

### 6.2. Segment B

The Segment B is interpreted as the product of accumulation on lagoons and/or coastal swamps. The lagoons environment is supported by a series of rich organic light-gray mudstones, with non-continuous plane-parallel lamination (lithofacies B1) or with wave-cross lamination and lenticular bedding stratification (lithofacies B2), where *A. parkinsoniana* is dominant.

*Ammonia* specimens from the Arroyo Piedras section were reported by Redmond (1953) as *Ammonia beccarii* (Linné). However, these morphotypes are more related to *A. parkinsoniana* (d'Orbigny) *typica* form, and in some rare cases to *A. parkinsoniana* (Cushman) *tepida* form (Poag, 1978). Typically, *Ammonia* is a genus restricted to inner shelf environments (e.g. Murray, 1991), particularly, *A. parkinsoniana typica* form (Poag, 1978) that is a euryhaline species associated to lagoonal and coastal swamp environments (e.g. Sen Gupta et al., 1986).

Examples of recent benthonic foraminifera assemblages with a low diversity and a high proportion of *A. parkinsoniana* have been reported from lagoons in the Gulf of Mexico, especially those with a marked tidal influence (e.g. Alvarado lagoon; Phleger and Lankford, 1978). In the Caribbean Sea, assemblages with a marked predominance of *A. parkinsoniana* have been reported in coastal bays and lagoons from Puerto Rico (Seiglie, 1975) and St. Lucia (Sen Gupta and Schafer, 1973). Whereas, in Colombia, *Ammonia* is one of the predominant foraminifera genus in Baru Island coastal lagoons where it can reach relative abundance of up to 50% (Parada-Ruffinatti, 1996).

In addition, the coastal swamp interpretation for the Segment B is primarily supported by large fossil leaf fragments, mangroves roots and *Ophiomorpha* ichnofacies (lithofacies B3), interbedded with bioturbated very fine-grained lithoarenite sandstones and siltstones (lithofacies B4). The foraminifera-sterile interval in the middle part of the Segment contains a large number of fossil leaves and mangrove roots more related to coastal swamps deposited away from any marine influence (Fig. 5). Recent analogs for this environment are characterized by the presence of delicate agglutinated foraminifera species with a very poor preservation potential (e.g. Culver, 1990).

The foraminifera-sterile interval from the Segment B that is associated to massive graded beds of conglomeratic fossiliferous lithoarenites, with abundant fragments of poorly selected fossil mollusks (lithofacies B4), could be interpreted as the result of episodic torrential flows on lagoon/coastal swamps.

### 6.3. Segment C

The Segment C is interpreted as the product of sedimentation in the transition between foreshore and upper shoreface environments. The foreshore environment is associated with very

continuous low-angle plane-parallel bedding (lithofacies C2), whereas the shoreface facies is associated with wave-ripple cross laminated sandstones (lithofacies C3), which changed to cleaner, well-sorted and cemented sandstones, in a typical coarsening-upward pattern where beds are thicker and more continuous (lithofacies C4). In this segment, and overlying a clear erosive surface, the benthonic foraminifera assemblage *Hanza-waia*–*Textularia*–*Quinqueloculina*–*Triloculina* was recognized (Fig. 5).

The HzTQT assemblage is mainly characterized by *H. concentrica* (20–40%), *T. lateralis* (10–25%), and *Quinqueloculina* spp. (9–15%). In contrast, *A. parkinsoniana* decrease severely. *Triloculina* and *Quinqueloculina* are considered epifaunal morphotypes, usually related to normal saline conditions, unaffected or only moderately affected by siliciclastic influence (e.g. Murray, 1991). The HzTQT assemblage is characterized also by a higher content of *A. lessoni* (Fig. 5), which is typical of coral reefs and carbonate hard substrates. This species, therefore, occurs under warm and clear water conditions shallower than 30 m depth (Sen Gupta, 1999).

This change suggests that salinity was closer to normal marine conditions and that continental siliciclastic input from distributary channels would have significantly been reduced, probably as the result of the migration of these channels associated with the Pliocene Magdalena River paleodelta.

## 7. Planktonic foraminifera and age

Planktonic foraminifera were used to determine the age of the succession. However, the recovery of planktonic foraminifera was very poor, and characterized by the conspicuous absence of keeled forms (e.g. *Globorotalia tumida* plexus) and the dominance of *Globigerinoides* spp.; the only genera that can be common in marginal marine environments because of their life cycle is restricted to the upper water column (e.g. Hemleben et al., 1989).

Despite of low recovery, the co-occurrence of *Globigerinoides rubra*, *Globigerinoides obliqua*, and *Globorotalia conomiozea* cf. *Globorotalia subconomiozea*, in samples 29 and 30 (upper segment; Figs. 3b and 7), corresponds to the top of N-18 and N-19 Zones *sensu* Bolli and Saunders (1985), the upper part of MIR-6 Zone *sensu* Rincón et al. (2007), and partly coinciding with the PL-1 Zone by

Berggren et al. (1995), thus, suggesting that at least Segment C is Early Pliocene in age (Fig. 8).

On the Caribbean realm, the re-appearance of *G. rubra* (d'Orbigny) occurs during the Early part of the Early Pliocene (Bolli and Saunders, 1985), while the extinction of *G. obliqua* (Bolli) occurs roughly before Bolli and Saunders (1985)'s *Globorotalia margaritae* N-20 Early Pliocene Zone.

## 8. Magdalena river paleodelta system during the early pliocene

The reduction of continental siliciclastic input from distributary channels at the Arroyo Piedras Section during the Early Pliocene could be the result of the migration of Magdalena River paleodelta system. This migration could be the consequence of either autocyclic or allocyclic processes. Autocyclic processes, which are intrabasinal in origin and are related to the sedimentological behavior of the depositional system, including lobe switching and river avulsion and apparently were less important than allocyclic processes. Allocyclic processes are extrabasinal in origin (e.g. Bhattacharya and Walker, 1992) and may include:

### 8.1. Eustasy

As indicated above, the Arroyo Piedras section corresponds to a typical succession of fluvial-dominated delta affected by transgression (e.g. Bhattacharya and Walker, 1992). The marine to brackish marginal marine environments would correspond to the progradational delta phase (Segments A–B), whereas the upper part (Segment C), would correspond to a transgressive deposit accumulated over a transgressive surface (Fig. 7). This is in contrast to the widely recognized eustatic sea level drop that occurred during the Early Pliocene (~5.5–4.0 Ma; Miller et al., 2005). Therefore a different cause should be sought to the transgressive character of the succession (Fig. 7) as discussed below.

### 8.2. Tectonics

Tectonics could affect the Magdalena paleo-River by a) increasing the sediment yield in response to the upheaval of the

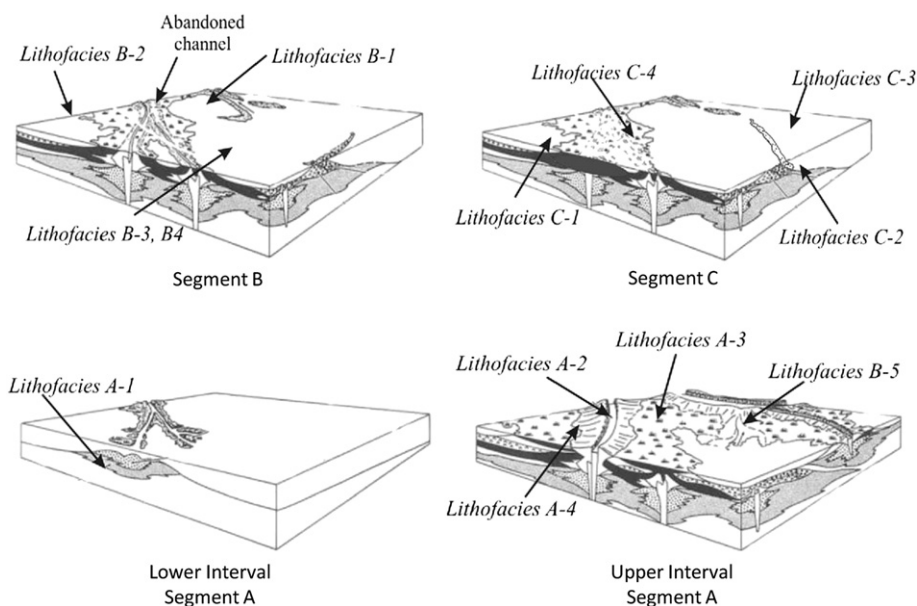
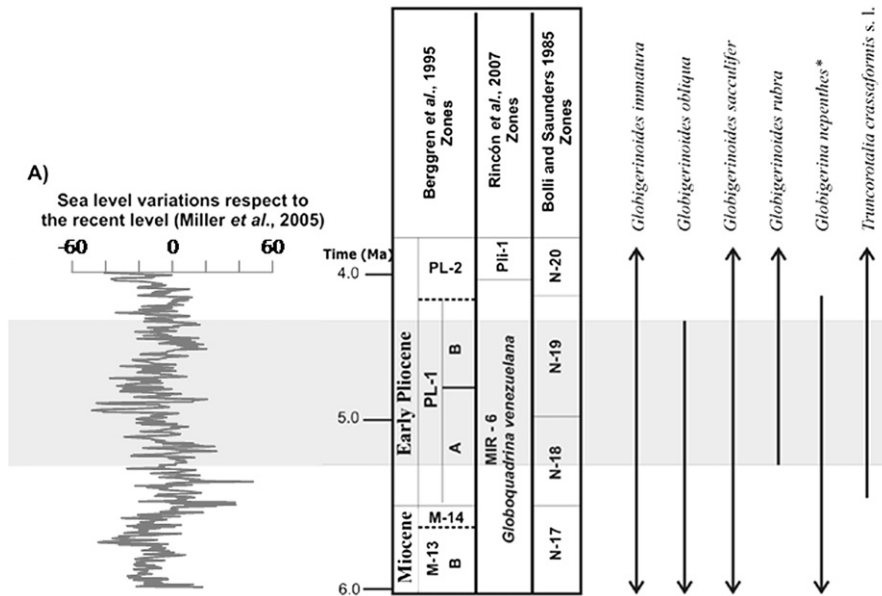


Fig. 7. Arroyo Piedras section (Tubará, northern Colombia). Schematic diagrams that illustrate the possible paleo-environmental evolution of the Arroyo Piedras succession, during the Early Pliocene (Modified from Horne et al., 1978).



**Fig. 8.** Sea level variation during the Early Pliocene with respect to the recent sea level, data from Miller et al. (2005). The shadow area represents the age ( $\sim 4.3$ – $5.3$  Ma), by the time of accumulation of Segment C. Age assignment based in bio-chronostratigraphy model proposed by Berggren et al. (1995) and the stratigraphic ranges of planktonic species when compared to, local (Rincón et al., 2007) and regional (Bolli and Saunders, 1985) biostratigraphic schemes. Arrows represent those species with longer stratigraphic ranges. \**Globobuccina nepenthes* was not identified in this work but was previously reported by Bordone (1974).

northern Andes during the Early Pliocene (e.g. Van der Hammen et al., 1973; Kellogg and Bonini, 1982; Kolla et al., 1984; Pince et al., 2003; Mora et al., 2008). b) Altering the potential sediment reception areas near to the Arroyo de Piedras site (e.g. Totto and Kellogg, 1992). Continental erosion might reflect both tectonic uplift (e.g. Raymo et al., 1988) and climate change (Molnar and England, 1990). Harris and Mix (2002) observed, however, that changes in accumulation rates of Late Cenozoic terrigenous sediment from the Amazonas river basin are mainly driven by climate rather than by tectonic events. Tectonics plays a significant, but possible secondary role, by shaping the drainage basin to include regions in which climate is more favorable to erosion (Harris and Mix, 2002).

Late Miocene to Early Pliocene tectonic events have been supported by stratigraphical, paleobotanical, thermochronological, and geochronological data (e.g. Shagam et al., 1984; Helmens and Van der Hammen, 1994; Hooghiemstra and Van der Hammen, 1998; Hoorn et al., 1995; Mora et al., 2008; Bayona et al., 2008). However, these Early Pliocene uplift pulses would produce a topographic relief that would lead to more erosion and an increase in sedimentation rates, which is opposite to the evidence presented herein.

Furthermore, the uplift pulses of the northern Sinu and San Jacinto fold belts (e.g. Duque-Caro, 1979, 1984; Molina et al., 1986; Totto and Kellogg, 1992; Flinch, 2003), located southwest of the Magdalena delta would have reduced the accommodation space, thus producing a regressive succession rather than a transgressive one as described herein.

### 8.3. Regional climate

Precipitation regimes in northern South America, at present, are mostly caused by the seasonal, and latitudinal migration of the Intertropical convergence zone (ITCZ) and the intra-annual variability of El Niño Southern Oscillation (ENSO) phenomenon. During the Northern Hemisphere summer the ITCZ is located over

northern Colombia and the Central American isthmus. Conversely, during the winter it is located over the Amazon basin, southern Colombia and Ecuador (Poveda et al., 2006). Climate variability also correlates with extreme phases of the ENSO phenomenon. Seasonal cross-correlation analyses show that El Niño events produce longer and drier dry seasons, whereas La Niña events produces wetter rainy seasons (Poveda et al., 2006; Restrepo and Kjerfve 2000a, b).

ENSO variability correlates to changes in climate and river flow on distant regions (e.g. Probst and Tardy, 1989; Waylen et al., 1996; Vörösmarty et al., 1996; Peterson and Haug, 2006). For northern South America, Restrepo and Kjerfve (2000b) clearly show that the Magdalena River's water discharge and sediment load are strongly coupled to the El Niño and La Niña phases. For northern South America, Restrepo and Kjerfve (2000b) show that the Magdalena River's water discharge and sediment load are strongly coupled to the El Niño and La Niña phases. For example, the 1988–1989 Niña event resulted in an increase in the Magdalena River's sediment load, whereas low sediment loads occurred during the 1977–1978, 1982–1983 and 1991–1992 El Niño events (Restrepo and Kjerfve, 2000b). The mean daily sediment load during La Niña years double in amount those during El Niño years with concentrations of  $511 \text{ t day}^{-1}$  and  $256 \text{ t day}^{-1}$ , respectively (Restrepo and Kjerfve, 2000b).

Data from the tropical Pacific (Chaisson, 1995; Wara et al., 2005; Ravelo et al., 2006; Fedorov et al., 2006) show that surface water temperature and depth of the thermocline resemble permanent El Niño conditions, during the warm Early Pliocene. Furthermore, land records (DeMenocal, 1995; Molnar and Cane, 2002) on distant regions also show climate conditions associated with a permanent El Niño event during the Early Pliocene. Permanent El Niño conditions would reduce the Magdalena River's sediment load during the Early Pliocene as can be seen under modern conditions. This sediment load reduction during the Early Pliocene would, therefore, be reflected in the transgressive pattern observed in the upper segment of the Arroyo de Piedras section. However, the explanation for the change in the course of the Magdalena River by



this time could rely on autocyclic processes. This hypothesis could be completely discarded by studying more surrounding stratigraphic sections.

## 9. Conclusions

From the stratigraphic and micropaleontological study of the Tubura Formation at the Arroyo Piedras section it is concluded that:

The succession is divided in three segments. The lower segment A is interpreted as the result of siliciclastic sedimentation in a proximal prodelta/delta plain transition. The intermediate segment B is interpreted as the result of sedimentation on a lagoon and/or coastal swamps, whereas the upper Segment C is interpreted as the product of deposition at a foreshore/upper shoreface transitional environment, where the continental input was drastically reduced.

The regressive succession from outer shelf to coarse-grained marginal marine environments, previously reported by [Bordine \(1974\)](#), would correspond to Segments A and B described herein, whereas the overlying transgressive Segment C would correspond to Zone II reported by [Redmond \(1953\)](#).

The transgressive Segment C is dated as Early Pliocene. Eustasy and tectonic changes do not explain the decreased continental input during the Early Pliocene interpreted from the Arroyo Piedras section. A permanent El Niño-like condition during the Early Pliocene could lead to a decrease in sediment delivery to the delta seems to agree with the described sedimentary succession. Thus, climate together with autocyclic processes could explain the collapse of the Magdalena delta in the Arroyo de Piedra region during the Early Pliocene.

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