Spanish Journal of Palaeontology

The *Phycosiphon* record in the Ladrilleros-Juanchaco section (Miocene, Colombian Pacific): palaeoecological implications

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Celis, S.A., Rodríguez-Tovar, F.J. & Pardo-Trujillo, A. 2018. The *Phycosiphon* record in the Ladrilleros-Juanchaco section (Miocene, Colombian Pacific): palaeoecological implications. [El registro de *Phycosiphon* en la sección Ladrilleros-Juanchasco (Mioceno, Pacífico de Colombia): implicaciones paleoecologicas]. *Spanish Journal of Palaeontology*, 33 (2), 277-288.

Manuscript received 20 December 2017
Manuscript accepted 29 June 2018

ABSTRACT

Miocene rocks of the Ladrilleros-Juanchaco section, located on the NW margin of South America, contain a high diverse and abundant trace fossil assemblage. The relative abundance of *Phycosiphon*, together with its morphological variations, provides new insights into the environmental conditions. Detailed outcrop stratigraphic, ichnological, and geochemical analyses carried out in the section focused on the trace fossil assemblages (distribution, relative abundance), ichnofabric index, and, especially, in the general ichnological features of *Phycosiphon*. In addition, the detailed photographic documentation and the use of the digital image treatment technique facilitate the precise study of particular ichnological properties.

Based on the stratigraphic analysis of the section, together with the abundance, size and distribution of the specimens of *Phycosiphon*, as well as the analysis of total organic carbon, the record of *Phycosiphon* is proved as related to the food content in the sediment, and then as a proxy in the study of ancient environments.

Keywords: Ichnology, *Phycosiphon*, Miocene, Ladrilleros-Juanchaco section, Colombia, palaeoecological and depositional conditions.

RESUMEN

La sección Ladrilleros-Juanchaco, de edad Mioceno, localizada en el margen NW de Suramérica, presenta alta diversidad y abundancia de icnofósiles. La relativa abundancia de *Phycosiphon*, junto con sus variaciones morfológicas abre una nueva línea de interés en la investigación paleoambiental. El detallado análisis estratigráfico e icnológico que se realizó en la sección, se centró en el estudio de las asociaciones de trazas fósiles (distribución, abundancia relativa) e índice de icnofábricas, y, especialmente, en las características icnológicas generales de *Phycosiphon*. Además, el registro fotográfico detallado y el uso de la técnica de tratamiento de imágenes facilitaron precisar algunas características icnológicas.

Sobre la base del estudio estratigráfico de la sección, junto con la abundancia, tamaño y distribución de los especímenes de *Phycosiphon*, así como el análisis de carbono orgánico total, se ha demostrado la relación entre el registro de *Phycosiphon* y el contenido de nutrientes en el sedimento, y, por tanto, su interés como indicador en estudios paleoambientales.

Palabras claves: icnología, *Phycosiphon*, Mioceno, sección Ladrilleros-Juanchaco, Colombia, condiciones paleoecológicas y deposicionales.

https://doi.org/10.7203/sjp.33.2.13603

1. INTRODUCTION

In tropical Eastern South America, Miocene strata have been increasingly studied in recent years, because their location retains valuable information about the geological history not only local, but also regional and possibly global by processes related to the uplift of the Andes, and the formation of the Panama Isthmus (e.g., Duque-Caro, 1990a, 1990b; Coates *et al*., 2004; Farris *et al*., 2011; Montes *et al*., 2012; 2015; Villagómez & Spikings, 2013; Echeverri *et al*., 2015; Vallejo *et al*., 2016; Plata *et al*., 2018; Duque-Herrera *et al*., 2018).

The Ladrilleros-Juanchaco section, located at the SW margin of Colombia (NW of South America) (Fig. 1), becomes of special interest to interpret the Colombian Pacific area, recently dated as Miocene (Burdigalian-Tortonian) in age (Vallejo *et al*., 2016; Plata *et al*., 2018). Ichnological and stratigraphic analyses reveal hemipelagic sedimentation constituted by pelagic material, low-density turbidites, bottom currents, together with minor contribution of continental material through hyperpicnal flows (Celis, 2016). However, the sedimentological characterization does not provide information about the ecological and depositional factors.

In the last years, ichnological studies have been revealed as a tool in sedimentary research, improving characterization of deep marine environments (Rodríguez-Tovar & Uchman, 2004a, 2004b, 2006, 2010, 2017; Rodríguez-Tovar *et al*., 2009a, 2009b, 2011a, 2011b, 2013, 2014, 2016; Monaco *et al*., 2012; Uchman & Wetzel, 2012; Wetzel & Uchman, 2012; Callow *et al*., 2014; Bayet-Goll *et al*., 2015, 2016). In combination with the analysis of the ichnological assemblage, some distinct ichnotaxa acquire a special relevance due to their particular characteristics and their relation with specific environmental conditions. This is the case of *Phycosiphon*, frequently associated with abundant benthic food and sufficient oxygenation (Wetzel & Uchman, 2001; Pervesler & Uchman, 2007; Wetzel, 2010; Rodríguez-Tovar *et al*., 2014). The high abundance of this ichnogenus in the studied section and its morphological variability provide new information about the palaeoenvironmental conditions. This is even more significant and increases the validity of the results obtained, if other abiotic proxies are considered in addition. For instance, total organic carbon (TOC) values can be very useful because they are closely related to the availability of benthic food in the substrate.

The aim of the present study is the integration of ichnological observations with special attention to the trace fossil *Phycosiphon,* as well as TOC data and the stratigraphic information, in order to understand and interpret the environmental conditions during deposition of the sediments exposed in the Ladrilleros-Juanchaco section in more detail.

2. GEOLOGICAL SETTING AND STRATIGRAPHY

The geological configuration of Colombia exhibits a complex mixture of allochthonous blocks, bounded by tectonic structures (faults systems) that cross the country in north-south direction, parallel to the current subduction zone between the Nazca and South American Plates. The combined activity of these mechanisms (subduction and thrusting) has given rise to the division of the Colombian Andes into three mountain ranges, Eastern, Central and Western. The Western Cordillera basement is composed by oceanic terranes that became attached to the NW of Colombia during the Late Cretaceous (Spikings *et al*., 2001, 2010). These allochthonous blocks are constituted by igneous (mafic) and sedimentary rocks formed in oceanic plateau and/or island arc environments (Villagómez *et al*., 2011). To the west of the Western Cordillera there is the Colombian Pacific area which is formed by two sedimentary basins, the Tumaco and Choco Basins (Barrero *et al*., 2007; Suárez-Rodríguez, 2007). The Choco Basin is subdivided by the Istmina Condoto High into the Atrato and San Juan Sub-basins (Cediel *et al*., 2010). The Juanchaco-Ladrilleros section is located in the San Juan Sub-basin, which has a surface area of 10,500 km^2 (Suárez-Rodríguez, 2007). Numerous stratigraphic studies have been carried out in the San Juan Sub-basin. They focus on local aspects and mainly address the so-called Istmina Condoto High, and upper valley of the San Juan River (Rojas, 1967; BGR - Ingeominas, 1989; Figueroa & Nuñez, 1990; Dunia Consultores Ltda, 2006; Bedoya *et al*., 2009; Gallego, 2017). These studies reveal that the Paleocene to Pliocene sediment succession consists of five lithostratigraphic units: Iró Formation (Eocene), Istmina Formation (lower Miocene), Conglomerados de la Mojarra Formation (lower Miocene), Condoto Formation (middle Miocene) and Raposo/Mayorquín Formation (Pliocene) (Bedoya *et al*., 2009; Cediel *et al*., 2010). The section addressed in the present study was investigated by Montoya (2003), and for the first time the informal name of Sedimentitas de Ladrilleros is introduced and the overlaying younger Mayorquín Formation was recognized as such.

The Ladrilleros-Juanchaco section is located west of the Western Cordillera in the San Juan Sub-basin in southwestern Colombia (3º57`N - 77º22`W and 3º55`N - 77º21`W) between the towns of Ladrilleros and Juanchaco, 40 km NW of the Buenaventura city (Fig. 1) (Duque-Caro, 1991; Barrero *et al*., 2007). It belongs to the sedimentary fill of the basin at the Colombian Pacific. The section is exposed almost continuously along coastal cliffs, where siliciclastic strata of approximately 680 m of thickness are outcropping (ANH-U Caldas, 2011; Celis, 2016).

Biostratigraphic and biochronologic studies based on calcareous nannofossils, planktonic foraminifera and diatoms reveal seventeen astronomically and standard

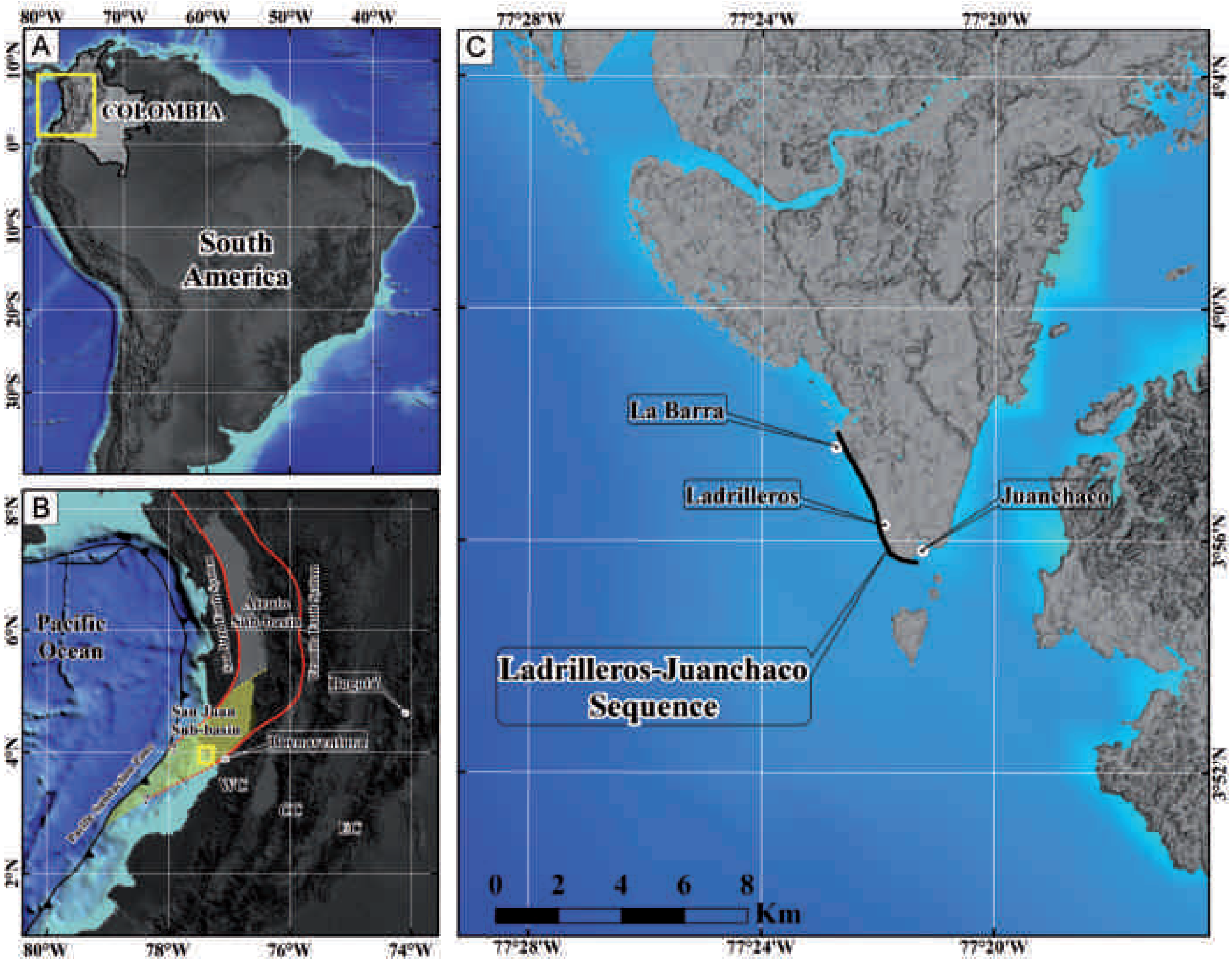

Figure 1. a) Location map of South America. **b)** Regional tectonic configuration of the study area. WC: Western Cordillera; CC: Central Cordillera; EC: Eastern Cordillera. (Basin limits from Barrero *et al*., 2007; red lines: faults from Cediel *et al*., 2010). **c)** Location map of Ladrilleros-Juanchaco section.

calcareous microfossil calibrated biohorizons as well as two tropical diatom biozones (Vallejo *et al*., 2016; Plata *et al*., 2018). Based on stratigraphic data a chronologic framework was established between 16.27 and 10.79 Ma (Burdigalian-Tortonian) (Vallejo *et al*., 2016; Plata *et al*., 2018).

3. MATERIAL AND METHODS

The outcrop (685 m-thick) was studied in detail at bed-by-bed scale, in particular with respect to ichnological aspects, focusing on assemblage, distribution, and relative abundance of trace fossils as well as on bioturbation index (Taylor & Goldring, 1993). Special attention was paid to *Phycosiphon* burrows, including their relationships to lithology and sedimentary structures, as well as to the diameter of the traces, the pattern of distribution, and abundance. The abundance of *Phycosiphon* in the beds was semi-quantitatively considered: without *Phycosiphon* traces (0%), low abundance (1-30%), middle abundance (30-60%), high abundance (60-90%), very high abundance (90-100%).

A photographic documentation was taken along the succession to complete the description in the laboratory. Subsequently, the treatment of the images in computer was conducted using several digital image techniques to enhance trace fossil visibility following previous methodologies (Dorador & Rodríguez-Tovar, 2014a, 2014b, 2018; Rodríguez-Tovar & Dorador, 2015).

Whole-rock analyses of TOC were carried out on 60 beds, with a sampling interval of around 10 m, showing a variable abundance of *Phycosiphon*. These analyses were performed in the laboratories of Universidad Nacional de Colombia - Medellín, and GMAS LTDA, Colombia.

4. RESULTS

4.1. Lithological features

The 685 m thick hemipelagites constituting the Ladrilleros-Juanchaco section are dominated by mudrocks interlayered with sandstones beds less than 1 m thick (Figs 2-3). The contacts between beds are mostly planar, and rarely irregular or gradational. Most of the mudrock beds are heavily bioturbated and only occasionally laminated. These beds are dark gray, grayish black or light gray colored. Woody fragments and mollusks were observed in some intervals. The sandstones are very fine to very coarse grained, while sorting within each layer varies. Sphericity and roundness of grains vary considerably. Sandstone beds exhibit normal and inverse grading, massive structure, parallel lamination, cross-bedding, and, in some cases, synsedimentary deformation structures such as slumps and convolute bedding. Throughout the section microfossils are abundant, such as calcareous nannofossils, foraminifera (benthic and planktonic), pollen, diatoms and dinoflagellates (ANH-Universidad de Caldas, 2011; Plata, 2012; Trejos, 2012; Vallejo, 2012; Correa, 2015; Hernández-Rendón, 2015; Celis, 2016; Vallejo *et al*., 2016; Garzón, 2017; Plata *et al*., 2018).

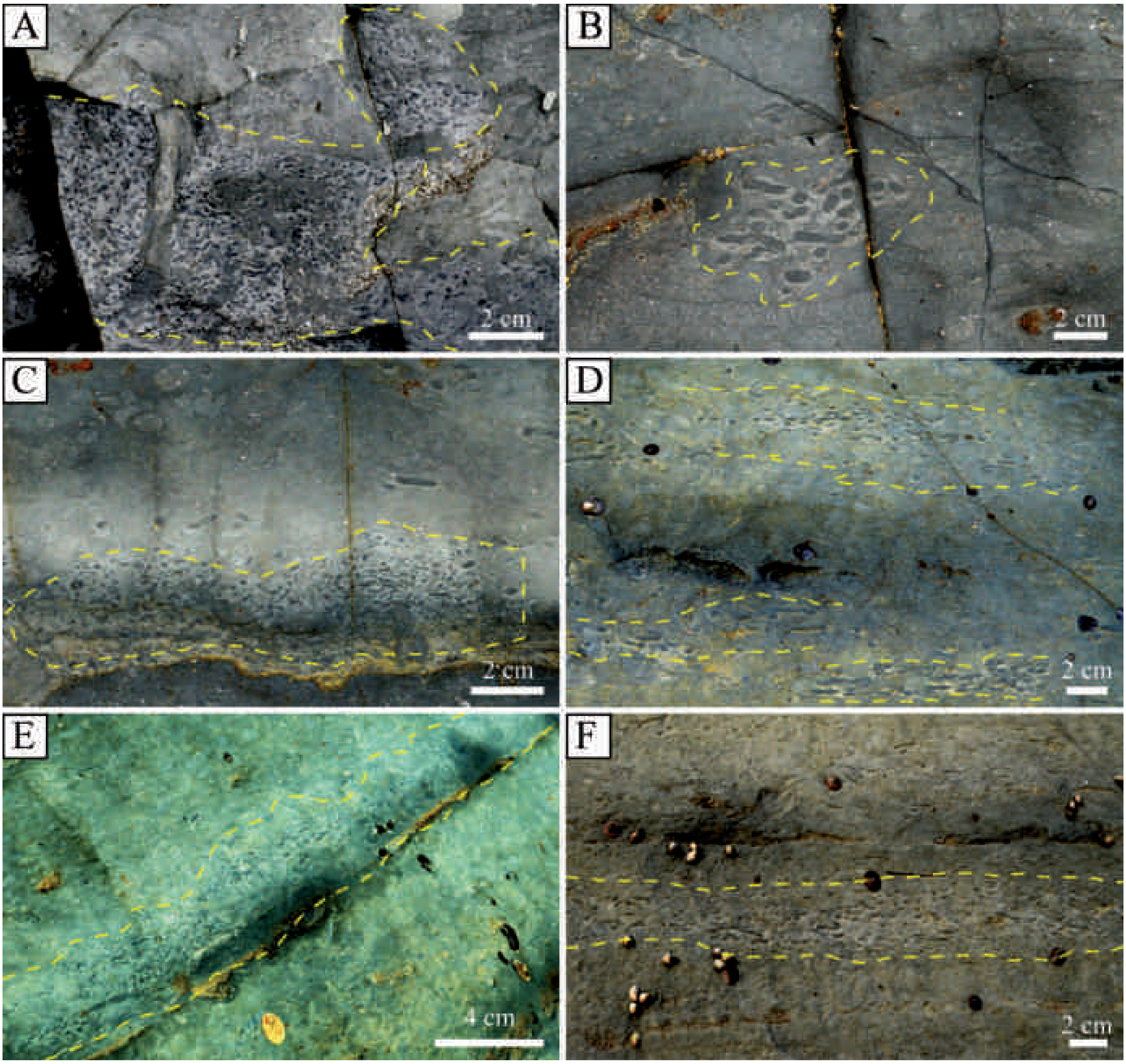

Figure 2. Distribution patterns of *Phycosiphon* structures in the Ladrilleros-Juanchaco section. **a-b)** Patchy arrangement of small **(a)** and large **(b)** *Phycosiphon*. **c-d)** Beds partly occupied by small **(c)** and large **(d)** *Phycosiphon*. **e-f)** Layers arrangement of small **(e)** and large **(f)** *Phycosiphon*.

4.2. Ichnology

The studied section contains highly diverse and abundant trace fossils consisting of pre-depositional (*Cladichnus*, *Cosmorhaphe*, *Glockerichnus*, *Gyrophyllites*, *Helminthopsis*, *Lorenzinia*, *Paleodictyon*, *Punctorhaphe*, *Spirorhaphe*, and *Stelloglyphus*) and post-depositional traces (*?Asterosoma*, *Chondrites*, *Halopoa*, *Nereites*, *Ophiomorpha*, *Palaeophycus*, *Phycodes*, *Phycosiphon*, *Phymatoderma*, *Planolites*, *Rosselia*, *Scolicia*, *Spongeliomorpha*, *Taenidium*, *Teichichnus*, *Thalassinoides*, as well as *Zoophycos*). This trace fossil association is typical of the *Nereites* and *Zoophycos* ichnofacies, with a variable occurrence throughout the studied section: *Nereites* ichnofacies (0-59 m), *Zoophycos* ichnofacies (67-300 m), *Nereites* ichnofacies (300-360 m), *Zoophycos* ichnofacies (360-492 m), and impoverished *Zoophycos* ichnofacies (492-685 m) (Celis, 2016) (Fig. 3). Impoverished *Zoophycos* ichnofacies is characterized by dominance of *Chondrites*, *Phycodes*, and *Phycosiphon*, together with *Nereites*, *Ophiomorpha*, *Palaeophycus*, *Phymatoderma*, *Planolites*, *Scolicia*, *Spirohaphe*, *Stelloglyphus*, *Taenidium*, *Thalassinoides*, and *Zoophycos*. Occasionally, some graphoglyptids (i.e., *Spirorhaphe* and *Stelloglyphus*) are observed.

4.3. *Phycosiphon* at the Ladrilleros-Juanchaco sequence

Phycosiphon is present at abundance and in different spatial arrangement throughout the 685 m-thick section. It preferably occurs in mudrock.

Phycosiphon traces appear in cross-sections, and longitudinal sections as cylindrical dark cores of varying size enveloped by a light halo around the dark tubes. Often sinuous forms or pairs of black spots surrounded by the lighter mantle are seen. The local presence of a spreiten, the outer halo and the pronounced curvatures are fundamental in the diagnosis of the ichnogenus *Phycosiphon* (Wetzel & Bromley, 1994; Uchman, 1998). In section, small and extensive branched forms having narrow lobes with connections (spreiten) or U-shaped structures forming meandriform complexes are seen, while all of them show a light halo and a dark central part parallel or oblique to the stratification.

According to the size of *Phycosiphon*, two classes are differentiated: a) small traces having in maximum 0.3 to 0.5 cm length, 0.1 cm width, and marginal tubes 0.02 cm in diameter; and b) large forms with length of individual spreiten of up to 2 cm and 0.4 cm width, and marginal tubes having up to 0.1 cm diameter (Fig. 2). The small forms dominate throughout the section.

Detailed analysis reveals variable distribution patterns into the beds throughout the section, with differentiation of 3 different arrangements: a) patches: *Phycosiphon* is sparse and randomly distributed, exhibits variable orientation, and small forms are more scattered than large ones (Figs 2a-b, 3); b) horizons: *Phycosiphon* burrows are concentrated discontinuously in intervals less than 1 m thick and parallel to stratification; small traces dominate over large ones (Figs 2c-d, 3); and c) layers: *Phycosiphon* are densely packed in intervals parallel to the stratification with a lateral continuity exceeding 1 m. Occurrence in patches is most frequent, while occurrence in layers is mainly observed in the intervals 245-270 m and 500-540 m where small *Phycosiphon* are present (Figs 2e, 3), and at the top of the section where large forms occur (Figs 2f, 3).

The abundance of *Phycosiphon* shows pronounced variations within the entire section (Fig. 3), being low (1-30 %) in the intervals 0-59 m and 300-360 m, and high (60-90 %) and very high (90-100 %) at the top of the section between 492 and 685 m. Middle abundance (30-60 %) is observed in the intervals 67-300 m and 360-492 m. Particularly, in the interval 239-268 m, very high values of *Phycosiphon* abundance are presented.

4.4. Total organic carbon

Total organic carbon varies between 0.15 wt % and 0.80 wt %. TOC values within the studied section show two well-differentiated intervals with minor fluctuations inside (Fig. 3). From 0 to 442 m, the average of TOC values fluctuate between 0.2 wt % and 0.45 wt % with some peaks reaching up to 0.80 wt % in the interval of 237-267 m. From 462 to 685 m, the TOC values generally increase, ranging between 0.36 wt % and 0.57 wt % and showing a maximum of 0.65 wt % in the interval of 635-648 m.

5. INTERPRETATION AND DISCUSSION

The behavior of the trace makers and, therefore, the biogenic structures they produce, are strongly influenced by environmental conditions. Consequently, bioturbational structures are useful as tool to decipher environmental parameters at the time of sedimentation, such as, benthic food content, temperature, salinity, oxygenation, hydraulic energy, and sedimentation rate, among others. (Uchman, 1991, 1992; Buatois & López-Angriman, 1992; Netto & Rossetti, 2003; Netto *et al*., 2009; Buatois & Mángano, 2011; Buatois *et al*., 2011; Knaust & Bromley, 2012). To evaluate the environmental conditions in the studied section occurrence of *Phycosiphon* is compared with already published findings.

The producer of *Phycosiphon* is especially sensitive to sediment grain size, mainly registered in mud to fine sand (Ekdale & Lewis, 1991, in reference to *Anconichnus*).

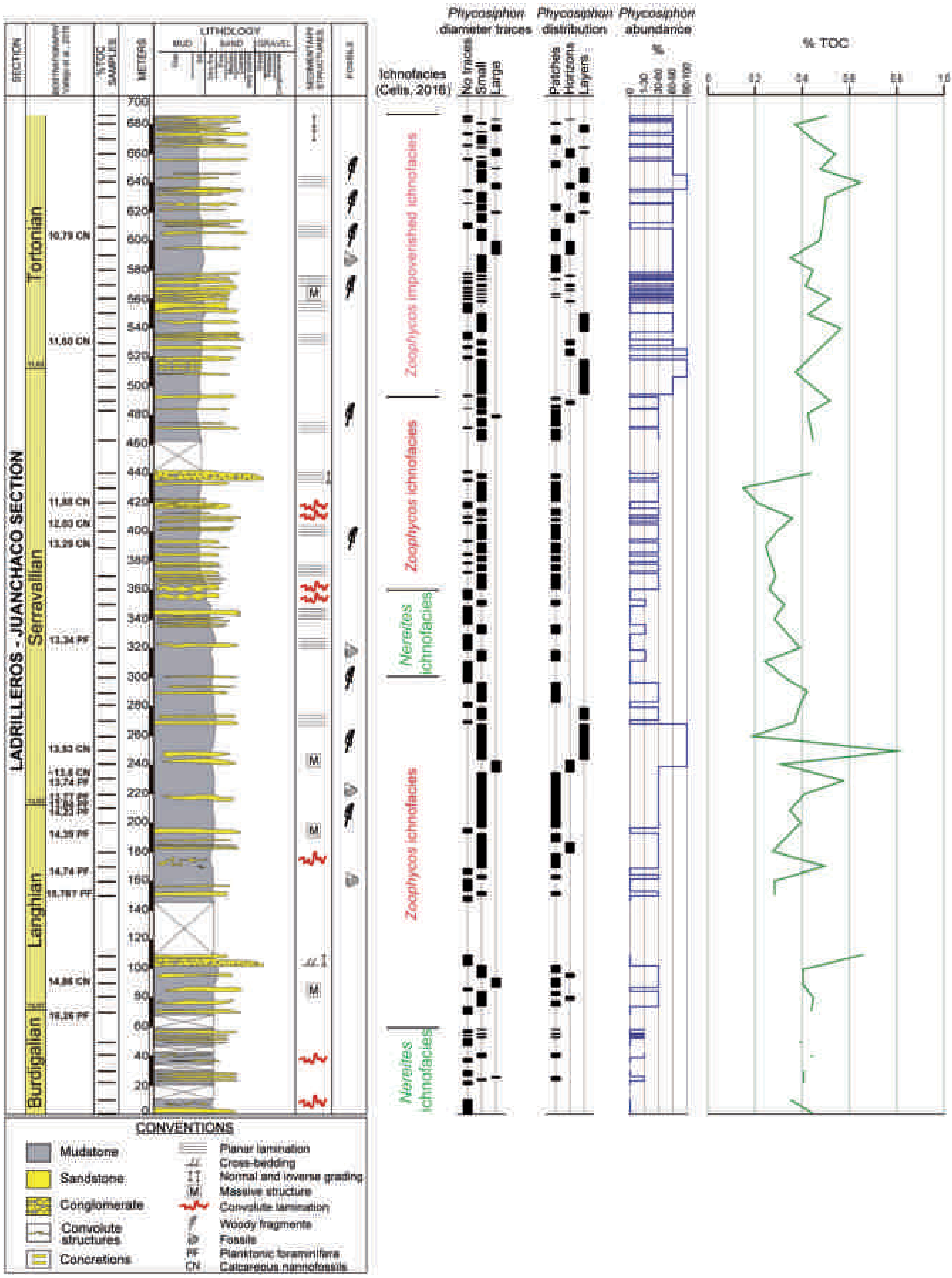

Figure 3. Graph summarizing the results: lithological column of the Ladrilleros-Juanchaco section, including data on grain size and sedimentary structures, fossils, ichnofacies (Celis, 2016), information on *Phycosiphon* (diameter, distribution and abundance), and stratigraphic distribution of the Total Organic Carbon (TOC) data.

The trace is considered a pascichial/fodinichnial structure (Ekdale & Masson, 1988; Wetzel & Bromley, 1994); the organism selectively ingests the clay material of the sediment leaving a continuous fecal chain rich in clay in the center surrounded by a halo of sorted-out sand. The producer is usually considered as an opportunistic organism, at different tiers depths up to 15 cm below the sediment-water interface, in an extent range of bathymetric conditions from shallow marine to bathyal and even abyssal depths (Wetzel & Balson, 1992; Wetzel & Bromley, 1994; Wetzel & Uchman, 2001). Occasionally an equilibrium population strategy has been suggested (Wetzel, 2010). The trace maker of *Phycosiphon* has not yet been recognized (Wetzel, 2008), but the organism producing phycosiphoniform burrows are supposedly vermiform (Wetzel & Bromley, 1994; Bednarz & McIlroy, 2009). It generates a series of feeding enclosing structures, lateral to the marginal tube (based on Fu, 1991; Goldring *et al*., 1991; Wetzel & Bromley, 1994; Uchman, 1995, 1999; Bromley, 1996; Seilacher, 2007; Wetzel, 2010). However, there are doubts about the behavior of the producer, its opportunistic nature or the limiting palaeoecological factors that determine its distribution, abundance and morphological features.

Phycosiphon occurs within the Ladrilleros-Juanchaco section almost continuously and appears to indicate a close relationship to the palaeoenvironmental conditions and the associated *Nereites* ichnofacies, *Zoophycos* ichnofacies, and impoverished *Zoophycos* ichnofacies (Celis, 2016) (Fig. 3). The abundance of *Phycosiphon* is closely related to each of the ichnofacies. In general, the abundance of *Phycosiphon* is low when the *Nereites* ichnofacies is present and is high in the *Zoophycos* ichnofacies. This agrees with the usual composition of both ichnofacies; even *Zoophycos* is the typical ichnogenus in the *Zoophycos* ichnofacies, in some cases *Phycosiphon* can be the dominant ichnogenus (Frey & Pemberton, 1984; Buatois & Mángano, 2011). In the *Nereites* ichnofacies, *Phycosiphon* also occurs, but not as dominant ichnotaxon. Within the upper part of the section, above 492 m, where the impoverished *Zoophycos* ichnofacies is present, the abundance of *Phycosiphon* increases, showing the highest values throughout the entire section.

The occurrence of *Phycosiphon* shows an apparent relation to the general trend of the total organic carbon content. In the upper part of the section where the abundance of *Phycosiphon* increases (492–685 m), the average TOC values increase too (Fig. 3). In addition, the greatest abundance of *Phycosiphon* occurring along the section (237–267 m, 492–552 m, and 635–648 m) coincides with increasing TOC values (Fig. 3). With respect to the rest of observed ichnological features (diameter, distribution, and abundance of *Phycosiphon* traces), the high abundance of *Phycosiphon* associated with high TOC values is also accompanied by the dominance of this trace within the beds. Moreover, large specimens are mainly located in the upper part of the section, where the average of TOC values is high.

Abundance, size and distribution of *Phycosiphon* are narrowly related with organic matter content, as coherent with previous works showing that *Phycosiphon* is frequently associated with food availability (Ekdale & Masson, 1988; Wetzel & Uchman, 2001; Hovikoski *et al*., 2008; Pervesler & Uchman, 2007; Wetzel, 2010; Rodríguez-Tovar *et al*., 2014). In the studied case, this interpretation supports previous findings suggesting increasing productivity in oceanic waters and resultant eutrophication towards the top of the section (Plata *et al*., 2018). Concomitantly, also the number/thickness of sandstone beds and terrigenous material, and fossil remains increase. An upper slope environment is interpreted being influenced by channels that drag the material within hyperpycnal flows (Celis, 2016), according to the characteristics proposed for this mechanism by Zavala & Pan (2018).

6. CONCLUSIONS

The mudrocks from Ladrilleros-Juanchaco section (Miocene, Colombia Pacific), are characterized by a diverse trace fossil assemblage. *Phycosiphon* occurs throughout the entire section. Dense aggregations of *Phycosiphon* having variable size are present in different arrangements, in patches, or occupying beds partly or completely. Likewise, the relative abundance of *Phycosiphon* shows a close relationship with the encountered ichnofacies; *Phycosiphon* abundance decreases in the *Nereites* ichnofacies and increases in the *Zoophycos* ichnofacies. Within the impoverished *Zoophycos* ichnofacies, in the upper part of the studied section the highest abundance of *Phycosiphon* was found. In general, larger specimens and higher abundance of *Phycosiphon*, and the dominant presence within beds correlates with high TOC values. This supports the relationship between burrow size and food availability. In combination, ichnological, sedimentological and geochemical data from the Ladrilleros-Juanchaco section reveal high productivity conditions during times when the upper part of the section accumulated, as well as episodically in the lower part.

ACKNOWLEDGEMENTS

We would like to thank the technical and scientific staff of Instituto de Investigaciones en Estratigrafía-IIES (Universidad de Caldas) for the economic and logistic support. Thankful with the Colombian Association of Petroleum Geologist and Geophysicists (ACGGP) and the Corporación Geológica ARES, Bogotá, for providing economic support through the ARES-Corrigan. We also thank Agustin Cardona and Universidad Nacional de Colombia - Medellín for assisting and providing economic support in the preparation of TOC samples. Funding for research of RT was provided by Project CGL2015-66835-P (Secretaría de Estado de I+D+I, Spain), Research Group RNM-178 (Junta de Andalucía), and Scientific Excellence Unit UCE-2016-05 (Universidad de Granada). We are grateful to Gonzalo Jiménez Moreno for his editorial work, and to Andreas Wetzel, and one anonymous reviewer for their diligent review and comments.

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