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ICHNOLOGY AND SEDIMENTOLOGICAL ASPECTS OF THE FLORIANO FORMATION (MIOCENE OF THE RESENDE BASIN), SOUTHEAST OF BRAZIL

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ABSTRACT – Many previous studies identified depositional systems for the Resende Basin using sedimentological and petrographic techniques. However, the lack of ichnological research leaves a gap in our understanding of paleoenvironment and paleoecology of this basin. Therefore, this study reports the first occurrence of trace fossils in the Floriano Formation (Miocene) and suggests more refined paleoenvironmental interpretations for this unit. We only observed ichnofossils in an outcrop on the RJ-161 road in Resende municipality, Rio de Janeiro State. The deposit represents a floodplain overlayed by a crevasse splay, both sedimented in a meandering fluvial context. Trace fossils of terraphilic organisms – represented by *Taenidium* isp., *Planolites* isp. and *Arenicolites* isp. – were found in the fine-grained sediments of the outcrop. This ichnocoenosis is composed of feeding (fodinichnia), locomotion (repichnia) and/or habitation (domichinia) structures produced by worm-like invertebrates. The ichnotaxonomic assemblage consists of the first record of Scoyenia ichnofacies for a typical meandering fluvial system in Brazil.

Keywords: continental ichnology, sedimentology, ichnofacies, paleoenvironment.

RESUMO – Muitos estudos prévios identificaram sistemas deposicionais para a Bacia do Resende usando técnicas sedimentológicas e petrográficas. No entanto, a falta de pesquisas paleontológicas deixa uma lacuna na compreensão do paleoambiente e paleoecologia desta bacia. Portanto, este estudo relata a primeira ocorrência de icnofósseis na Formação Floriano (Mioceno) e sugere interpretações paleoambientais mais refinadas para esta unidade. Foram observados icnofósseis apenas em um afloramento na rodovia RJ-161 no município de Resende, Estado do Rio de Janeiro. O afloramento é constituído por depósitos de planície de inundação sobrepostos por um crevasse splay, ambos depositados em um contexto fluvial meandrante. Icnofósseis de organismos terrafílicos – representados por *Taenidium* isp., *Planolites* isp. e *Arenicolites* isp. – ocorrem nos sedimentos finos do afloramento. Esta icnocenose é composta por estruturas de alimentação (fodinichnia), locomoção (repichnia) e/ou habitação (domichinia) produzidas por invertebrados vermiformes. A associação icnotaxonômica representa o primeiro registro brasileiro da icnofácies Scoyenia para um típico sistema fluvial meandrante.

Palavras-chave: icnologia continental, sedimentologia, icnofácies, paleoambiente.

INTRODUCTION

Even when organisms are not present in the environment, paleontology can shed light on how their presence and behavior through the ichnology. To paleoichnology, *i.e.*, the branch of ichnology that studies trace fossils (Buatois & Mángano, 2011), we can also deduce the presence of soft-bodied organisms, which commonly are poorly preserved in the fossil record. One of the advantages of paleoichnology is that trace fossils are found *in situ* in the sediments or rocks

in which they were produced, thereby avoiding the transport and consequent time-averaging that is typically observed in hard-part accumulations (McIlroy, 2004; Buatois & Mángano, 2011).

Studies of continental trace fossils as tools for characterizing paleoenvironment and paleoclimate are still uncommon in Brazilian geoscientific literature (*e.g*., Fernandes *et al*., 1992; Ramos *et al*., 2006; Menezes *et al*., 2019), despite their prevalence in continental successions of lacustrine, fluvial, alluvial, wetland, and eolian environments. Deposition rates, type of sediments and substrates, erosion, and type of climate are the factors that determine the ichnological diversity and level of colonization development (Kraus & Aslan, 1999).

Other ichnological concept that aids to understand paleoenvironments is the analysis of ichnofacies, which is a set of characteristics shared by different ichnocoenoses during broadly similar time periods and environmental conditions (Buatois & Mángano, 2011). It takes ethological, ecological, and taphonomic factors into account and enables us to better integrate sedimentological and stratigraphic data.

Due to the lack of ichnological studies in some Brazilian basins, we aim to describe the ichnotaxa and determine the bioturbation index and ichnofacies of the Floriano Formation, Miocene of the Resende Basin, in southeastern Brazil, and integrate sedimentary data to refine the paleoenvironmental setting of this region. Besides, our data and conclusions shed light on the ichnodiversity in the area of the southeastern Brazil and paleoenvironmental aspects regarding the substrates of the region during the Miocene.

GEOLOGICAL SETTING

The Resende Basin is a Cenozoic sedimentary basin inserted in the western portion of the Rio de Janeiro State, between the municipalities of Barra Mansa (District of Floriano), Quatis, Porto Real, Resende, and Itatiaia. Its outcrops include rocks dated from the Paleogene, Neogene and Quaternary and cover 240 km^2 in area and 550 m in maximum thickness (Escobar, 1999) (see chronostratigraphic chart of Resende Basin in Figure 1). This basin, along with the Volta Redonda, Taubaté, and São Paulo basins, is in the central segment of the Continental Rift of Southeast Brazil (Riccomini, 1989).

Amador (1975) was the first author to include the Floriano Formation in the lithostratigraphic proposition for the Resende Basin, but this denomination was not used in subsequent lithostratigraphic revisions. Ramos (2003) proposed rescuing the term "Floriano Formation" (with its

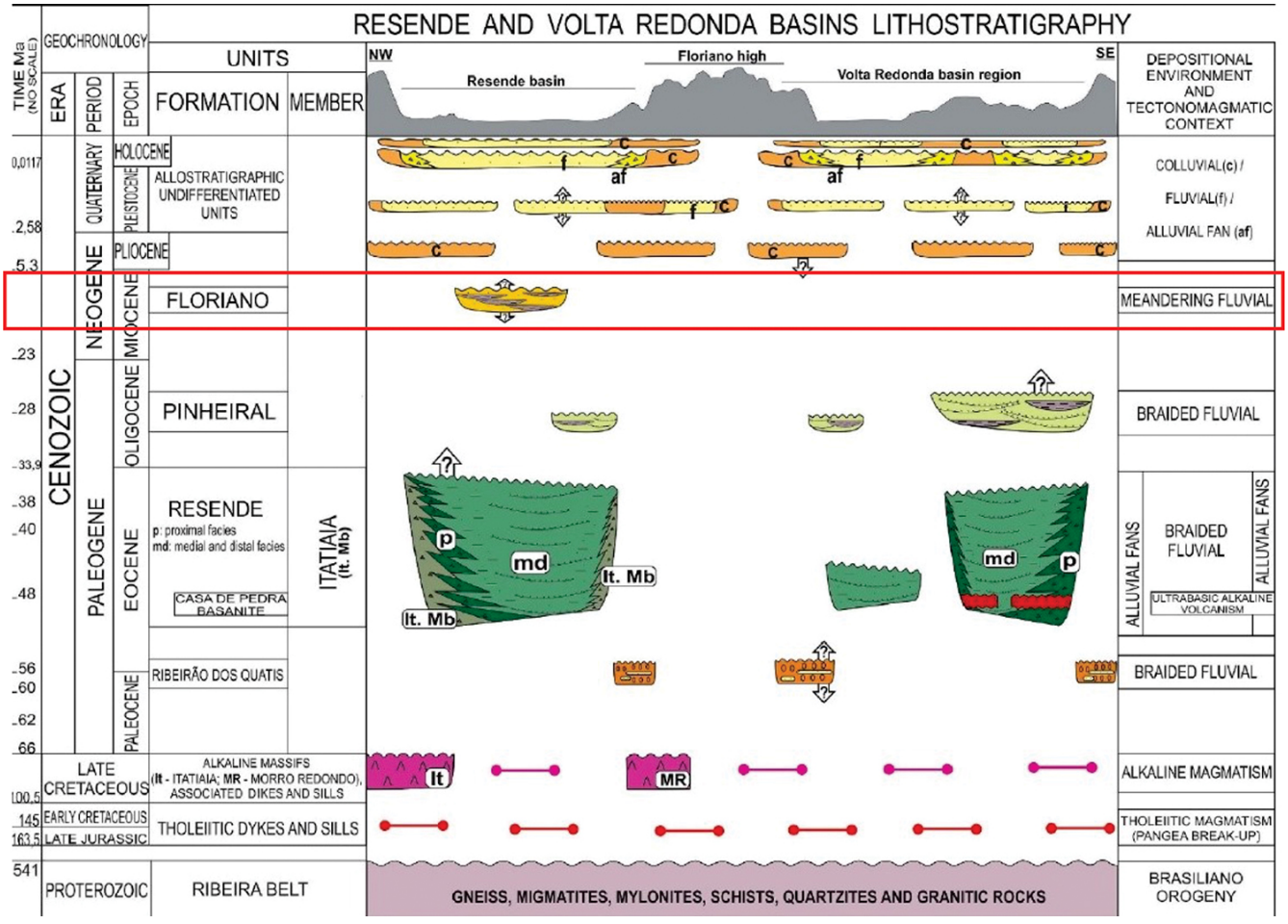

Figure 1. Chronostratigraphic chart of Resende and Volta Redonda basins. Modified from Negrão *et al*. (2020). Floriano Formation highlighted in red.

redefinition) to encompass the succession of sandstones and mudstones, interpreted as the record of a meandering river system that filled the basin. This succession – whose maximum thickness is 20 m – overlap discordantly both the Resende Formation deposits and the Proterozoic basement. The contact relationship with the Resende Formation could not be clearly determined, which is the main reason for the proposal of rescuing the name "Floriano" rather than the names "São Paulo" or "Pindamonhangaba", which have been used to represent the meandering river systems recognized in the stratigraphy of the Continental Rift of Southeast Brazil, specifically in the São Paulo and Taubaté basins (Ramos *et al*., 2006). The Floriano Formation only occurs in the Resende Basin and is considered a post-rift sedimentation (Negrão *et al*., 2020). The succession of sandstone and mudstone beds described by Carmo (1996) have been proposed as a type-section of the Floriano Formation.

The Floriano Formation dates from the Miocene (Amador, 1975; Ramos *et al*., 2005, 2006) and is characterized by conglomerates, grading to reddish very fine to coarse sandstones and claystones, with frequent levels of paleosols indicating depositional events with decreased transport energy, as well as weathering processes after the sedimentation. They were interpreted as coalescing alluvial cones partially reworked by fluvial channels, with the predominance of mudflow processes and, subordinately, fluvial processes. A "Rudaceous Member" was also formalized for this unit, represented by outcropping deposits on the road to the Itatiaia National Park (Ramos *et al*., 2006). The association of facies and the depositional architecture of the sigmoidal sandy and pelitic tabular to lenticular layers attest to a meandering fluvial environment (Negrão *et al*., 2020).

PALEONTOLOGICAL BACKGROUND

Fossil content is scarce in the Resende Basin. Riccomini *et al*. (1987) cited the occurrence of impressions of leaves in mudstones of a channel abandonment facies, also found by Ramos (1997). Scheel-Ybert *et al*. (2007) also described a rolled fragment of a 60 cm-long silicified trunk or root. This was found at the exit of a gully at the head of the Alegrete creek, close to the Aço railroad, where sandstone and rudaceous successions (correlated to the Resende Formation) appear. However, the possibility that this plant fragment was reworked from an older stratigraphic unit (*e.g*., Ribeirão dos Quatis Formation) cannot be ruled out, in view of the roundness of the block. An expeditious analysis carried out by Prof. Dr. Diana Mussa, from the National Museum/UFRJ, indicated that the material constitutes a trunk or root of a dicotyledonous angiosperm (Ramos, 2003).

The most common fossil evidence in the pelitic and fine sandstone sediments of the Resende Formation is the *Skolithos*-type trace fossils, described and interpreted as generated by arthropods (Fernandes *et al*., 1992). Root marks are also observed in pelitic layers of the fluvial and alluvial fan successions of the Resende Formation (Ramos, 2003). Until now, body fossils have not been identified in the Miocene Floriano Formation.

MATERIAL AND METHODS

Ichnological descriptions were realized and collected from an outcrop of the Floriano Formation along the road RJ-161 (UTM 0557458, 7517625, DATUM WGS 84, zone 23S) in the municipality of Resende, Rio de Janeiro State (Figure 2). We collected 21 samples from five sedimentary beds of the outcrop and compared them with trace fossils published in the literature (*e.g*., Fernandes *et al*., 2002). In addition, we assessed the Bioturbation Index (*sensu* Taylor & Goldring, 1993). Finally, we attributed the ichnological assemblage to the probably ichnofacies.

We also evaluate the trace makers based on their behavior and response to soil moisture: (i) terraphiles, organisms that live between the surface and the upper vadose zone and tolerate short periods of soil moisture; (ii) hygrophiles, organisms that live in the vadose zone; and (iii) hydrophilic, organisms that live in equilibrium with the water table (Hasiotis *et al*., 2007).

We described the outcrop according to the color (*sensu* Munsell Color Chart, 1994), grain size, mineral composition, roundness and sphericity of particles, and sedimentary structures. Four samples are collected for distinct layers, aiming thin section description based on sedimentary texture, compositional aspects and identify biological activity. All thin sections were made at the Laboratório Geológico de Processamento de Amostras of the Universidade do Estado do Rio de Janeiro (**LGPA/UERJ**) and their descriptions occurred in the Laboratório de Paleontologia (**LABPALEO/UERJ**).

SEDIMENTOLOGICAL ASPECTS AND BIOTURBATION INDEX

The outcrop is 2 m high and 30 m in lateral extent, subdivided by seven sedimentary beds according to textural descriptions, compositional distinction, and bioturbation characteristics.

The first bed (Stratum 1; Figure 3) is 10 cm thick, composed by sandy mudstone. The sandy granulometry is very fine, with textural set of angular to subangular, and poor to moderately sorted grains. The bed has a purple color (2.5YR 6/4) and a bioturbation index around 40%. We identified *Planolites* isp. macroscopically, and *Taenidium* isp. on a petrographic thin section (Figure 4A).

The second bed (Stratum 2; Figure 3) has a thickness of 12 cm, purple color (2.5YR 6/4), granulometry ranging from fine to medium sand, and subangular to angular grains, and poorly sorted. Under petrographic description, the sandstone composition shows mono- and polycrystalline quartz, plagioclase, and opaque minerals (Figure 4B). In addition, redoxmorphic features classified as concentration redox and mechanical clay infiltration were observed. This bed has a

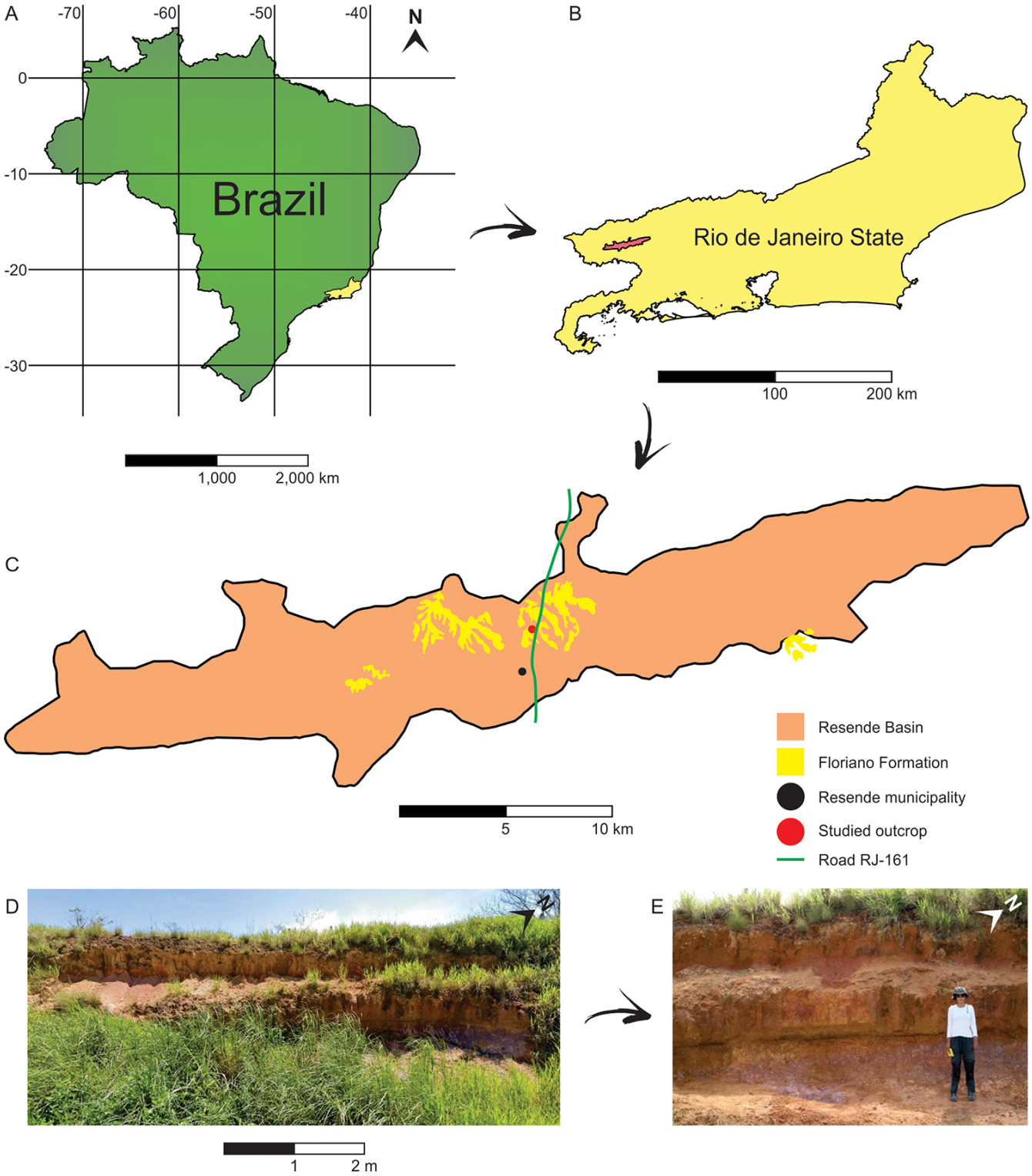

Figure 2. Location of the Resende Basin. **A**, map of Brazil with emphasis on Rio de Janeiro State. **B**, map of Rio de Janeiro State with emphasis on the Resende Basin. **C**, Resende Basin with emphasis on the Floriano Formation, the outcrop and the Resende Municipality. **D-E**, studied outcrop.

bioturbation index of 20% and includes trace fossils assigned to *Taenidium* isp.

The third bed (Stratum 3; Figure 3) consists of a purple (2.5YR 6/4) fine sandstone, with subangular to sub-rounded grains. Pebbles occur sparsely in this bed. It is composed primarily of quartz, plagioclase, and mafic minerals and has cement of iron oxide adjacent to tubiform structures (Figure 4C). According to the tensile strength of this bed, the bioturbation index is 20%, with abundant of *Planolites* isp., *Taenidium* isp. and *Arenicolites* isp.

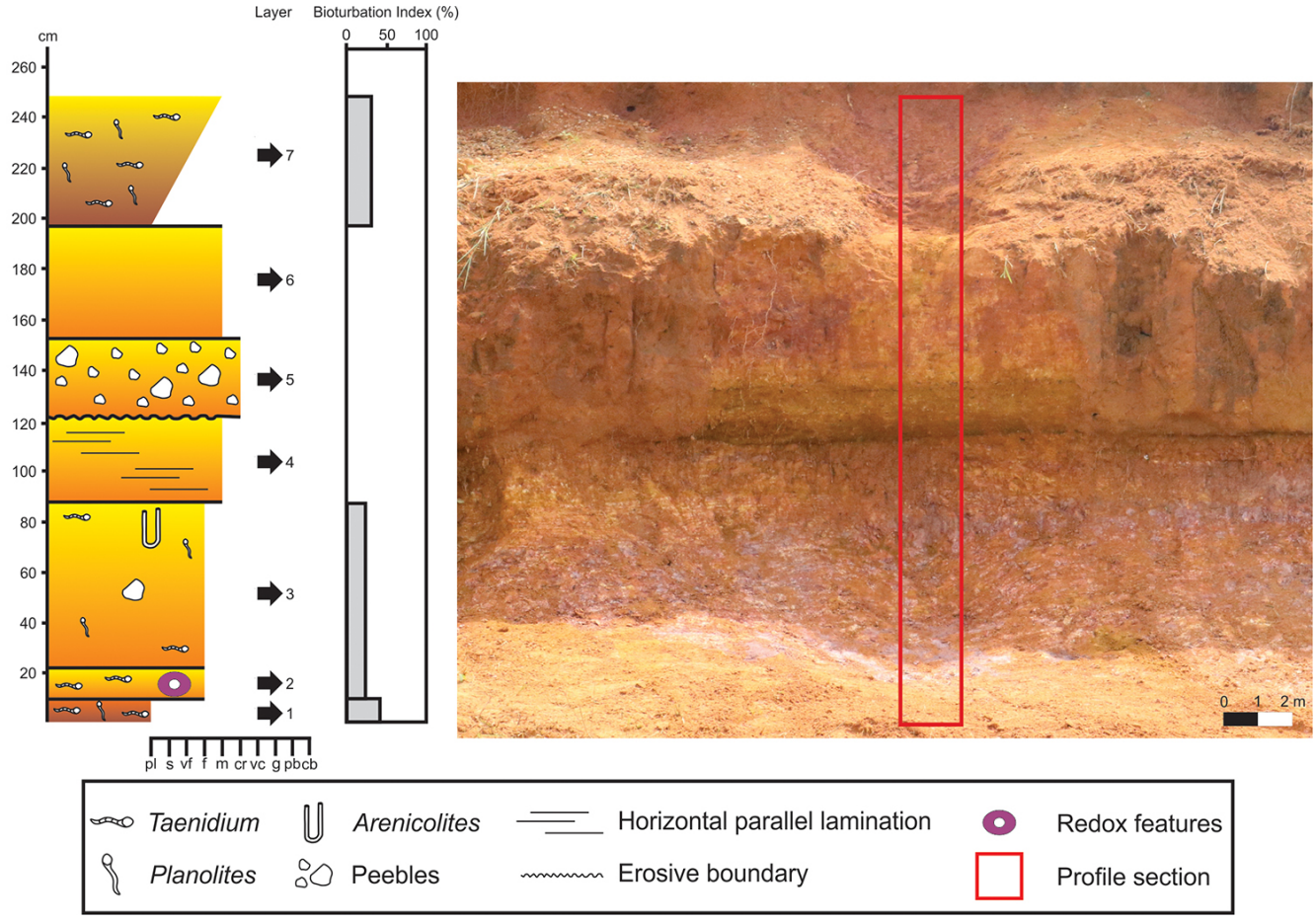

Figure 3. Sedimentary log of the outcrop and stratigraphic distribution of the ichnofossils.

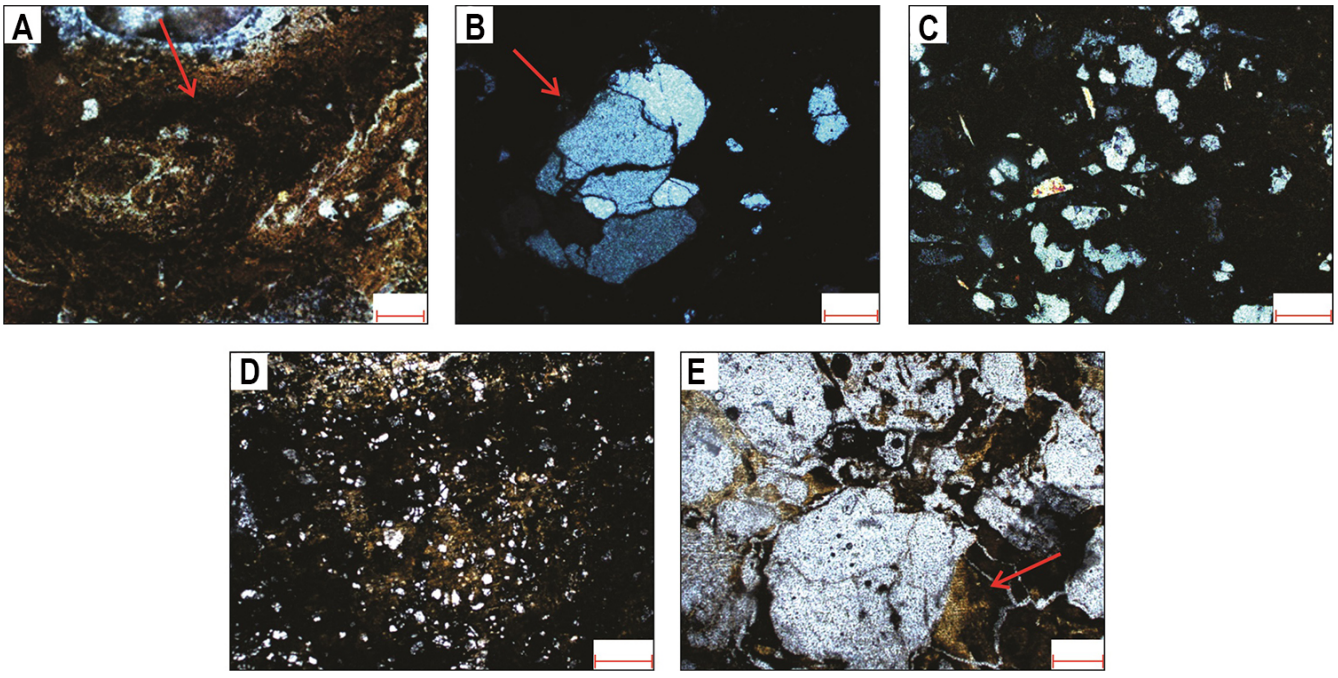

Figure 4. A, *Taenidium* in thin section in the bed 1. **B**, polycrystalline quartz grain in bed 2. **C**, fine sand composed by quartz, plagioclase and opaque minerals in bed 3. All of grains are angular and with low sphericity. **D**, Medium sand with oriented quartz grains, opaques and plagioclase in bed 5. **E**, Fine to coarse grains, most composed of quartz and cement of iron, in bed 5. Scale bars: A = 200 µm; B = 7.5 µm; C = 10 µm; D = 1050 µm; E = 830 µm.

The fourth bed (Stratum 4; Figure 3) is weathered and has a thickness of 33 cm, brown color (7.5 YR 7/5), basal planar parallel lamination, grain size ranging from fine to medium sand, and subangular to subrounded grains with a moderately sorted. It consists primarily of quartz, feldspar, muscovite, and opaque minerals (Figure 4D). There is an erosive surface on the top of this bed with depth of erosion between 4–8 cm.

The fifth bed (Stratum 5; Figure 3) is 35 cm thick and varies in color from yellow (2.5 Y 8/4) to brown (7.5 YR 7/5). It is a conglomeratic sandstone, whose framework is composed of medium to coarse sands. The conglomeratic fraction includes quartz pebbles ranging from 3.0 mm to 1.0 cm, and subangular to sub-rounded grains with poor sorted. The mineral assemblage is composed by primary minerals as quartz, feldspar, muscovite and mafic minerals, and the cementation is mainly formed iron oxides (Figure 4E). There is no evidence of bioturbation or sedimentary structures.

The sixth bed (Stratum 6; Figure 3) has a thickness of 34 cm and yellow color (7.5 YR 8/4). It is a medium sandstone, with poorly sorted, subangular to sub-rounded grains. Quartz, feldspar, muscovite, and mafic minerals make up the bulk of its composition. There is no evidence of bioturbation or sedimentary structures.

The seventh bed (Stratum 7; Figure 3) presents inverse gradation ranging from siltstone to medium-grained sandstone. It has thickness of 50 cm and purple color (2.5YR 6/4). The sandstone composition consists of quartz, feldspar, muscovite, and mafic minerals. Trace fossils are subvertical to horizontal, the bioturbation index is of 30%, and *Taenidium* isp. and *Planolites* isp. are reported.

In relation to the preservation degree of substrate, the rates of bioturbation in the outcrop range from 0 to 40 % (see Figure 3). Muddy to fine sandstone beds (beds 1and 7) have the higher index of bioturbation (30% to 40%), whereas the sandier beds (layers 2, 3, 4, 5, and 6) are slightly bioturbated or absent of bioturbation; thus, trace fossils are concentrated in fine sediments. This pattern can result from the differences of energy involved in the sedimentation processes: high-energy processes – that transport and deposit coarse sediments – have the potential to destroy biogenic structures, whereas low-energy processes – that transport and deposit fine sediments – has a high potential for preserving biostructures (Buatois & Mángano, 2011).

SYSTEMATIC ICHNOLOGY

Ichnogenus *Taenidium* Heer, 1887

Taenidium isp.
(Figure 5)

Ethology. Feeding (fodinichnia), locomotion (repichnia) and dwelling behaviors (domichinia) (Hembree & Hasiotis, 2008).
Related material. Samples collected in the layers 1, 2, 3 and 7.
Description of traces. Horizontal to subvertical excavations with straight, sinuous, and curved segments, a meniscated internal structure, and mud and/or sand filling. They lack walls and range in diameter from 0.3 to 0.5 cm and in length from 4 to 5 cm.
Differential diagnosis. The ichnogenera *Taenidium* Heer, 1887, *Beaconites* Vialov, 1962, *Scoyenia* White, 1929, *Ancorichnus* Heinberg, 1974, and *Naktodemasis*, Smith *et al*., 2008, are comparable to the trace fossils we discovered. *Beaconites* and *Scoyenia* have smooth and longitudinal groove-coated walls (D'Alessandro & Bromley, 1987; Keighley & Pickerill, 1994; Retallack, 2001), respectively, which is not observed in our specimens. Internal and external filling stages distinguish the ichnogenus *Ancorichnus* from the trace fossils we discovered. Despite the absence of walls in our sample, we also exclude *Naktodemasis* due to its serial filling of discontinuous bundles and very thin and subparallel menisci (Smith *et al*., 2008), which differ from our trace fossil characteristics. Therefore, we ascribed the observed ichnofossils to *Taenidium*, which has no walls, a simple structure, and a clearly defined meniscus framework.
Comments. In continental environments, *Taenidium* is produced by beetles and annelids in floodplain, lakeshores, and vegetation-covered deposits (Hasiotis *et al*., 2007). The observed filling in meniscus pattern represents a backfill activity of an excavation, *i.e*., the packaging of sediment after the animal has moved on the substrate, resulting in a minimal expenditure of energy (Buatois *et al*., 2002; D'Alessandro & Bromley, 1987).

Ichnogenus *Planolites*, Nicholson, 1873

Planolites isp.
(Figure 6)

Ethology. Feeding trace fossil (fodinichnia).
Related material. Samples collected in layers 1, 3 and 7.
Description of traces. Horizontal and subvertical, 0.3 to 0.8 cm long cylindrical tubes with smooth walls, which are oriented perpendicular to the bedding of the layer. They are filled by a sediment different from the rock matrix (passive fill).
Differential diagnosis. These trace fossils resemble those of *Planolites* Nicholson, 1873 and *Paleophycus* Hall, 1874. Both ichnogenera are composed of horizontal to oblique tubes that occasionally overlap and rarely branch. We assigned the trace fossils to *Planolites* isp. due to its passive infilling, that is not observed in *Paleophycus* (Pemberton & Frey, 1982).
Comments. *Planolites* are filled with mud and sand and are the products of worm-like animals searching for food. In continental ecosystems, these animals commonly inhabit alluvial and lake systems (Hasiotis *et al*., 2007).

Icnogenus *Arenicolites* Salter, 1857

Arenicolites isp.
(Figure 7)

Ethology. Dwelling (domichnia) and suspension-feeding (fodinichnia) traces.

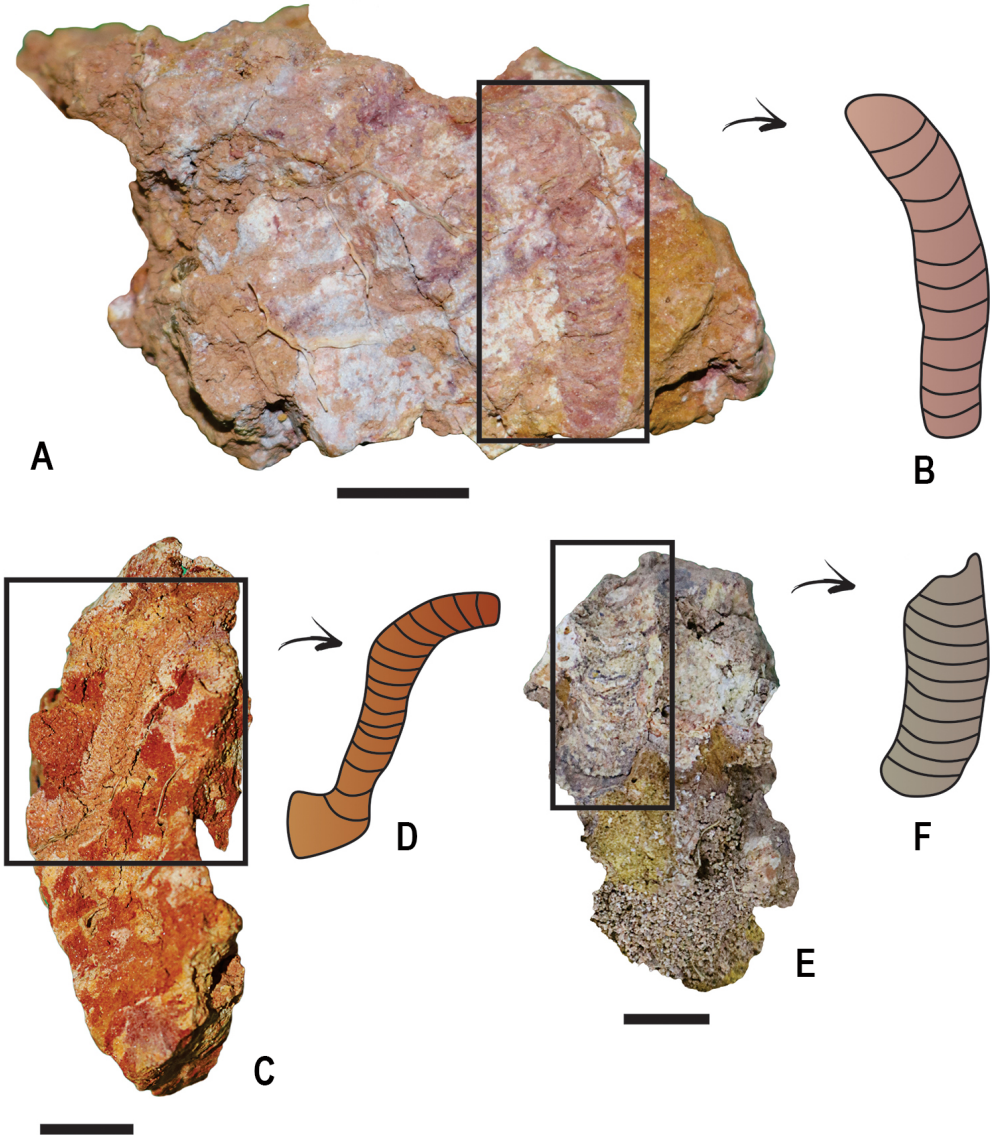

Figure 5. Samples assigned to *Taenidium* isp. from bed 3 (A-B) and bed 4 (C-F). Scale bars = 10 mm.

Related material. Samples collected in layer 3.

Description of traces. The trace fossils are formed of U-shaped tubes sizing 3.0 to 5.0 cm long with smooth walls arranged vertically to the plane of bedding. They do not overlap and, less frequently, they also have a J-shaped morphology and funnel-shaped openings.

Differential diagnosis. Similar trace fossils can be related with *Arenicolites* Salter, 1857, *Laevicyclus* Quenstedt, 1879, *Cylindricum* Linck, 1949, and *Planolites*. *Cylindricum* comprises groups of test-tube-shaped excavations with rounded bottoms and smooth walls that are oriented perpendicular to the bedding plane (Kegel, 1966). This ichnogenus was ruled out because our specimens were not found in groups and did not have the shape of test tubes. *Laevicyclus* includes cylindrical traces with a central channel arranged vertically to the bedding plane (Kegel, 1966), which are absent from our samples. *Planolites* includes cylindrical to subcylindrical excavations that are straight to slightly curved, unbranched, generally sub-horizontal to the bedding plane, filled, and overlapping. These features do not correspond to the traces we discovered, which are straight, vertically aligned with the bedding plane, and overlap-free (Kegel, 1966). These characteristics correspond to those of *Arenicolites*.

Comments. Despite being common in shallow-water marine environments, *Arenicolites* have also been recorded in both deep-water and non-marine environments (Buatois & Mángano, 2004). In non-marine environments, it occurs in *Scoyenia* and *Mermia* ichnofacies (Buatois & Mángano, 1995).

DISCUSSION

Paleoenvironmental insights

The observed intercalation between muddy and sandy layers indicates changes in energetic conditions of the fluvial flow (Best & Bridge, 1992). The low textural maturity in the

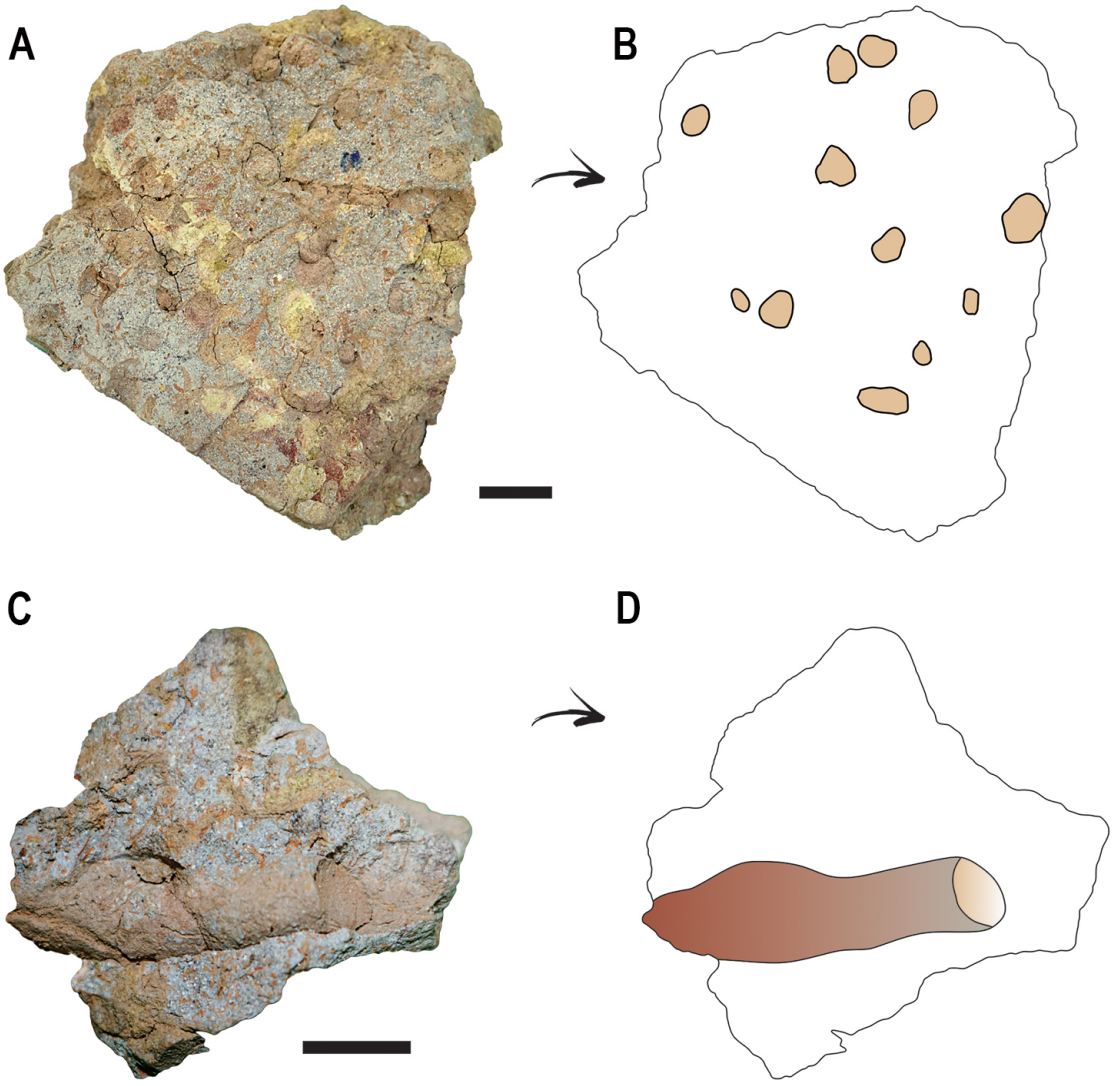

Figure 6. Samples assigned to *Planolites* isp. from bed 6. Scale bar = 10 mm.

sandstones suggests a nearby source area and a low sediment reworking in the depositional system (Boggs, 2006). In addition, the presence of coarse sediments in the bed 5 and an erosive surface (between beds 4 and 5) may be associated with a crevasse splay deposit lying on floodplain deposits (beds 1–4) (Miall *et al*., 2006).

Regarding the paleoenvironmental interpretation, previous tectonic-stratigraphic studies (*e.g*., Ramos, 2003; Negrão *et al*., 2020) inferred a meandering fluvial environment for the Floriano Formation. This interpretation is reinforced in this work based on our trace fossils analysis.

Concerning the ichnology, the Floriano Formation ichnocoenosis includes *Planolites*, *Taenidium*, and *Arenicolites*, which were associated with the habitation, feeding and locomotion habits of annelids and arthropods. The bioturbation index indicates that the fine substrates are stable and suitable for colonization.

Redox characteristics are present in the bed 2 are associated with periods of an increased water retention, which produced reducing microenvironments close to macropores (Vepraskas, 2015). The association of this feature with ichnofossils suggests that the tracemakers are terraphilic, which implies that the trace fossils were produced by surface-dwelling organisms adapted to low humidity (Hasiotis *et al*., 2007). Due to the sensitivity of the organisms to water, this fluctuation in the water table posed a problem for their proliferation. At least, the presence of *Planolites* and *Taenidium* indicates a substrate with a medium degree of compaction of the sediments, ranging from soft to firm substrates (Buatois & Mángano, 2011).

Ichnofacies

Ichnofacies are characterized by a set of attributes shared by different ichnocenoses, in similar environmental conditions and time intervals (Buatois & Mángano, 2011). Six archetypal ichnofacies were proposed for the continental domain: Scoyenia (Seilacher, 1967), Mermia (Buatois & Mángano, 1995), Coprinisphaera (Genise *et al*., 2000), Termitichnus (Smith *et al*., 1993); (Genise *et al*., 2000), Celliforma (Genise *et al*., 2010) and Entradichnus-Octopodichnus (Buatois & Mángano, 2008).

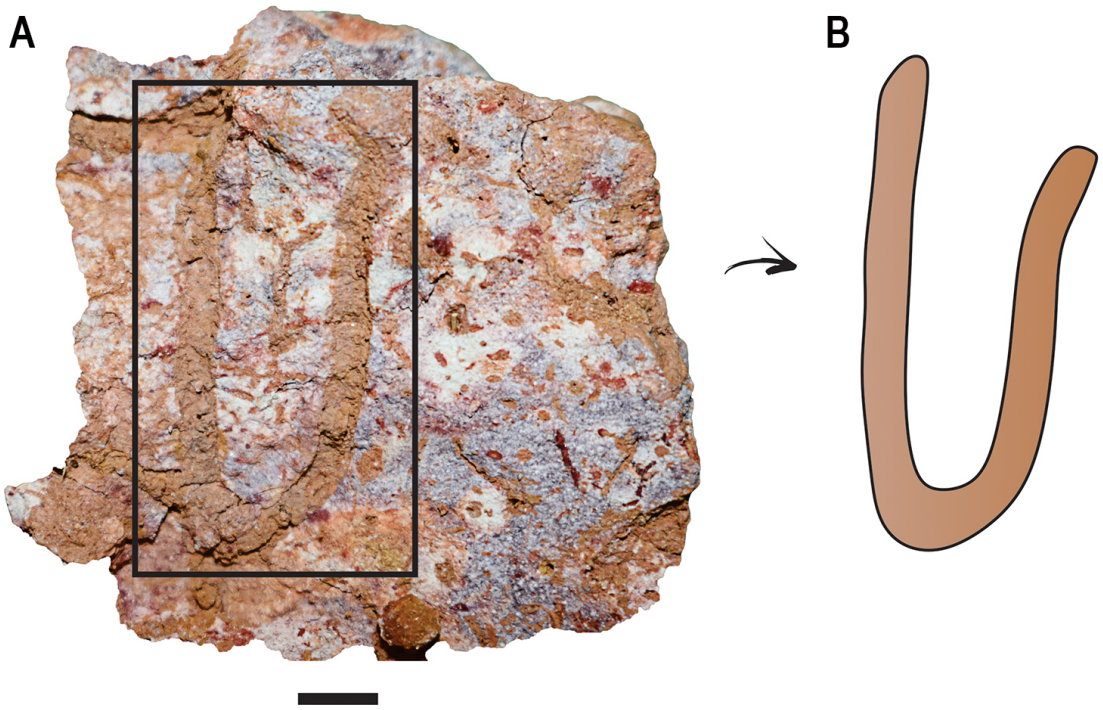

Figure 7. Sample assigned to *Arenicolites* isp. from bed 3. Scale bar = 10 mm.

The sedimentary deposit studied presents an ichnological assemblage with low diversity, moderate abundance of bioturbations and trace fossils including invertebrate tubes and meniscated traces. This assemblage includes *Taenidium*, *Planolites*, and *Arenicolites*. Among the associations of fossil traces found in continental environments previously discussed, the ichnofacies that matches to the detailed set of the study area is Scoyenia. This ichnofacies – which represents the transition between the subaerial and underwater environment or periodically flooded areas – presents a low diversity, in turn monospecific, consisting mainly of trace fossils associated to habitation, food and locomotion. It is mostly represented by cylindrical vertical excavations produced by invertebrates (mainly arthropods), abundance of horizontal meniscated traces, and the subordinated presence of vertebrate and plant traces. It is common in depositional environments associated with lake shores, river channel shores and sandy bars or floodplains (Buatois & Mángano, 2011). Generally, this ichnofacies includes the ichnogenera *Taenidium*, *Beaconites*, *Scoyenia*, *Fuersichnus*, *Rusophycus*, *Camborygma*, *Diplichnites*, *Mirandaichnium*, *Umfolozia* and *Cruziana* (Buatois & Mángano, 2011), however, the most common are *Planolites*, *Palaeophycus*, *Beaconites*, *Scoyenia*, and *Taenidium* (Buatois & Mángano, 2011).

This ichnofacies was previously recognized in deposits of other Brazilian sedimentary basins by Mineiro *et al*. (2017) and Menezes *et al*. (2019), which reported traces of plants, invertebrates, and vertebrates in paleosols formed in Cretaceous alluvial systems of Bauru and Parnaíba basins, respectively. Our ichnofaciological assignment for the Miocene Floriano Formation expands the occurrence of Scoyenia ichnofacies for fluvial deposits, in the case of Brazil.

CONCLUSIONS

The outcrop includes sediments deposited in the context of a floodplain overlayed by a crevasse splay deposit. Our sedimentological and ichnological data reinforce the interpretation of a meandering fluvial environment for the Miocene Floriano Formation. Trace fossils of terraphilic organisms were found in the fine-grained sediments of the outcrop. The ichnocoenosis is composed by *Taenidium* isp., *Planolites* isp. and *Arenicolites* isp. and is assigned to the Scoyenia ichnofacies. The trace fossils association is characterized by traces of worm-like invertebrates, representing feeding (fodinichnia), locomotion (repichnia) and/or habitation (domichinia) structures. This is the first record of the Scoyenia ichnofacies in a typical meandering fluvial system in Brazil.

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