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## **Low-Latitude Miocene Calcareous and Siliceous Microfossil Biostratigraphy from NW South America: Ladrilleros-Juanchaco Section, Colombian Pacific**

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**Abstract.** The Neogene sedimentary basins of the Colombian Pacific coast were formed in forearc basins associated with the uplift of the Andes. In this area, some marine sequences remain unexplored and are marked by a lack of biostratigraphic information. Additionally, available high-resolution biostratigraphic and biochronologic data from this region are limited almost exclusively to open sea research conducted by the Integrated Ocean Drilling Programs (IODP). The Ladrilleros-Juanchaco section is a continuous and well-exposed marine terrigenous sedimentary sequence with abundant Miocene microfossils. Biostratigraphic and biochronologic studies with calcareous nannofossils, planktonic foraminifera and diatoms carried out there revealed the presence of seventeen astronomically calibrated and standard calcareous microfossil biohorizons as well as two tropical diatom biozones. Such information enabled the establishment of a chronologic framework between the Base of *Praeorbulina glomerosa* and *Catinaster coalitus* Base, corresponding to 16.27 and 10.79 Ma, respectively (Burdigalian–Tortonian). The proposed biozonation favoured the observation of a high correlation between low-latitude planktonic foraminifera and calcareous nannofossil bioevents whereas diatom biozones and calcareous nannofossil biohorizons are marked by variations since the lowest occurrence of diatoms around 12.2 Ma. Furthermore, by means of interpolating age between the *Sphenolithus heteromorphus* Top and *Fohsella praefohsi* Base bioevents, the fact that the *Reticulofenestra pseudoumbilicus* (>7 µm) Base common took place around 13.6 Ma is interpreted and correlated with other sites, therefore revealing that it can be considered a good bioevent for the base of the Serravallian in these tropical areas.

**Key words.** Neogene. Calcareous nannofossils. Planktonic foraminifera. Diatoms. Forearc basin.

**Resumen.** BIOESTRATIGRAFÍA DE MICROFÓSILES CALCÁREOS Y SILÍCEOS DEL MIOCENO EN BAJAS LATITUDES DEL NW DE SUR AMÉRICA: SECCIÓN DE LADRILLEROS-JUANCHACO, PACÍFICO COLOMBIANO. El relleno sedimentario del Neógeno de las cuencas de antearco del Pacífico Colombiano está estrechamente relacionado con la dinámica tectónica de los Andes y los cambios paleoceanográficos que ocurrieron durante el Cenozoico. Las unidades marinas en el área permanecen inexplicadas y carecen de estudios bioestratigráficos detallados. Los trabajos de este tipo en la zona están restringidos a los realizados en las campañas del *Integrated Ocean Drilling Programs* (IODP) en el Pacífico ecuatorial oriental. La sección de Ladrilleros-Juanchaco es una secuencia continua y bien expuesta con abundantes microfósiles del Miocene que pueden llenar este vacío en la información. El análisis bioestratigráfico y biocronológico de nanofósiles calcáreos, foraminíferos planctónicos y diatomas ha permitido generar un modelo de edad de media-alta resolución, identificando 17 bioeventos bioestratigráficos estándares calibrados astronómicamente en estudios previos. Esto permitió establecer un modelo de edad y establecer el tiempo de sedimentación entre los bioeventos *Praeorbulina glomerosa* Base y Base de *Catinaster coalitus*, correspondientes a 16.27 y 10.79 Ma (Burdigaliense–Tortoniense, respectivamente). Por otro lado, la biozonación propuesta facilitó observar una alta correlación entre los biohorizontes de nanofósiles calcáreos y foraminíferos planctónicos, mientras que el nanoplancocentro y las biozonas de diatomas tropicales demuestran variaciones desde su aparición a los ~12.2 Ma. Además, por medio de la interpolación entre los bioeventos *Sphenolithus heteromorphus* Top y *Fohsella praefohsi* Base se logró estimar la edad del Base común de *Reticulofenestra pseudoumbilicus* (>7 µm) a ~13.6 Ma. Esta edad había sido propuesta anteriormente, sin embargo no se le había dado importancia a este bioevento.

**Palabras clave.** Neógeno. Nanofósiles calcáreos. Foraminíferos planctónicos. Diatomas. Cuenca de antearco.

THE Neogene sedimentary record of western Colombia proves a critical component when understanding the tectonic/sedimentary processes related to the uplift of the Andes and the formation of the Panama Isthmus during the

Neogene (Duque-Caro, 1990a,b; Coates *et al.*, 2004; Farris *et al.*, 2011; Montes *et al.*, 2012; 2015; Villagómez and Spikings, 2013; Echeverri *et al.*, 2015). Dense tropical forests and the lack of outcrops make geological research

in this region difficult. Additionally, continuous and fine-grained sequences are not common due to the tectonic episodes that occurred during the Miocene in the north of South America (Ramos, 2009). However, along the Colombian Pacific coastal cliffs, between the towns of Ladrilleros and Juanchaco, outcrops one of the best-exposed Miocene sections consisting of mudrocks and sandstones with abundant and well-preserved calcareous microfossils (foraminifera and calcareous nannofossils) and diatoms (Fig. 1).

Available biostratigraphic and biochronologic data for western Colombia is limited almost exclusively to information yielded by the Integrated Ocean Drilling Programs (IODP) (Houghton, 1989; Shackleton *et al.*, 1995; Flores *et al.*, 2006). Other sources of information include unpublished biostratigraphic studies from private company oil wells (Haffer, 1967; ANH-Servigecol, 2008; ANH-Universidad de Caldas, 2011). Some results from these wells focus mainly on

cutting samples, thus rendering biostratigraphic studies problematic, especially when defining biohorizon levels (Duque-Caro, 1990a).

Local biostratigraphic studies on land sections have focused on palynology as well as on planktonic and benthic foraminifera, hence revealing an absence of integrated biostratigraphic works on marine sequences around low-latitude Pacific coasts (Haffer, 1967; Duque-Caro, 1990a; Koizumi, 1992; Montoya, 2003; ANH-Servigecol, 2008). The aim of this study is to present, for the first time, an integrated biostratigraphic and biochronologic framework of the northern South America Miocene interval via the use of several micropalaeontologic proxies such as calcareous nannofossils, planktonic foraminifera and diatoms. It is also the first biostratigraphic study of Neogene marine beds in Colombia using marine diatoms. With these new results, future geological models and palaeoceanographic reconstruc-

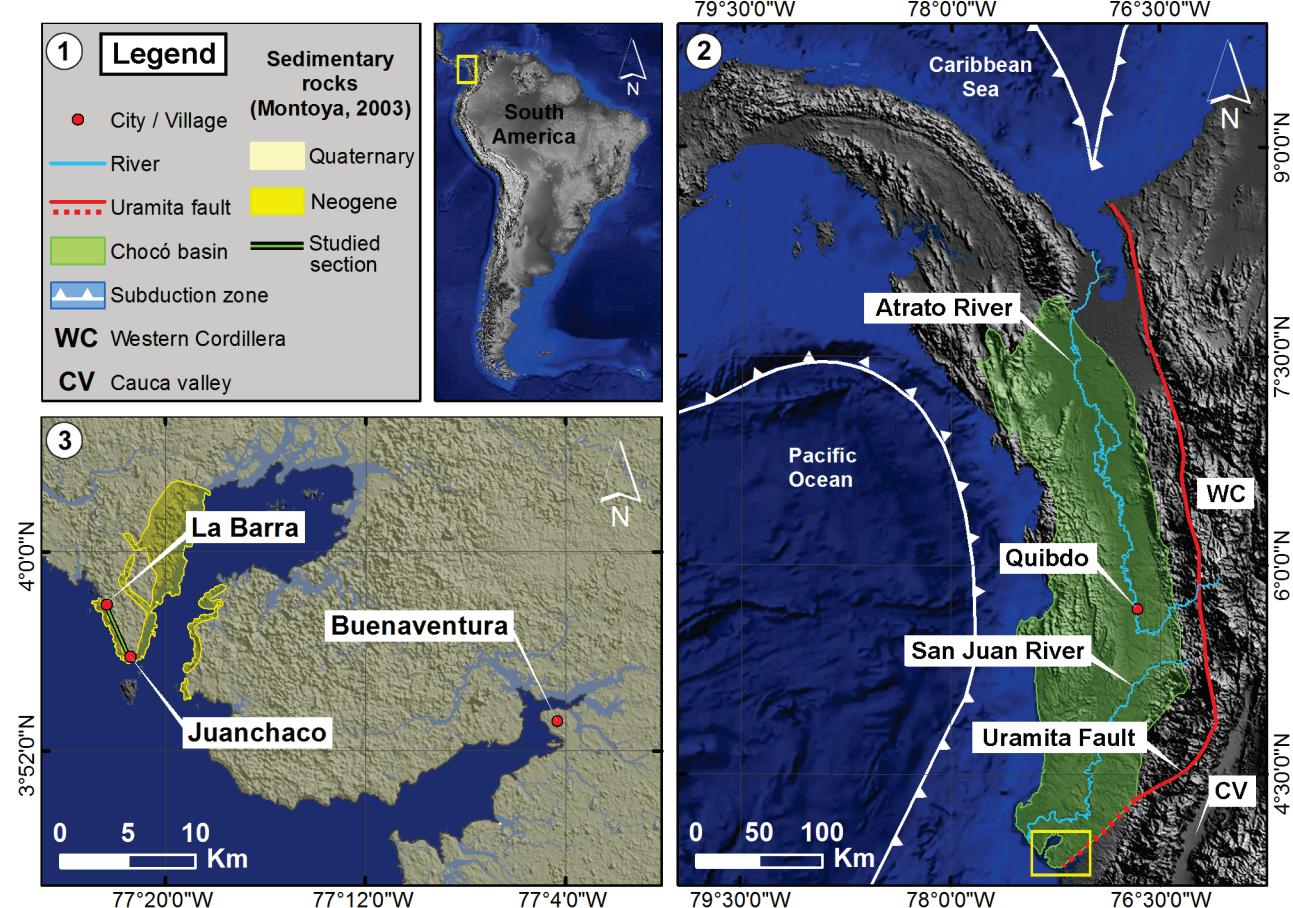


Figure 1. 1–2, Location map; 3, general geology of the Ladrilleros-Juanchaco section. Geological map modified from Montoya (2003).

tions will boast a well-dated marine section in a strategic area of South and Central America.

## GEOLOGICAL FRAMEWORK

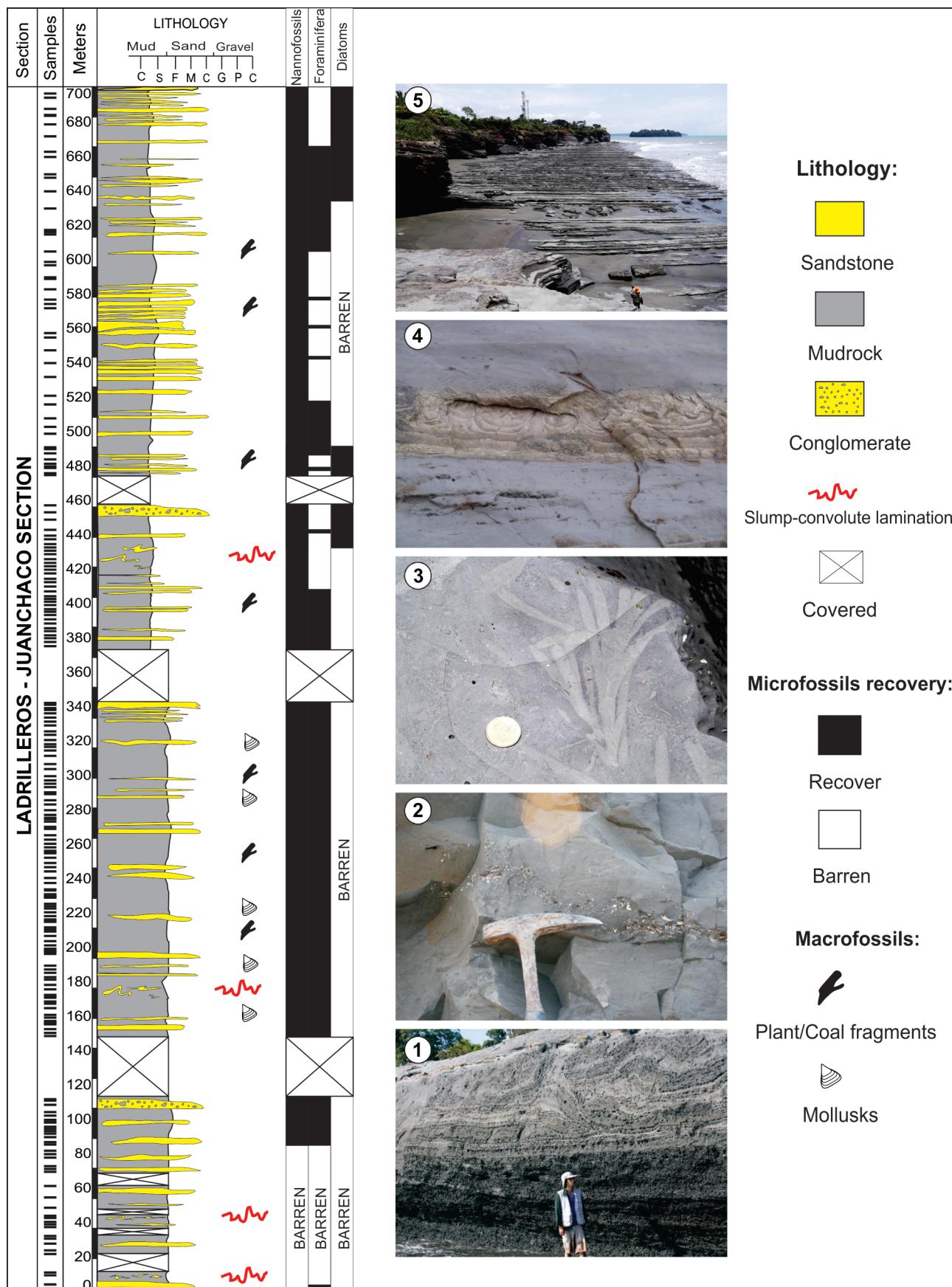
The geology of Colombia has been interpreted as a series of tectonic blocks juxtaposed through Paleozoic and Cenozoic times (Restrepo and Toussaint, 1988; Kerr *et al.*, 1996; Cediel *et al.*, 2003; Moreno-Sánchez and Pardo-Trujillo, 2003; Kennan and Pindell, 2009; Villagómez *et al.*, 2011). These tectonic blocks formed the Andean chain, which in Colombia branches into three Cordilleras, *i.e.* Eastern, Central and Western (Fig. 1). The Western Cordillera is mainly composed of Cretaceous volcanic and marine sedimentary rocks partially covered with Cenozoic volcanoclastic and siliciclastic units that are part of at least two allochthonous provinces: 1) the Caribbean Large Igneous Province and 2) the Panamá-Chocó Block (Duque-Caro, 1990a; Kerr *et al.*, 1996; Nivia, 2001; Villagómez *et al.*, 2011). Previous works propose that these provinces were accreted against NW South America via Cretaceous to Miocene collisional events (Restrepo and Toussaint, 1988; Duque-Caro, 1990b; Collins *et al.*, 1996; Spikings *et al.*, 2001; Moreno-Sánchez and Pardo-Trujillo, 2003; Coates *et al.*, 2004; Pindell and Kennan, 2009; Ramos, 2009; Villagómez *et al.*, 2011; Farris *et al.*, 2011; Montes *et al.*, 2012, 2015; Villagómez and Spikings, 2013). The studied section is part of the sedimentary fill of the Chocó Basin, which is located near the southern limit of the Panamá-Chocó Block (Duque-Caro, 1990b; Cediel *et al.*, 2003; Barrero *et al.*, 2007; Fig. 1). Information about the boundaries of the western sedimentary basins of Colombia and their geological evolution is still debated. The geology of the area consists of igneous and marine sedimentary rocks intruded by Eocene calc-alkaline magmatic bodies that were deformed during the Oligocene-Miocene (Duque-Caro, 1990a,b; Cediel *et al.*, 2003; Moreno-Sánchez and Pardo-Trujillo, 2003; Farris *et al.*, 2011; Montes *et al.*, 2012). The sedimentary record of the basin suggests the occurrence, during the Neogene, of a regional transition from an oceanic to a continental environment with regional unconformities in a forearc setting (Nivia, 2001; Borrero *et al.*, 2012). Earlier works assigned the name "*Sedimentitas de Ladrilleros*" to this section and reported a Pliocene age based on foraminifera and lithostratigraphic correlations (Montoya, 2003).

## LITHOSTRATIGRAPHY

The Ladrilleros-Juanchaco section is a ~700 m thick Miocene sedimentary sequence outcropping between the Ladrilleros and Juanchaco towns on the Colombian Pacific coast, in the southernmost part of the Chocó basin (Barrero *et al.*, 2007; Figs. 1–3). This sedimentary succession is mainly composed of gray mudrocks interbedded with thin beds of sandstones (Montoya, 2003; ANH-Servigecol, 2008; ANH-Universidad de Caldas, 2011; Fig. 2). In general, gradual changes in the frequency and size distribution of the sandstone beds constitute the most remarkable feature in the section. The mudrocks are thick beds, gray in colour and strongly bioturbated, therefore obscuring the identification of the original sedimentary structures (Fig. 2.1–3). Bivalves and gastropods are concentrated in the thin levels (Fig. 2.2). Charred woody debris and leaf remains are also present. Calcareous concretions are recognised in several levels. Among the ichnofossils, some of the reported genera are *Zoophycos*, *Chondrites*, *Cosmophaphe*, *Paleodictyon*, *Planolites* and *Spirophyton* (ANH-Servigecol, 2008; ANH-Universidad de Caldas, 2011; Fig. 2.3). The sandstones are tabular and medium to thin in thickness, at times irregular and/or lenticular beds, fine to very fine in grain and composed of lithic fragments. Also, they can be either structureless or laminated (mainly plane-parallel or ripple lamination) and present different degrees of bioturbation (Fig. 2). Thick beds of medium to coarsely grained sandstones in some cases conglomeratic at the base occur in low proportions (Fig. 2). Graded bedding and internal lamination are also common, thus favouring comparisons with Ta-b, Tb-e Bouma turbidites (ANH-Servigecol, 2008) in which mud intraclasts are common. Some levels reveal metric-scale soft-sediment deformation structures such as load casts, slumps and convolute bedding (Fig. 2.1–4). Towards the upper part, the frequency of sandstone beds notoriously increases (Fig. 2.5).

## MATERIALS AND TECHNIQUES

Biohorizons or biostratigraphic ranges considered herein are based on changing taxa-abundance patterns as well as on microfossil assemblages from low latitudes and tropical areas. These changes may represent the Base (B), Top (T), Base common (Bc) and Top common (Tc) of the taxa record. Besides, the astronomical scale used in Lourens *et al.*



(2004), Wade *et al.* (2011), Backman *et al.* (2012) and Hilgen *et al.* (2012) was resorted to for the assignment of biohorizons ages. Previous micropalaeontologic results from the oceanographic expeditions DSDP Leg-85, ODP Leg-138 and IODP-Expedition 320/321 were also drawn upon for establishing the age model.

### **Calcareous nannofossils**

For the study of calcareous nannofossils, two hundred samples were collected at intervals of two and four metres (Fig. 2). These samples were prepared following the decantation method of Flores and Sierro (1997) and analysed using a polarised light microscope (1000x) at the Universidad de Salamanca (Spain). Abundant calcareous nannofossils were obtained when counting 500 specimens in random fields of view, in agreement with the ecologic load (>1%) (Fatela and Taborda, 2002). Our biostratigraphic results correspond to the calcareous nannofossil standard biozones proposed for the Miocene by Martini (1971)-NN: Nanno-plankton Neogene; Okada and Bukry (1980)-CN: Neogene Coccolith; (Backman *et al.*, 2012)-CNM: Calcareous Nannofossils Miocene, and the astrobiochronological calibration described by Raffi *et al.* (2006) and Backman *et al.* (2012).

### **Planktonic foraminifera**

A quantitative study of planktonic foraminifera was performed with the same two hundred samples which were used for calcareous nannofossil analyses (Fig. 2). The samples were firstly dried and weighed and then sieved using a 150 and 63 µm mesh. All specimens larger than 150 µm were considered. More than 100 specimens were identified and counted in each sample split (Fatela and Taborda, 2002). The taxonomic identification of the specimens follows the descriptions proposed by Kennett and Srinivasan (1983). The total number of specimens counted in the tested samples was extrapolated to the total dry weight to obtain the number of planktonic foraminifera per gram. The biohorizons identified follow the zonal schemes defined by Blow

(1969)-N: Neogene and Berggren *et al.* (1995)-M: Miocene and the astronomical calibrations proposed by Lourens *et al.* (2004) and Wade *et al.* (2011).

### **Diatoms**

For diatom analyses, 98 samples were prepared (Fig. 2). The dried samples (1 gram) were treated with hydrogen peroxide for organic matter removal and sediment disintegration. Clay and carbonate particles were removed with polyphosphate and diluted hydrochloric acid, respectively. For diatoms, the standard decantation method, which allowed us to calculate the absolute value of valves per gram, was applied. An OPTIKS microscope set at 1000x was used in order to classify and count approximately 300 specimens per sample. In this study, diatom biozones follow low latitudes and tropical areas schemes proposed by Burckle (1972), Baldauf (1985), Barron (1985a,b, 1992), and Baldauf and Iwai (1995). Traditionally, diatom biozones have been calibrated by means of different palaeomagnetic scales (Berggren *et al.*, 1985; Cande and Kent, 1992; Baldauf and Iwai, 1995). Nevertheless, the Astronomically Tuned Neogene Time Scale (ATNTS2004) proposed by Lourens *et al.* (2004) was adopted herein.

## **RESULTS**

Seventeen calcareous nannofossils and planktonic foraminiferal bioevents were recognised (Fig. 3; Tab 1). Based on the appearance of *Praeorbulina glomerosa* (Base) and *Catinaster coalitus* Base, the sequence can be located between the Burdigalian and the Tortonian (16.27 and 10.79 Ma, respectively; Fig. 3). Although diatom bioevents were not recognised, the assemblages of associations *Coscinodiscus lewisiatus* and *Craspedodiscus bcoscinodiscus* suggest a Miocene age in accordance with tropical diatom biozones. While reworked microfossils in the section are a minimum, reworked Langhian–Serravallian taxa such as *Cyclicargolithus floridanus* and *Fohsella peripheroaranda* were found in the upper part of the section (Fig. 3; Tab. 1).

**Figure 2.** Lithostratigraphic summary of the Ladrilleros-Juanchaco section showing principal lithologies and microfossil recovery: 1, 4, soft-sediment deformation structures; 2, mollusk level; 3, interval with high grade of bioturbation; 5, high frequency of sandstone layers.

### Biostratigraphy and biochronology of calcareous microfossils

**Burdigalian.** The Base of *P. glomerosa* and *Globorotalia archeomenardii* are, at around 68 m from the base of the section (Fig. 3; Tab. 1), the first bioevents to be recognised in the sequence and were found shortly after a barren interval with low and discontinuous values regarding abundance (Fig. 3). *Globorotalia archeomenardii* presents higher abundance values and a more continuous distribution pattern than *P. glomerosa*. According to Lourens *et al.* (2004) and Hilgen *et al.* (2012), the first evolved shape of *P. glomerosa* occurred near the base of the Langhian, in the N8 (M5a)

biozone (Fig. 3). Nevertheless, Lourens *et al.* (2004) resorted to both bioevents, the Base of *P. glomerosa* and *G. archeomenardii*, to identify the top of the Burdigalian at 16.27 and 16.26 Ma, respectively (Tab. 1). Besides, this datum is corroborated by calcareous nannofossil taxa representative of the early Miocene such as *Helicosphaera ampliaperta*, which was observed in low proportion and with a discontinuous pattern at the base of the sequence (Fig. 3).

**Langhian.** Before an interval of the section thickly covered and just above the Base of *P. glomerosa* and *G. archeomenardii* B, the top of *H. ampliaperta* was observed at 93 m (Fig. 3). Even though such calcareous nannofossil marks the base

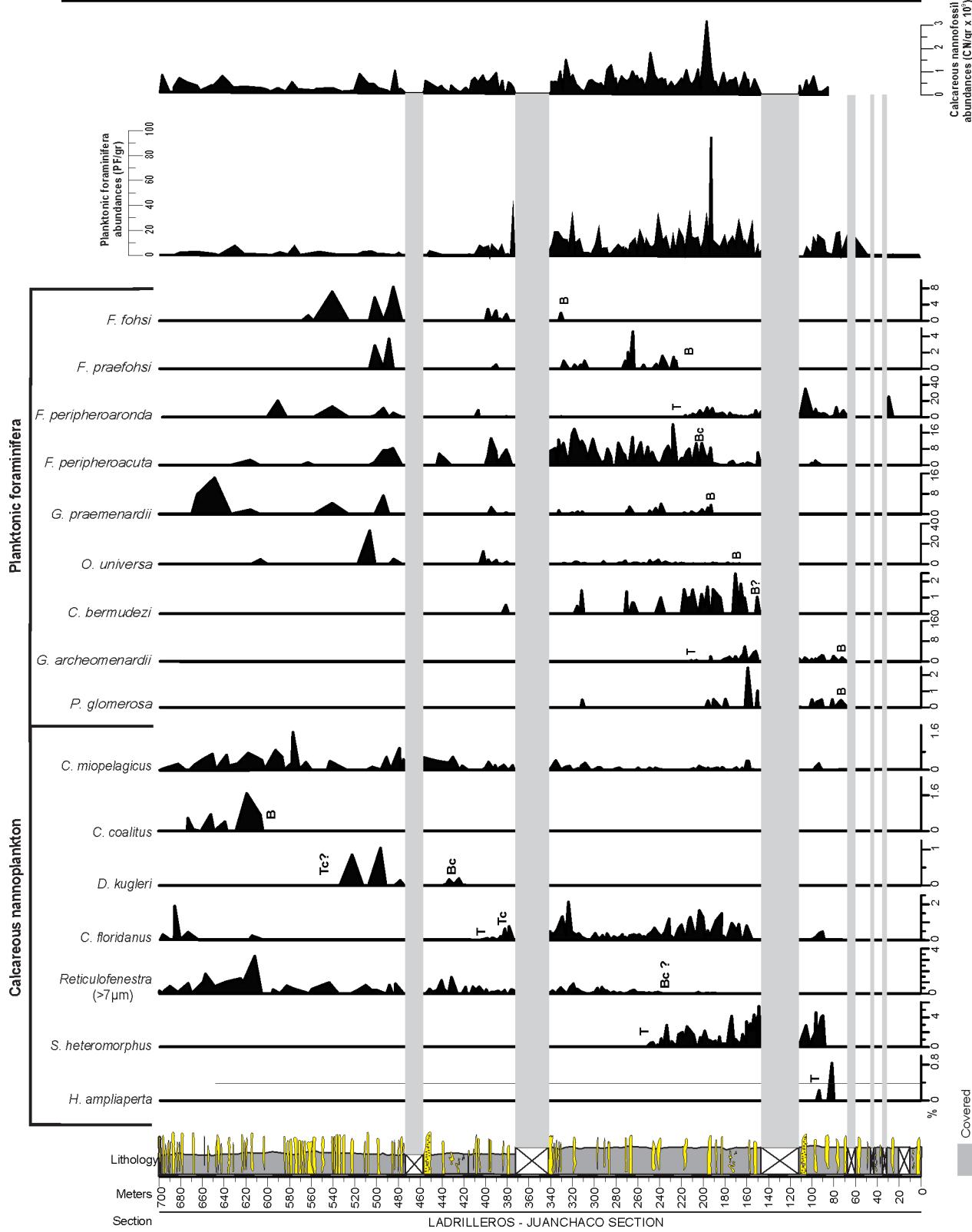
TABLE 1 – Summary of bioevents described at the Ladrilleros-Juanchaco sequence - CN: Calcareous nannofossils. PF: Planktonic foraminifera. B: Base, T: tope, Bc: Base common, Tc: Top common. Ref: References: 1. Backman and Raffi (1997); 2. Raffi *et al.* (2006); 3. Raffi *et al.* (1995); 4. Schneider (1995); 5. Wade *et al.* (2011); 6. Lourens *et al.* (2004); 7. Backman *et al.* (2012).

Microfossil	~Meters	Bioevent	Age (Ma)	Ref.
CN	602	<i>B C. coalitus</i>	10.79	1,2
CN	533	<i>Tc D. kugleri</i>	11.60	1,2
CN	421	<i>Bc D. kugleri</i>	11.88	1,2
CN	405	<i>Tc C. floridanus</i>	12.03	3,4
CN	390	<i>Tc C. floridanus</i>	13.29	3,4
PF	326	<i>B F. fohsi</i>	13.34	5
CN	250	<i>TS. heteromorphus</i>	13.53	1,2
CN	237	<i>Bc R. pseudoumbilicus (&gt;7µm)</i>	~13.6	*
PF	225	<i>B F. praefohsi</i>	13.74	5
PF	219	<i>TF. peripheroaronda</i>	13.77	5
PF	210	<i>TG. archeomenardii</i>	13.84	5
PF	205	<i>Bc F. peripheroacuta</i>	14.23	5
PF	193	<i>B G. praemenardii</i>	14.39	5
PF	166	<i>B O. universa</i>	14.74	6
PF	151	<i>B C. bermudezi</i>	15.76?	5
CN	93	<i>TH. ampliaperta</i>	14.86	7
PF	68	<i>B G. archeomenardii</i>	16.26	6
PF	68	<i>B P. glomerosa</i>	16.27	6

\* Age according to interpolation in this work.

Figure 3. Distribution patterns of selected calcareous microfossils for biostratigraphic analyses in the section. \*CN/gr= Calcareous nannofossils per gram of sediment.

Planktonic foraminifera biozones	Lourens et al. (2004)	?	N12	N11	N10	N9	N8	
		?	M9b	M8/M9a	M7	M6	M5b	M5a
Calcareous nannofossil biozones	Okada and Bukry (1980)	CN6	CN5b	CN5a	CN4	CN3		
	Martini (1971)	NN8	NN7	NN6	NN5	NN4		
	Backman et al. (2012)	CNM12	CNM11	CNM10	CNM9	CNM8	CNM7	

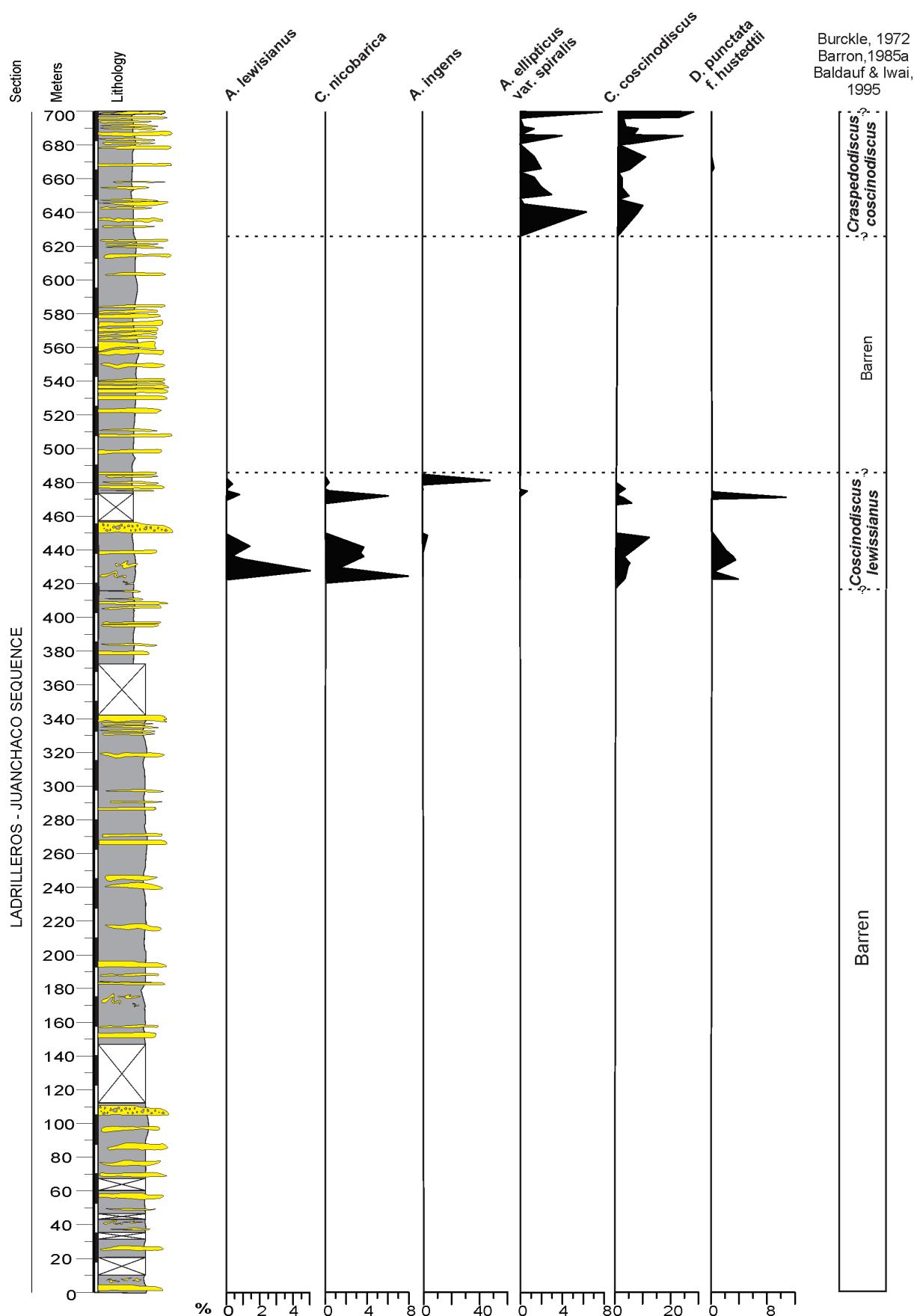


of the Langhian and the CN3/CN4 (NN4/NN5) boundary (Fornaciari *et al.*, 1997), some authors have demonstrated that this bioevent displays a regionally-controlled distribution and proves diachronous along the equatorial Pacific (Martini, 1971; Olafsson, 1991; Fornaciari *et al.*, 1993). Backman *et al.* (2012) reported the extinction age for *H. ampliaperta* at 14.86 Ma. Even so, our data reveal that most planktonic foraminiferal bioevents took place during this interval (Fig. 3). *Orbulina universa* B and the Base of *Globorotalia praemenardii*, which have been recognised near the M5b/M6 biozones, Langhian (Lourens *et al.*, 2004; Wade *et al.*, 2011), proved some of the first biohorizons observed in the section (Tab. 1). In effect, the recovery of *Clavatarella bermudezi* from the sequence indicates the base of the Langhian. However, the fact that its first occurrence is above a covered interval, makes such an assertion unreliable (Fig. 3; Tab. 1). Many authors described, for the middle Miocene, the extensive morphological change of the "*Fohsella* group" and its biostratigraphic value (Kennett and Srinivasan, 1983; Pearson and Chaisson, 1997). This transitional lineage involves non-keeled (*Fohsella peripheroaronda* and *Fohsella peripheroacuta*), partially keeled (*Fohsella praefohsi*) and completely keeled specimens (*Fohsella foehsi*) (Pearson and Chaisson, 1997; Turco *et al.*, 2002). In the Ladrilleros-Juan-chaco section, one of the first bioevents associated with these transitional shapes is *F. peripheroacuta* Bc, which occurred at 205 m (Fig. 3). Lourens *et al.* (2004) and Wade *et al.* (2011) proposed that this biohorizon might be used as a marker for the M6/M7 (N9/N10) boundary of 14.23 Ma of age (Fig. 3). In the studied material, the latest bioevent observed in this period is *G. archeomenardii*T (13.84 Ma; Wade *et al.*, 2011), which exhibits a similar behaviour to that of *P. glomerosa* and disappears about 210 m after *F. peripheroacuta* Bc (Fig. 3). Calcareous nannofossil species such as reticulofenestrids showed an increase in size during this period. In agreement with the taxonomic concept of Raffi and Rio (1979), we considered specimens exhibiting reticulofenestrids larger than 7 µm as *Reticulofenestra pseudoumbilicus* (Fig. 3). Although the Bc of *R. pseudoumbilicus*

set off with low abundances and discontinuous distribution patterns, its record after 237 m proved consistent and dominated by calcareous nannofossil assemblages in some levels (Fig. 3). Large forms of *Reticulofenestra* spp. can be observed near the extinction level of *S. heteromorphus*, near the CN4/CN5a (NN5/NN6) boundary, and just above the planktonic foraminiferal bioevents *F. peripheroaronda* T and *F. praefohsi* B (Fig. 3). Olafsson (1991) reported for the North Atlantic Ocean the first level of *R. pseudoumbilicus* after *S. heteromorphus* T. Yet, many studies have described this bioevent, for low-mid-high latitudes, before the extinction of *S. heteromorphus* in the upper part of the NN5 (CN4) biozone (Rio *et al.*, 1990; Fornaciari *et al.*, 1993; Raffi *et al.*, 1995; Shackleton *et al.*, 1995; De Kaenel and Villa, 1996; Kameo and Bralower, 2000; Marino and Flores, 2002).

**Serravallian.** The micropaleontologic analysis evinces a condensed interval of biostratigraphic events at the Langhian/Serravallian boundary (Fig. 3). The base of the Serravallian is well documented by two calcareous microfossil bioevents: the *S. heteromorphus* and *C. floridanus* extinctions at ~300 m. The Top of *F. peripheroaronda* was identified at 219 m, before the *F. praefohsi* B (Fig. 3), thus suggesting an age of 13.77 Ma (Wade *et al.*, 2011). *Foshella praefohsi* is considered an intermediate form between *F. peripheroacuta* and *F. foehsi* (Blow and Banner, 1966). This species was observed at 225 m with low and discontinuous abundance patterns (Fig. 3). Wade *et al.* (2011) calibrated *F. praefohsi* B at 13.74 Ma and used it as a marker of the N10/N11 boundary (Fig. 3; Tab. 1). The latest planktonic foraminiferal bioevent identified at the Ladrilleros-Juan-chaco section at around 326 m, is the Base of *F. foehsi*, which presented scattered and low abundance values (Fig. 3). The first appearance of *F. foehsi* indicates the boundary of the N11/N12 (M7/M8–M9a) biozones and has been dated by Wade *et al.* (2010) at 13.34 Ma. After the *F. foehsi* extinction, planktonic foraminiferal recovery proved low and sporadic (Figs. 2–5). On the other hand, because of the calcareous nannofossils, a biostratigraphic control for this part of the section was possible (Figs. 3–6). Tropical species such as *S.*

Figure 4. Distribution patterns of diatoms recovered from the Ladrilleros-Juanchaco section.



*heteromorphus* show a good preservation and a continuous distribution pattern. The Top of *S. heteromorphus* was identified at 250 m and its extinction is considered as the guide bioevent for the base of the Serravallian between the CN4/CN5a (NN5/NN6) biozones at 13.53 Ma (Fig. 3; Tab. 1; Backman and Raffi, 1997). The Tc and T of *C. floridanus* were also recorded around 390 and 405 m, respectively, and just above the extinction of *S. heteromorphus* (Fig. 3; Tab. 1; Hernández, 2015). *Cyclicargolithus floridanus* exhibits poor to moderate preservation with some reworked levels in the upper part of its record (Fig. 3). Controversial and low-abundance tropical species such as *Discoaster kugleri* (Raffi *et al.*, 1995) were recovered and displayed low abundances and sporadic occurrences. *D. kugleri* Bc was observed at 421 m, which suggests a late Serravallian age of around 11.88 Ma (Backman and Raffi, 1997).

**Tortonian.** Despite the fact that this interval of the section displayed an increase in terrigenous input which affected calcareous microfossil preservation and abundance, well-preserved low-latitude calcareous nannofossil biohorizons were also observed (Figs. 2–6). In this period, the earliest identified bioevent was T of *D. kugleri*, which was calibrated astrobiocronologically at 11.60 (Backman and Raffi, 1997). The Base of *Catinaster coalitus* was the last bioevent identified in the section and occurred at 602 m, near the Tc of *D. kugleri* (Fig. 3). This biohorizon was observed conjointly with reworked species from the early–middle Miocene such as *C. floridanus* and *F. peripheroaranda*. The Base of *C. coalitus* was dated by Backman and Raffi (1997) at 10.79 Ma (Tab. 1).

### Diatom biostratigraphy

Diatom recovery started with good preservation, a moderate -to low- abundance pattern and no reworking signals near the 400 m. Even though we could not identify biostratigraphic events, there are two well-defined diatom assemblages separated by a barren interval (Fig. 4). Barron (1985b) defined three tropical biozones: *Coscinodiscus*

*lewisianus*, *Coscinodiscus gigas* var. *diorama* and *Craspedodiscus coscinodiscus*, respectively, for this part of the Miocene. Only in the Ladrilleros-Juanchaco section, two diatom assemblages could be distinguished: *C. lewisianus* and *C. coscinodiscus* (Fig. 4).

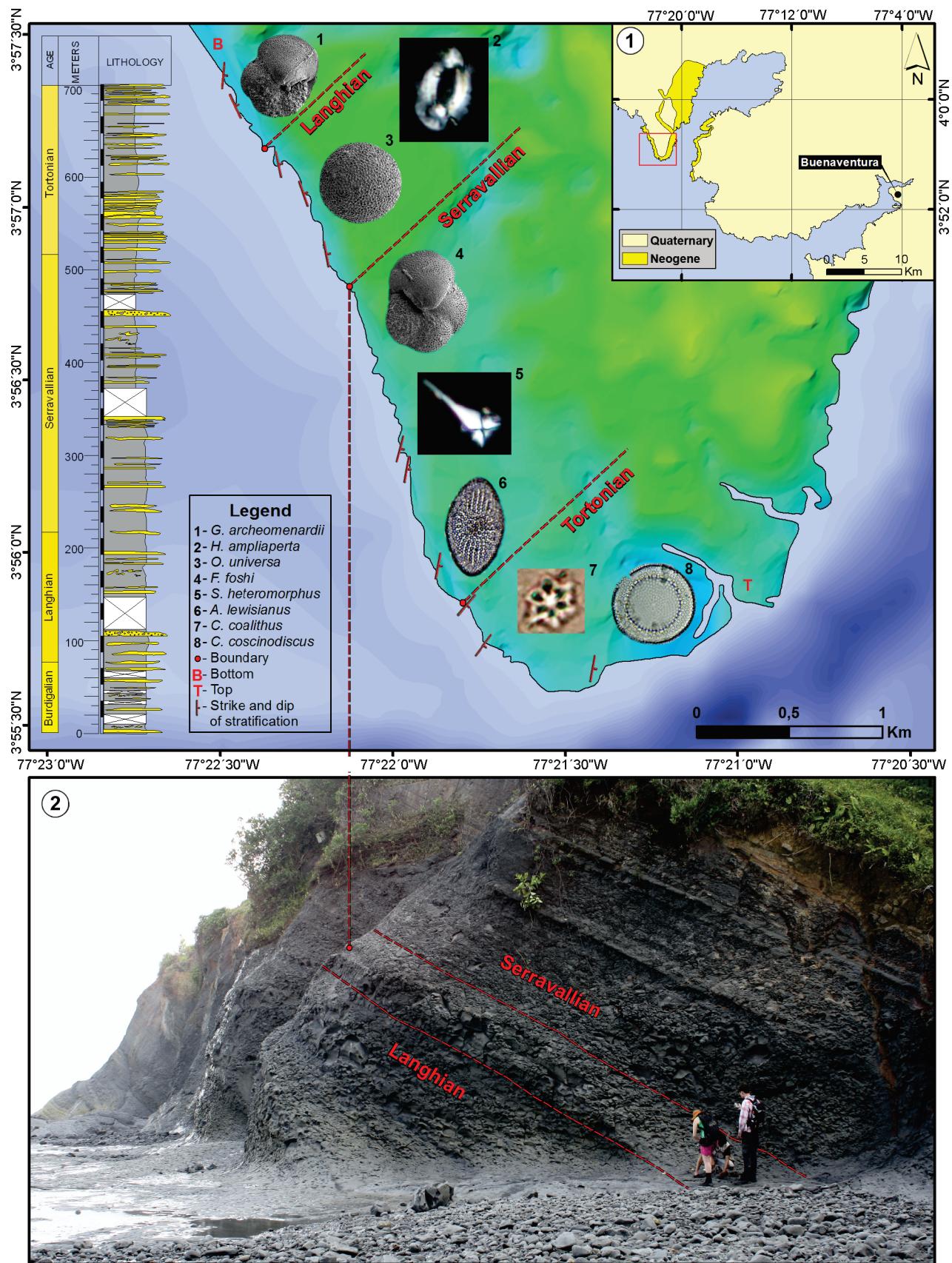
***Coscinodiscus lewisianus* biozone.** This biozone is located at 414–470 m (Fig. 4, 6). It is characterized herein by the recovery of *Araniscus lewisiatus*, *Crucidenticula nicobarica* and *Actinocyclus ingens*. According to Barron (1985b), this diatom assemblage is present in the *C. lewisianus* biozone. These species are continuous and abundant although poorly preserved. In agreement with the palaeomagnetic scale of Berggren *et al.* (1985), the *C. lewisianus* biozone is situated around 14.2 to 12.8 Ma. In accordance with the Cande and Kent (1992) time scale, the age of this biozone is calculated at 14.36 to 12.92 Ma. When considering the ATNTS2004 scale, the *C. lewisianus* biozone spans between 14.2 and 13.05 Ma (Fig. 4).

***Craspedodiscus coscinodiscus* biozone.** The second diatom biozone spans from 626.5 to 683.5 m and is located immediately on top of the barren interval (Fig. 4). The diatom assemblage observed in this biozone presents a continuous record of *C. coscinodiscus*, *Actinocyclus ellipticus* var. *spiralis* and *Denticulopsis punctata* f. *hustedtii*. These species have enabled the identification of the *C. coscinodiscus* biozone Barron (1985b). Based on the palaeomagnetic scales proposed by Berggren *et al.* (1985) and Baldauf and Iwai (1995), this biozone spans, in age, from 11.8 to 10.6 Ma and from 12.6 to 11.0 Ma, respectively. In agreement with Lourens *et al.* (2004), the *Craspedodiscus coscinodiscus* biozone is placed at 12.1 to 11.15 Ma (Fig. 4).

### DISCUSSION

Few integrated calcareous plankton and diatom data are reported from the on-land pacific marine sections in South America (Koizumi, 1992). In fact, biostratigraphic studies in Colombia have been restricted to palynology and foraminifera while being very limited regarding calcareous

**Figure 5.** General and detailed location of the section. Additionally, stratigraphic column information and biostratigraphic zonation are shown in the upper part, indicating the identified microfossil bioevents along the sequence (numbers 1–8). 2, Serravallian/Langhian boundary situated in the lower part of the section.



nannofossils (Haffer, 1967; Duque-Caro, 1990a; Montoya, 2003; ANH-Servigecol, 2008; ANH-Universidad de Caldas, 2011; Bedoya *et al.*, 2013). In this study, calcareous and siliceous marine microfossil results from on-land outcrops in the NW of South America are integrated (Fig. 5).

#### **Correlation between calcareous and siliceous microfossils**

In order to analyse the correlation between biostratigraphic schemes and biohorizons, we compared data gathered from planktonic foraminifera and diatoms with the continuous record of calcareous nannofossil bioevents found in the sequence (Fig. 5). In general, low-latitude planktonic foraminifera and calcareous nannofossils display a high correlation whereas diatom biozones and calcareous microfossil biohorizons are marked by some variations (Figs. 3–6). Later in the sequence, in the upper part of the Serravallian (~12.2 Ma), the diatom record suddenly sets off between the calcareous nannofossil biohorizons *D. kugleri* Tc and *C. floridanus* T (Fig. 4, 6). While Koizumi (1992) used the time scale proposed by Berggren *et al.* (1985) to calibrate diatom bioevents along the coasts of South America, we noted that our diatom recovery took place at the same time as it did in Ecuador, Peru and Chile, and may be a regional signal for the eastern Pacific. Barron (1985a) correlated the *C. lewisiatus* biozone with the CN4 and CN5a calcareous nannofossil schemes (NN5-NN6 of Martini, 1971) whilst our data suggest that this diatom assemblage is situated around the CN5a/CN5b biozones (Fig. 6). This boundary is well known for the *D. kugleri* Bc, which indicates an age of 11.88 Ma (Fig. 3; Tab. 1). Using the ATNTS2004 timescale, the extensiveness of the *C. lewisiatus* biozone is estimated to range from 14.2 to 13.05 Ma (late Langhian–early Serravallian). Nevertheless, results drawn from the Ladrilleros-Juanchaco section suggest a late Serravallian–early Tortonian age (Fig. 6). Similarly, Barron (1985a) associated the *C. coscinodiscus* biozone with the CN5b (NN7) and CN6 (NN8) calcareous nannofossil bioevents. The base of the NN8 biozone was identified with the Base of *C. coalitus*, a tropical calcareous nannofossil biohorizon calibrated at 10.79 Ma (Fig. 3; Tab. 1). The *C. coscinodiscus* biozone spans from 12.1 to 11.15 Ma (ATNTS2004 scale). Therefore, the recovery of *C. coalitus* from this interval of the section reveals a wider temporal range for the tropical diatom biozone (Fig. 6).

#### **Base common (Bc) of *Reticulofenestra pseudoumbilicus* (>7µm)**

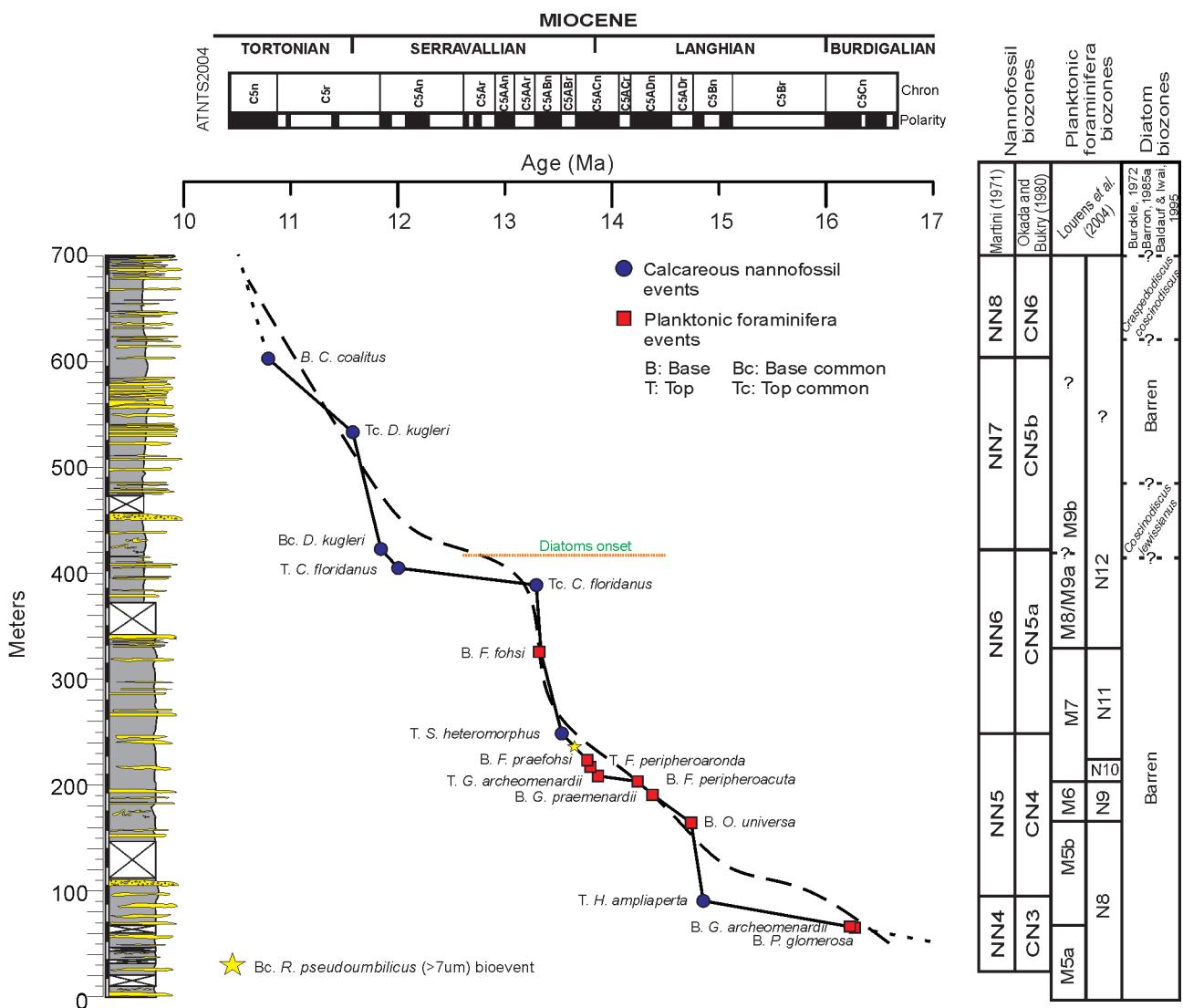
Large size reticulofenestrids with an open area from the Cenozoic ages have been named differently by several authors (Raffi and Rio, 1979; Backman, 1980; Perch-Nielsen, 1985; Pujos, 1987; Young, 1990). Nowadays, the principal classification of the species that conform this group of calcareous nannofossils is based on size and age (*i.e.*, distinction between Paleogene *R. pseudoumbilicus* and Neogene *R. pseudoumbilicus*), thus making taxonomic and biostratigraphic observations more complicated (Bown and Dunkley-Jones, 2012). Following such approach, we used the name *R. pseudoumbilicus* (= *Reticulofenestra* >7µm) for Miocene–Pliocene large reticulofenestrids (Raffi and Rio, 1979; Backman and Shackleton, 1983). The extinction of *Reticulofenestra* (>7µm) during the Zanclean and the virtually absent interval during the late Miocene convey fundamental biostratigraphic and biochronologic information for the late Neogene biochronological scale (Rio *et al.*, 1990; Raffi and Flores, 1995; Backman and Raffi, 1997; Shackleton and Crowhurst, 1997; Raffi *et al.*, 2006). Conversely, reliability regarding the first occurrence of *Reticulofenestra* (>7µm) has been argued based on the fact that the lowermost peaks of this species have been reported from younger biostratigraphic levels than those of the tropical zones for mid-latitude North Atlantic areas, above the *S. heteromorphus* T (Fornaciari *et al.*, 1990, 1993; Olafsson, 1991; Raffi *et al.*, 1995). In the Ladrilleros-Juanchaco section, the Bc of *Reticulofenestra* (>7µm) was found above the Top of *F. Peripheroaranda* and Base of *F. Praefohsi* as well as before the *S. heteromorphus* T (Figs. 3, 6; Tab. 1). Previous biostratigraphic results drawn from open sea research, including some obtained from mid–high southern latitudes, have conformed to the same stratigraphic position near the CN4/CN5a (NN5/NN6) boundary (Fornaciari *et al.*, 1990, 1993; Rio *et al.*, 1990; Raffi *et al.*, 1995; Shackleton *et al.*, 1995; De Kaenel and Villa, 1996; Kameo and Bralower, 2000; Marino and Flores, 2002; Pälike *et al.*, 2010). Although this bioevent has not been calibrated astronomically, palaeomagnetic studies conducted by Shackleton *et al.* (1995) in the eastern equatorial area, resulted in an age estimation of 13.88 Ma for the base of *Reticulofenestra* (>7µm). Interestingly, assuming that sedimentation rates were continuous for this period, our interpolation between

*S. heteromorphus* T and *F. praefohsi* B indicates an age of ~13.6 Ma for this biohorizon. Such age would suggest that the Bc of *Reticulofenestra* (>7 µm) may be used as a marker for the base of the Serravallian in the north of South America.

## CONCLUSIONS

The Ladrilleros-Juanchaco section is the first early-late Miocene mainland marine section in the northwest of South America to be biochronologically calibrated by means of calcareous nannofossils, planktonic foraminifera and diatoms. Seventeen calcareous nannofossils and

planktonic foraminiferal bioevents were identified, therefore suggesting a deposition time ranging from 16.27 to 10.79 Ma (Burdigalian–Tortonian). Low-latitude planktonic foraminifera and calcareous nannofossil bioevents present, in general, a high correlation while variations between diatom biozones and calcareous microfossil biohorizons were observed since its lowest record at ~12.2 Ma. The integrated section allowed us to estimate an age of ~13.6 Ma for the *R. pseudoumbilicus* (>7 µm) Bc, indicating a potential biohorizon in the north of South America for the base of the Serravallian.



**Figure 6.** Correlation between calcareous nannofossil, planktonic foraminifer, and diatoms bioevents found in the Ladrilleros-Juanchaco section.

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## SUPPLEMENTARY MATERIAL

List of species mentioned in the text are listed by alphabetical order.

### Calcareous nannofossils

- Catinaster coalitus* Martini and Bramlette, 1963
- Cyclcargolithus floridanus* (Tan 1927) Bramlette, and Riedel 1954
- Discoaster kugleri* Martini and Bramlette, 1963
- Helicosphaera ampliaperta* Bramlette and Wilcoxon, 1967
- Reticulofenestra pseudoumbilicus* (Gartner 1967) Gartner, 1969
- Sphenolithus heteromorphus* Deflandre, 1953

### Planktonic foraminifera

- Clavatarella bermudezi* Blow, 1965
- Globorotalia archeomenardii* Bolli, 1957
- Globorotalia peripheroacuta* Blow and Banner, 1966
- Globorotalia peripheroaranda*, Blow and Banner, 1966
- Globorotalia praemenardii* Cushman and Stainforth, 1945
- Globorotalia praefohsii*, Blow and Banner, 1966
- Globorotalia fohsi*, Cushman and Ellisor, 1939
- Orbulina universa* d'Orbigny, 1839
- Praebulina glomerosa* Blow, 1956

### Diatoms

- Actinocyclus ellipticus* var. *spiralis* Barron, 1985
- Actinocyclus ingens* Rattray, 1890
- Araniscus lewisanus* Greville, 1866
- Craspedodiscus coscinodiscus* Ehrenberg, 1844
- Crucidenticula nicobarica* (Grunow) Akiba and Yanagisawa, 1986
- Denticulopsis punctata* f. *hustedtii* (Schradter) Simonsen, 1979
- Coscinodiscus gigas* var. *diorama* (Schmidt) Grunow, 1884

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