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Ichnological analysis and paleoenvironmental inferences of Neogene meandering fluvial deposits in Continental Rift of Southeastern Brazil

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Abstract

The sedimentary basins in the Continental Rift of Southeastern Brazil (CRSB) provide an opportunity for ichnological analyses due to its well-known facies relationships and paleoenvironmental interpretations. This study reports invertebrate trace fossils from the Neogene fluvial deposits (Floriano Formation) and applies integrated ichnological and facies analyses to reconstruct the environmental conditions recorded in this lithostratigraphic unit. Fieldworks revealed a rich ichnofauna in the Floriano Formation, whose facies associations have been interpreted as indicative of meandering river environments. Four sedimentary facies were identified, including bioturbated sandstone, horizontally stratified sandstone, laminated sandstone, and mudstone. Six ichnogenera were identified, *Arenicolites, Beaconites, Camborygma, Palaeophycus, Skolithos,* and *Taenidium*. Those ichnogenera occur as *Skolithos*, *Taenidium*, and *Beaconites* ichnocoenoses. The *Skolithos* ichnocoenosis is primarily represented within sand bar deposits, indicating arthropod colonization in abandoned channels. The *Taenidium* ichnocoenosis, which is observed within mudstone layers and presents *Camborygma* burrows, suggests transitional environments between aquatic and subaerial conditions, locally with high water table levels. The *Beaconites* ichnocoenosis indicates changes in substrate consistency associated with progressive desiccation and extended exposure time. Therefore, the identified ichnocoenoses, combined with the analysis of physical sedimentary structures, suggest generally humid conditions during colonization by invertebrates of the meandering river deposits of the Floriano Formation.

KEYWORDS: paleosol; neogene; continental rift of Southeastern Brazil; ichnology; *Scoyenia* ichnofacies.

INTRODUCTION

Ichnological analyses allow us to infer several paleoecological parameters in a depositional setting (e.g., hydrodynamic energy, salinity, oxygenation, substrate consistency, and food availability), mainly because they are the manifestation of behaviors controlled by paleoenvironmental conditions (Buatois and Mángano 2011). Therefore, ichnology has played a crucial role in paleoecological and paleoenvironmental inferences since the rise of the ichnofacies concept (Seilacher 1953). In this sense, trace fossils can be a relevant tool to understand the depositional setting in rocks without body fossils (e.g., Assine 1996, Sedorko *et al.* 2017, Richter *et al.* 2023), which, in some cases, are more precise than microfossil data (MacEachern *et al.* 1999, Aquino *et al.* 2001). Although trace fossils have been applied to understand a wide range of depositional environments, marine and coastal settings are by far the most frequently studied (e.g., Buatois and Mángano 2011, Sedorko and Francischini 2020). In the case of meandering river systems in particular, research is often more focused on coastal zones with tidal influence (e.g., Pearson and Gingras 2006, Rebata *et al.* 2006, Dalrymple and Choi 2007, Gugliotta *et al.* 2016), with fewer studies investigating the ichnology of fluvial settings further inland (e.g., Gowland *et al.* 2018, Sedorko *et al.* 2020).

Within the context of the Continental Rift of Southeastern Brazil (CRSB), the Resende Basin is considerably well-understood in terms of facies relationships and their paleoenvironmental significance (Amador 1975, Melo *et al.* 1985, Riccomini *et al.* 2004, Ramos *et al.* 2006). However, the basin lacks detailed ichnocoenoses analyses, with a single report of *Skolithos* in fluvial braided deposits of the Resende Formation (Fernandes *et al.* 1992), and a report of trace fossils with paleoenvironmental attribution for the Floriano Formation (Motta *et al.* 2023). Interpreted as representing meandering river environments (Ramos *et al.* 2006, Negrão *et al.* 2020), the Floriano

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Formation has revealed an undocumented diverse ichnofauna, based on recent fieldwork observations, making it an interesting prospect to investigate the ichnological aspects of these environments. Furthermore, considering the rich fossil content of mammalian, birds, invertebrates, and plants preserved in the sedimentary record of Itaboraí, Taubaté, and Curitiba basins (Lima and Amador 1985, Bergqvist *et al.* 2004, Sedor 2017, Rangel *et al.* 2019, 2023a, 2023b), ichnological analyses of the siliciclastic filling of the CRSB represent a complementary approach to understanding Cenozoic biotas and paleoenvironments of southeastern Brazil. In addition, there is limited research on trace fossils related to meandering river systems (e.g., Sedorko *et al.* 2020), as well as few studies dealing with Cenozoic or recent biogenic structures for Brazilian strata (e.g. Netto and Rossetti 2003, Nascimento *et al.* 2021, Ramos *et al.* 2021, 2022, Sedorko *et al.* 2024). In this sense, this study aimed to (1) report undocumented invertebrate trace fossils from the Floriano Formation and (2) apply integrated ichnologic and facies analyses for reconstructing the environmental conditions represented in the unit.

GEOLOGICAL SETTING

The CRSB is a Paleogene geological province that extends for approximately 900 km in an NW-SE trend between the states of Paraná and Rio de Janeiro (Riccomini 1989, Riccomini *et al.* 2004; Fig. 1A). It developed over the Neoproterozoic Ribeira Belt, which is a part of the Brasiliano Orogenic Cycle (Hasui *et al.* 1975, Heilbron *et al.* 2004, Negrão *et al.* 2020). Jurassic-Cretaceous tholeiitic dikes associated with the opening of the Atlantic margin (Almeida *et al.* 2000, Guedes *et al.* 2005) and Late Cretaceous alkaline massifs are intruded in the Neoproterozoic basement (Riccomini 1989, Thomaz Filho and Rodrigues 1999, Rosa and Ruberti 2018).

The tectonic evolution of the CRSB can be divided into five stages, with the first stage responsible for its origin in the Eocene and the subsequent stages related to neotectonic deformations during the Neogene and Quaternary, including distensive, transcurrent, and compressive events (Riccomini *et al.* 2004).

The CRSB is divided into three distinct portions, each containing Cenozoic basins (Melo *et al.* 1985): the Western Segment (Curitiba Basin), the Central Segment (São Paulo, Taubaté, Resende, and Volta Redonda basins), and the Eastern Segment (São José de Itaboraí, Macacu, and Barra de São João basins; Fig. 1A).

Riccomini (1989) considered that the origin of the CRSB would be due to Paleogene tectonic reactivations along Neoproterozoic shear zones induced by thermomechanical subsidence of the Santos Basin in the adjacent offshore region. An Eocene NW-SE distensive tectonic phase caused the formation of NE-SW and ENE-WSW half-grabens, such as the Resende Basin.

The sedimentary filling of the CRSB basins consists of deposits related to alluvial fans along the tectonically active basin flanks, transitioning into axial braided and meandering fluvial systems, as well as lacustrine environments. Negrão *et al.* (2020) proposed the more recent lithostratigraphic chart of the Resende Basin, based on previous studies performed by Ramos *et al.* (2006). According to Negrão *et al.* (2020), the Paleogene sedimentation in the Resende Basin is related to three tectonic stages: Pre-Rift Stage, with braided river deposits of the Ribeirão dos Quatis Formation (massive or incipiently stratified orthoconglomerates and minor interbedded cross-stratified sandstones); Rift Stage I, with braided river and alluvial fan deposits of the Resende Formation (main syntectonic sedimentation, which is recorded by submature stratified conglomerates and feldspathic sandstones interbedded with greenish massive mudstones, and matrix- and clast-supported breccias and pebbly wackes); and Rift Stage II, with the braided river deposits of the Pinheiral Formation (quartzose orthoconglomerates and feldspathic sandstones interbedded with relatively thick mudstones layers).

The Neogene stratigraphic record corresponds to the Floriano Formation (stratified conglomerates and sandstones, and massive reddish mudstones), which is interpreted as a post-rift fluvial meandering system (Negrão *et al.* 2020). Sigmoidal lateral accretion features are observed, composed of stratified fine sandstones and laminated siltstones (Carmo 1996, Ramos *et al.* 2006, Negrão *et al.* 2020). Covering the succession, Pleistocene and Holocene alluvial deposits are associated with the filling of Quaternary grabens and valleys.

MATERIALS AND METHODS

The Floriano Formation deposits investigated in this study are exposed at an outcrop first described by Carmo (1996) in the Resende Municipality, Rio de Janeiro state (Brazil), along the RJ-161 road (22º26'49" S; 44º26'30" W, 443 m). The sedimentary facies were described and analyzed by considering their texture, geometry, composition, primary sedimentary structures, and trace fossil content. This analysis followed the protocol outlined by Miall (1996), and we selected three geological logs (P1, P2, and P3) to represent the outcrop (Figs. 2 and 3). In all stratigraphic horizons, we conducted a thorough search for trace fossils, and their descriptions were based on the ichnotaxonomic classification and ichnocoenosis approach as proposed by Bromley (1996), which considered ichnocoenosis as an ichnoassociation that can be related to one definite biocoenose, reflecting a depositional scenario. The amount of bioturbation was quantified using a visual scale, ranging from 0 (no bioturbated) to 6 (bed completely bioturbated), following the approach suggested by Reineck (1963) (see Netto 2020 for the visual scale). Few hand samples were analyzed in polished cross-sections to better examine key ichnotaxobases of some specimens.

RESULTS

The studied section exhibits lenticular to sigmoidal beds of poorly stratified and laminated sandstone interbedded with massive mudstone, showing fining upward cycles (Fig. 2). The high amount of trace fossils precluded the clear observation of primary sedimentary structures, but the sigmoidal

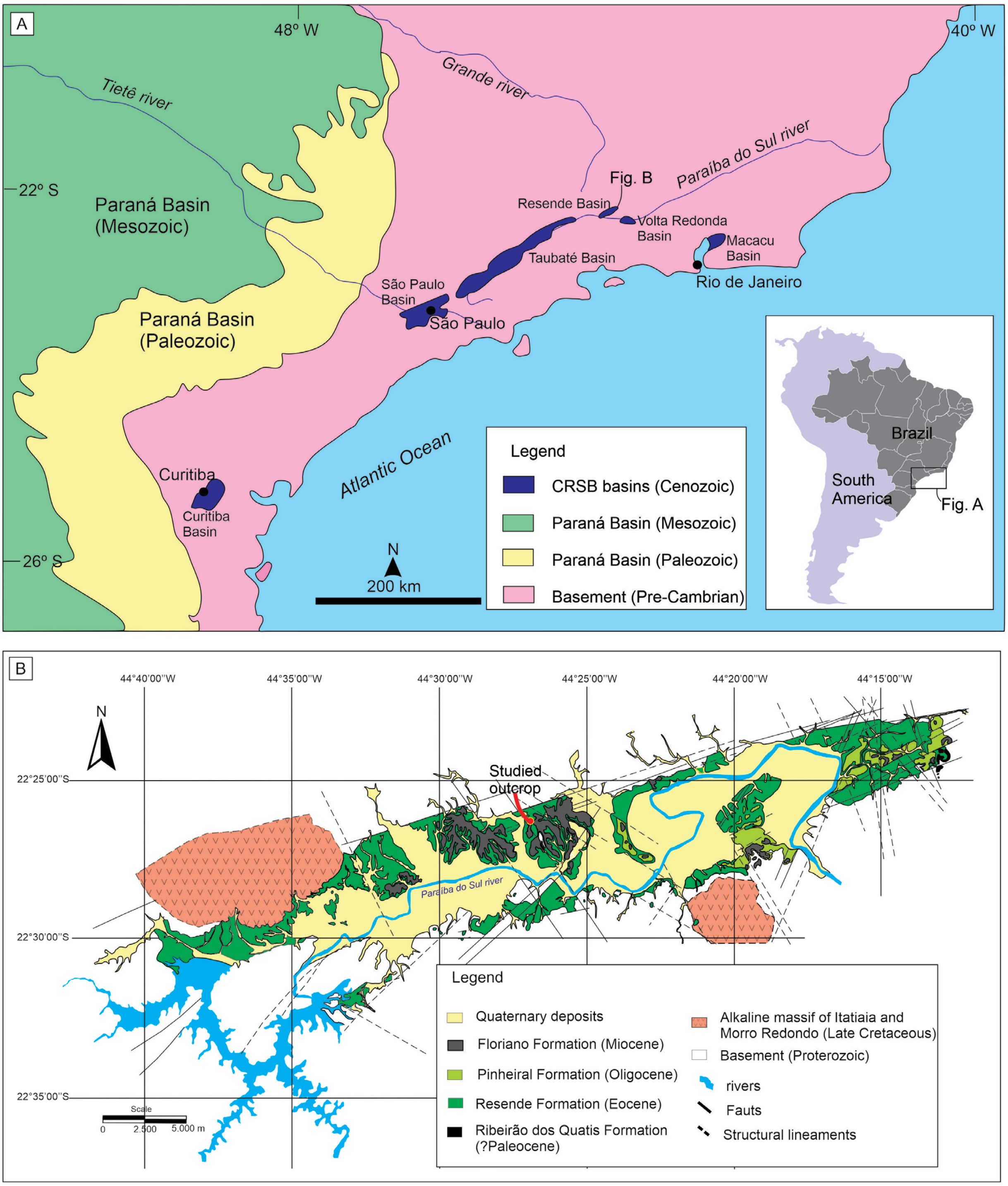


Figure 1. Geological setting of the studied area. (A) Position of the basins in the Continental Rift of Southeastern Brazil with emphasis on Resende Basin (modified from Riccomini *et al.* 2004). (B) Geological map of the Resende Basin with the position of studied outcrop in the cropping out area of Floriano Formation. Modified from Ramos *et al.* (2006).

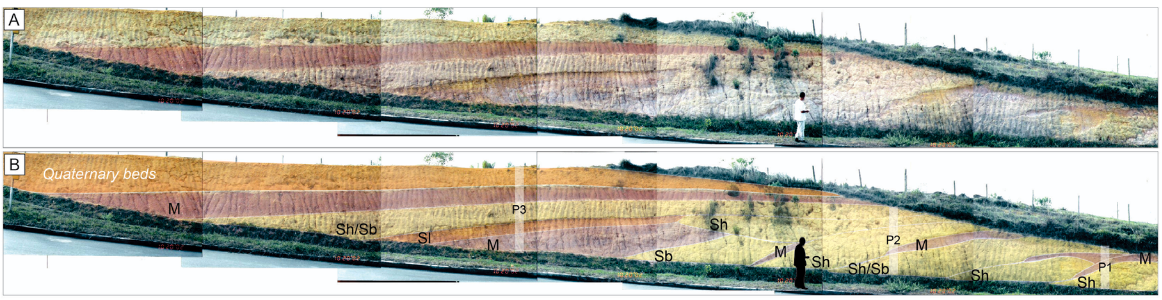


Figure 2. Panoramic view of the studied outcrop. (A) Composite field photographs of the exposed sedimentary deposits. (B) The same image with a superimposed interpretative drawing highlighting the general sigmoidal geometry of the deposits and the position of geological sections (P1, P2, and P3). See Table 1 for facies codes.

geometry is evident (Fig. 2B). The finning upward cycles are locally truncated by a more erosive sand-bar, and the whole deposit is truncated by conglomeratic beds of probable Quaternary age (Fig. 2).

Four sedimentary facies (Sb, Sh, Sl, and M facies) were recognized. The Sb and Sh facies crop out as lenticular to sigmoidal beds of poorly stratified, feldspathic sandstones with subangular to subrounded grains, moderate to well sorted, low compaction, and subordinate amounts of lutitic epimatrix probably originated by decomposition of the feldspathic framework. The Sl facies is more tabular and represents fine to very fine feldspathic sandstones mainly composed of subangular grains, with good selection and low compaction, also with subordinate amount of lutitic epimatrix. Finally, the mudstone presents a lenticular geometry when overlying the sand-bars or can be tabular in the upper portion of the section (Fig. 2), presenting a mottled texture with thin lenses of fine-grained sandstone, and blocky structures suggesting the effects of pedogenesis (Table 1).

Trace fossils ichnocoenosis

Six ichnogenera were identified in the studied section: *Arenicolites, Beaconites, Camborygma, Palaeophycus, Skolithos,* and *Taenidium*. Those ichnogenera were grouped considering the facies (Fig. 4) and interrelation with each other, resulting in three ichnocoenoses: *Skolithos*, *Taenidium*, and *Beaconites* ichnocoenoses.

The *Skolithos* ichnocoenosis is dominated by simple vertical structures, passively filled, with smooth to rarely irregular walls identified as *Skolithos* (Fig. 5A), associated with sparse, simple horizontal structures with a lined wall identified as *Palaeophycus* (Fig. 5B). Rarely, it is associated with passively filled burrows with U-shaped basal portion, identified as *Arenicolites* (Figs. 5B and 5E). The bioturbation scale is highly variable, between 1 and 5 (Fig. 3). A low bioturbation scale is commonly associated with coarser-grained facies (Figs. 3B and 3C), increasing toward the top of coarse-grained beds, where *Palaeophycus* becomes increasingly rarer (Figs. 3A–3C). This ichnocoenosis is restricted to Sh and Sb facies.

The *Taenidium* ichnocoenosis is dominated by horizontally or vertically oriented unwalled structures with tightly spaced menisci, identified as *Taenidium* (Figs. 5C and 5D). The biogenic structures range from 4 to 18 mm in diameter, and menisci in most vertical specimens show a concave-up orientation (see Figs. 5C and 5D). Additionally, there are also occasional occurrences of walled meniscate burrows attributed to *Beaconites* (Figs. 5F and 5G). Simple vertical structures identified as *Skolithos* are subordinated (Fig. 5G), as well as simple horizontal structures identified as *Palaeophycus.* On a single level, vertically oriented, passively filled, ramified structures were identified, and the lateral chambers, smooth walls, and regular diameter allowed the attribution to *Camborygma* (Figs. 5H and 5I). The described *Camborygma* specimens present a diameter between 1.6 and 2.1 cm, reaching 2.6 cm near the region of ramification, while the maximum depth is 9 cm. The bioturbation scale in this ichnocoenosis varies from 3 to 6 but is often very high (5–6; Fig. 3). This ichnocoenosis is restricted to M and Sl facies.

Finally, the *Beaconites* ichnocoenosis is the less diverse in the studied outcrop, dominated by simple vertical structures attributed to *Skolithos* (Fig. 4E), as well as walled, meniscated structures attributed to *Beaconites* (Fig. 5J) and unwalled meniscated structures attributed to *Taenidium.* Less often, *Palaeophycus* also occurs (Fig. 5J). The bioturbation scale is high (Fig. 6), obliterating the physical sedimentary structures. This ichnofabric is restricted to a mudstone bed in the uppermost section (P3), just below a conglomeratic bed (Fig. 3A) inferred as Quaternary (e.g., Carmo 1996). The structures are filled with material similar to that of the host rock, which is an argument to consider these structures as penecontemporaneous rather than produced in the overlying beds.

DISCUSSION

The four sedimentary facies (Sh, Sb, Sl, and M facies) were grouped into three architectural elements:

- Sand Bars (SB) composed of bioturbated sandstone (Sb facies) and sandstone with horizontal stratification (Sh facies);
- Crevasse Splays (CS) composed of laminated sandstone (Sl facies);
- Floodplain (FP) mudstones (M facies; Table 1).

The most common elements in the studied section are Sand Bars and Floodplain mudstones, presenting a low degree of pedogenesis (facies M). Crevasse Splays are restricted to one level (interval around 1 m of Fig. 3A). These deposits are generally organized as sigmoidal beds with finning upward cycles,

Table 1. Facies and inferred depositional processes of the studied outcrop, Floriano Formation.

Code	Facies	Description	Process	Figure
M	Mudstone	Mudstone with mottled texture, locally with thin lenses of fine-grained sandstone, with incipient pedogenesis	Decantation in the overbank locally disrupted by tractive flows	3A, 3E
Sb	Bioturbated sandstone	Medium-grained quartzose sandstone with mottled texture in lenticular beds	Tractive processes obliterated by high bioturbation activity	3B
Sh	Sandstone with horizontal stratification	Fine- to coarse-grained sandstone, highly bioturbated, with faint horizontal stratification locally presenting a mottled texture in lenticular beds	Tractive processes in unidirectional flow, locally obliterated by bioturbation activity	3C
Sl	Laminated sandstone	Very fine- to fine-grained sandstone with parallel lamination in tabular to lenticular bed	Tractive processes in unidirectional flow	3D

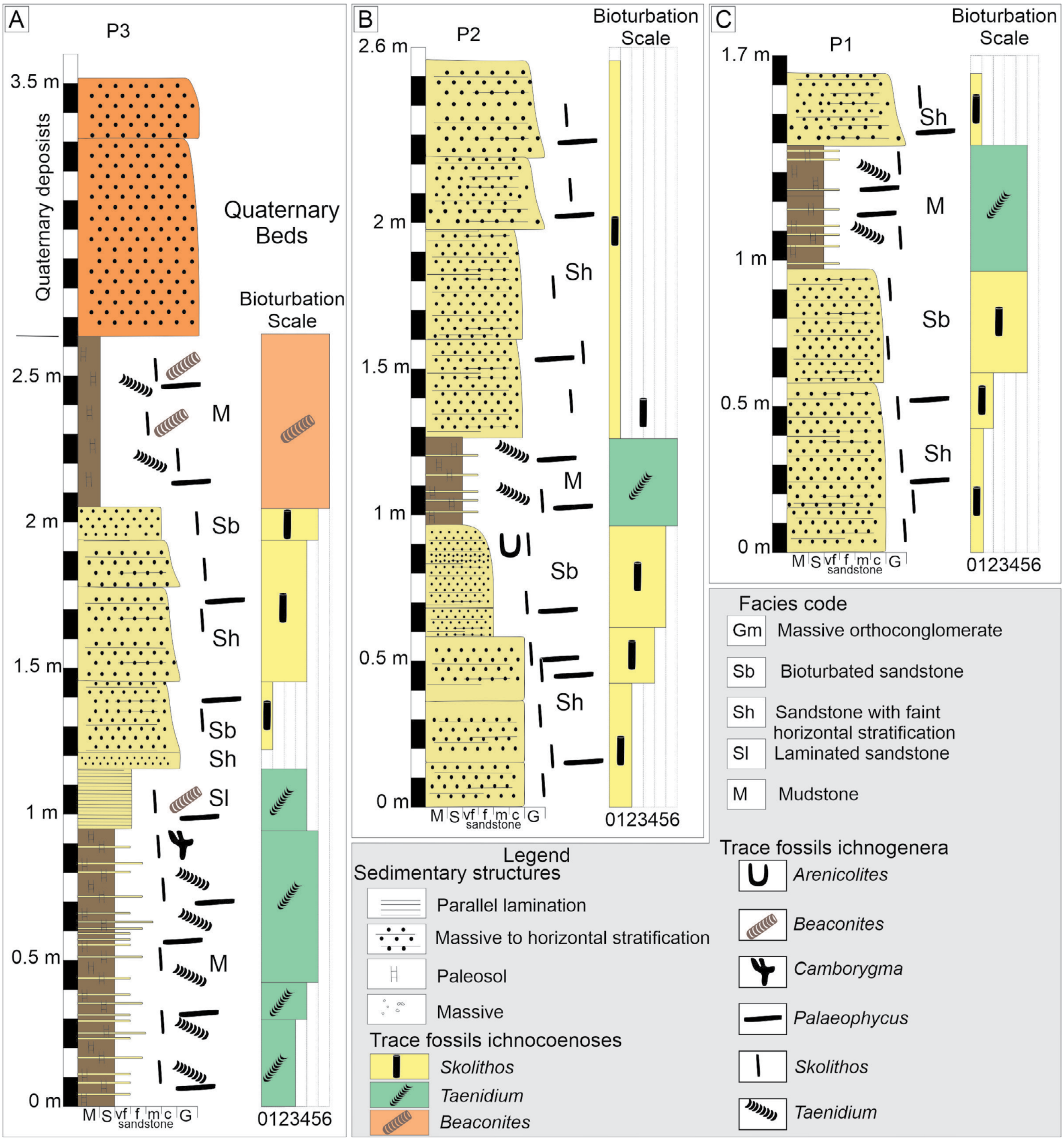


Figure 3. Facies and ichnocoenoses distribution in the studied outcrop. (A) Geological section of P3 with the level of occurrence of facies and trace fossils. (B) Geological section of P2 with the level of occurrence of facies and trace fossils. (C) Geological section of P1 with the level of occurrence of facies and trace fossils. P1 is inserted laterally and below P2 and P3 (see Fig. 2 for the position).

representing an initial dominance of tractive process (represented by Sh and Sb facies) followed by a decantation phase (M facies) (Nichols and Fisher 2007). Overlying those beds, a general tabular bed of reddish mudstone occurs, representing the FP element. These characteristics corroborate the inferred meandering fluvial system for the studied outcrop (Carmo 1996, Negrão *et al.* 2020, Motta *et al.* 2023).

The predominant facies in the outcrop consist of amalgamated sandy beds (Sb and Sh facies) bearing trace fossils of the *Skolithos* ichnocoenosis, which are characterized as Sand Bars macroforms. These facies are interpreted to be formed by the migration of sandy bedforms in fluvial channels with lateral accretion, interbedded with mudstone that represents the finning upward cycle (Figs. 2 and 3) (Carmo 1996). The horizontal stratified sandstone (facies Sh) was generated by upper regime flow at the top of fluvial bars (Miall 2014). The presence of *Skolithos* ichnocoenosis corroborates high energetic settings in the fluvial bars. On the contrary, bioturbated sandstone (Sb facies) in amalgamated beds evidences episodes of decrease in the velocity of fluvial discharge and sedimentation, allowing colonization of the top of the Sand Bars. The overall dominance of *Skolithos* ichnocoenosis in those facies (Sh and Sb) indicates colonization of sand bars by arthropods, which is the most common bioturbating group in continental settings, in subaqueous conditions (Ratcliffe and Fagerstrom 1980, Krapovickas *et al.* 2009). The higher

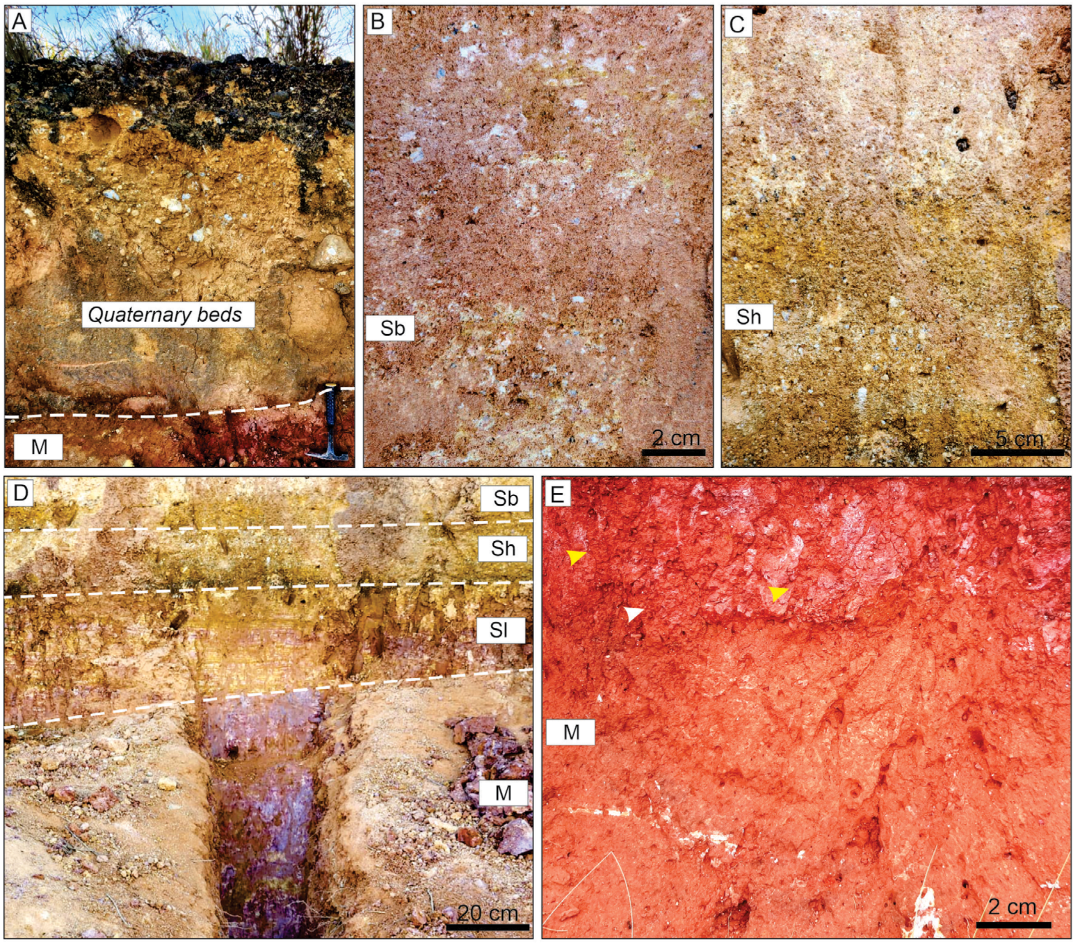


Figure 4. Sedimentary facies from the studied outcrop. (A) Massive orthoconglomerate facies from Quaternary levels (not the focus of this study). (B) Bioturbated and massive sandstone facies. (C) Sandstone with faint horizontal stratification. (D) Mudstones (M), Laminated sandstone (Sl), Horizontally-stratified sandstone (Sh), and bioturbated sandstone (Sb). (E) Mudstone with pedogenetic features; note the blocky structure (white arrow) and trace fossils with irregular walls (yellow arrow). See Table 1 for facies codes.

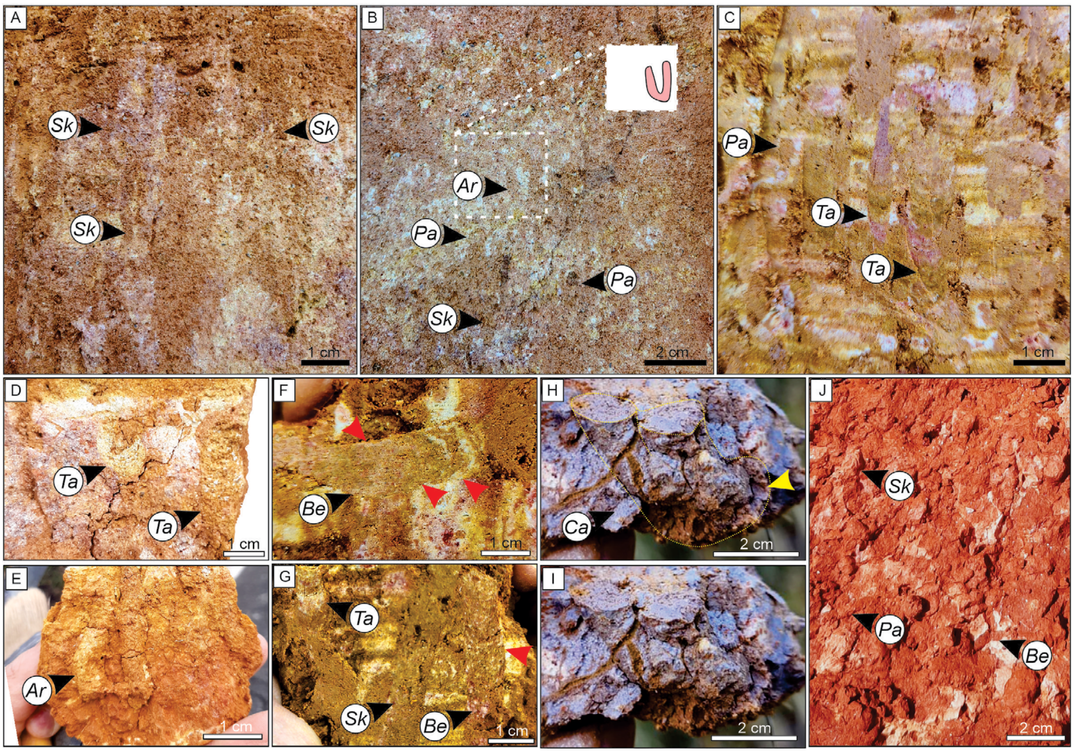
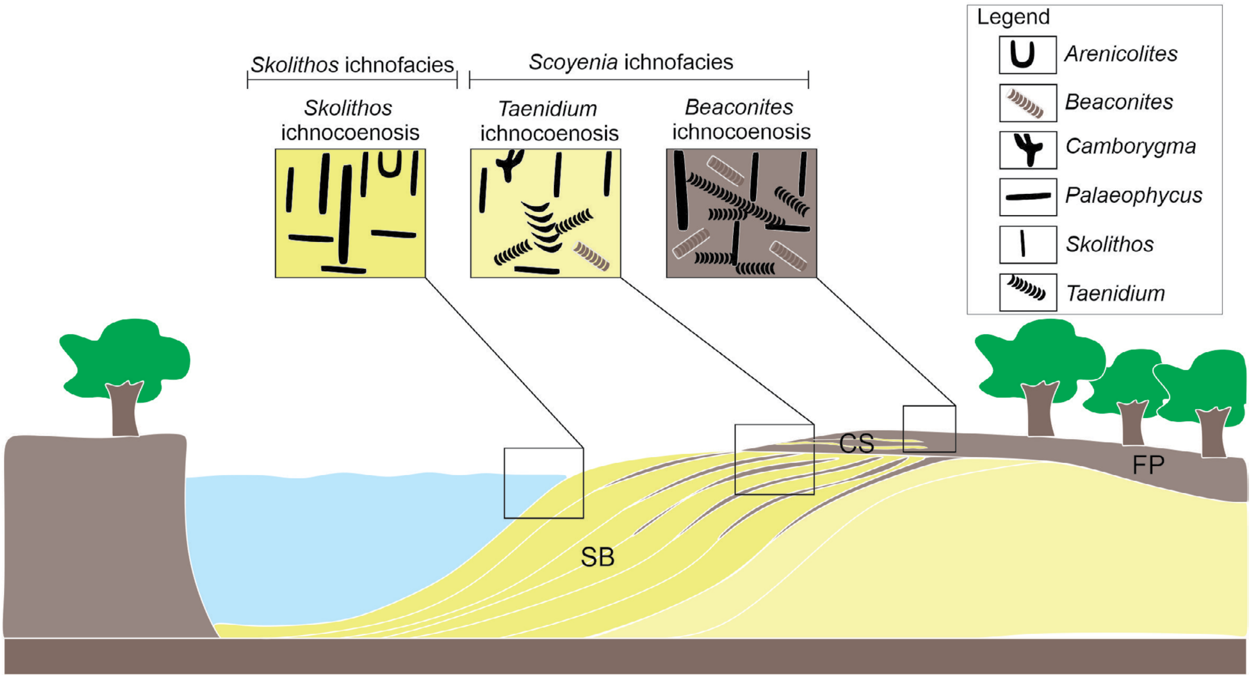


Figure 5. Trace fossils from the studied section. (A and B) The *Skolithos* ichnocoenosis with *Skolithos* (*Sk*), *Arenicolites* (*Ar*), and *Palaeophycus* (*Pa*). (C–I) The *Taenidium* ichnocoenosis with *Taenidium* (*Ta*), *Beaconites* (*Be*), and *Camborygma* (*Ca*) – the yellow arrow indicates the lateral chamber. (J) The *Beaconites* ichnocoenosis with *Skolithos* (*Sk*), *Beaconites* (*Be*), and *Palaeophycus* (*Pa*).



SB: Sand Bars; CS: Crevasse Splays; FP: Floodplain mudstones.

Figure 6. Idealized distribution of the ichnocoenoses in the meandering river system represented by Floriano Formation, Resende Basin.

bioturbation density in the top of the sand beds suggests that the main colonization took place during reduced hydraulic energy and sedimentation rate.

The Sand Bar deposits are occasionally interbedded with mudstone (M) or locally with fine-grained laminated sandstone (Sl). This intercalation is interpreted as representing low energy conditions and decantation of mud (M) within proximal sectors of the floodplain, and crevasse splay deposits (Sl). Within these intervals, the former represents a more restricted component (in both lateral extension and thickness), exhibiting an incipient degree of soil development, as evidenced by the density of trace fossils and local blocky structures in mudstone deposits (Fig. 4D). In both these mudstones and the Crevasse Splays deposits (Sl facies), trace fossils of the *Taenidium* ichnocoenosis occur in low diversity, representing a transition between aquatic and terrestrial depositional systems (Frey and Pemberton 1984). *Taenidium*, *Palaeophycus*, and *Skolithos* are commonly found in soft substrates, while the walled *Beaconites* suggest firmground conditions due to local subaerial exposure (Savrda *et al.* 2000, Buatois and Mángano 2002). The presence of antagonistic wall signatures (softground for *Taenidium* and firmground for *Beaconites*) in the same levels attests to the occasional exposure events at the top of the Sand Bars and proximal floodplain. The occurrence of *Camborygma* suggests crayfish-dwelling activity in crevasse splay deposits (e.g., Hasiotis and Mitchell 1993). The depth of *Camborygma* burrows can serve as an indicator of the water table level because its chambers remain submerged during colonization (Hasiotis 2007). Thus, the shallow depth of the studied *Camborygma* (maximum 9 cm) suggests colonization during a period of high groundwater levels. This characteristic is frequently associated with proximal floodplains where the low permeability of deposits is responsible for the poor drainage of the profile (Martinsen *et al.* 1999, Catuneanu 2006, Batezelli 2017).

The upper levels of the outcrop are dominated by mudstone deposits with tabular geometry associated with the FP element. The mudstone reflects low energy conditions and deposition of fine sediment through decantation in more distal settings of the floodplain, and the high bioturbation indexes observed and the mottled texture of the material indicate a low sedimentation rate associated with probable subaerial conditions (Nichols and Fisher 2007). The low diverse *Beaconites* ichnocoenosis preserved in those mudstones often presents traces with irregular walls, interpreted as a result of firmground conditions in the substrate, as a result of progressive desiccation of the water body. Although presenting low ichnodiversity, the high bioturbation scale corroborates a scenario of long periods of exposure to this reddish level close to the top of the outcrop (Buatois and Mángano 2007).

Typically, active fluvial channels are associated with the *Skolithos* ichnofacies, which are characterized by simple, vertical, cylindrical burrows primarily attributed to *Skolithos* (Buatois and Mángano 2007). On the contrary, ichnofabrics featuring distinct meniscate burrows like *Taenidium* are typically assigned to the *Scoyenia* ichnofacies, which represents inactive or abandoned channels as well as various overbank settings (Fig. 5). The overall absence of structures indicative of frequent subaerial exposure (e.g., mudcraks and rhizoliths), the predominance of softground over firmground ichnocoenoses, and the occurrence of *Camborygma* attest colonization under generally humid and possibly flooded conditions (Buatois *et al.* 2020). However, the local occurrence of well-defined walls in *Beaconites* ichnocoenosis suggests sporadic firm substrates (Buatois and Mángano 2004), as expected in a meandering fluvial system. The presence of the *Scoyenia* and *Skolithos* ichnofacies in the Floriano Formation provides evidence of biological activity during the Miocene in meandering rivers in an inferred prevalent humid condition due to the dominance of subaqueous ichnocoenoses without evidence of frequent subaerial exposure.

A recent study dealing with the same unit reported *Arenicolites, Planolites,* and *Taenidium* (Motta *et al.* 2023). The presence of *Arenicolites* and *Taenidium* is here confirmed. The horizontal structure attributed to *Planolites*, described as passively filled, would better fit in the diagnosis of *Palaeophycus* (e.g., Pemberton and Frey 1982, Fillion and Pickerill 1990). Motta *et al.* (2023) inferred that the deposits of the Floriano Formation were colonized by organisms adapted to low humidity and that fluctuation in the water table precluded the proliferation of trace fossils. However, Motta *et al.* (2023) only analyzed the interval from Sl facies to the upper reddish mudstone level, which, in fact, represent transitional subaqueous (our *Taenidium* ichnocoenosis) and subaerial (our *Beaconites* ichnocoenosis) conditions. On the contrary, when considering the whole section, our data suggest the predominance of generally humid conditions in these paleoenvironments. Finally, the authors argued that they made the first report of *Scoyenia* ichnofacies in meandering deposits from Brazil, but Sedorko *et al.* (2020) have already reported this ichnofacies for Capacete Formation (Cretaceous).

CONCLUSION

The integrated approach of ichnology and facies analysis corroborated a fluvial meandering depositional setting colonized under predominantly humid conditions for the Floriano Formation (Resende Basin). The identification and classification of three dominant ichnocoenoses, namely, *Skolithos, Taenidium*, and *Beaconites* ichnocoenoses, have revealed colonization patterns, substrate consistency changes, and paleoenvironmental conditions of a meandering fluvial environment with periods of sediment influx starvation and incipient soil formation processes. These ichnocoenoses represent expressions of *Scoyenia* and *Skolithos* ichnofacies. Further studies focusing on other basins and lithostratigraphic units within the CRSB can enhance our understanding of the controls in trace fossil distribution in continental settings.

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REFERENCES

Almeida F.F.M., Brito Neves B.B., Carneiro C.D.R. 2000. The origin and evolution of the South American platform. *Earth Science Review*, **50**(1-2):77-111. https://doi.org/10.1016/S0012-8252(99)00072-0

Amador E.S. 1975. Estratigrafia e sedimentação na Bacia de Resende- RJ. *Anais da Academia Brasileira de Ciências*, **47**:181-223.

Aquino R., Buatois L.A., Somoza D., Briceño M., Moreno, J. 2001. Integration of ichnology, palynology, foraminiferal paleoecology, sedimentology and sequence stratigraphy in reservoir characterization: Oligocene–Lower Miocene, Pirital Field, north of Monagas, Oriental Basin of Venezuela. *VI International Ichnofabric Workshop*, Abstracts, Isla Margarita & Puerto La Cruz, p. 22-23.

Assine M.L. 1996. *Aspectos da estratigrafia das seqüências pré-carboníferas da Bacia do Paraná no Brasil* [Doctoral Thesis]. São Paulo: Universidade de São Paulo, 207p.

Batezelli A. 2017. Continental systems tracts of the Brazilian Cretaceous Bauru Basin and their relationship with the tectonic and climatic evolution of South America. *Basin Research*, **29**(Suppl. 1):1-25. https://doi.org/10.1111/bre.12128

Bergqvist L.P., Avilla L.S., Abrantes E.A.L. 2004. The Xenarthra of São José de Itaboraí basin (upper Paleocene, Itaboraian), Rio de Janeiro, Brasil. *Geodiversitas*, **26**(2):323-337.

Bromley R.G. 1996. *Trace Fossils: Biology, Taphonomy and Applications*. London: Chapman and Hall. 361 p.

Buatois L.A., Mángano M.G. 2002. Trace fossils from Carboniferous floodplain deposits in western Argentina: implications for ichnofacies models of continental environments. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **183**(1-2):71-86. https://doi.org/10.1016/S0031-0182(01)00459-X

Buatois L.A., Mángano M.G. 2004. Animal-substrate interactions in freshwater environments: applications of ichnology in facies and sequence stratigraphic analysis of fluvio-lacustrine successions. *Geological Society, London, Special Publications*, **228**(1):311-333. https://doi.org/10.1144/GSL.SP.2004.228.01.14

Buatois L.A., Mángano M.G. 2007. Invertebrate Ichnology of Continental Freshwater Environments. In: Miller W. (Ed.). *Trace Fossils: Concepts, Problems, Prospects*. Amsterdam: Elsevier. p. 285-323. https://doi.org/10.1016/B978-044452949-7/50143-1

Buatois L.A., Mángano M.G. 2011. *Ichnology: Organism-substrate interactions in Space and Time*. Cambridge: Cambridge University Press, 370 p.

Buatois L.A., Wetzel A., Mángano M.G. 2020. Trace-fossil suites and composite ichnofabrics from meandering fluvial systems: The Oligocene Lower Freshwater Molasse of Switzerland. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **558**:109944. https://doi.org/10.1016/j.palaeo.2020.109944

Carmo I.O. 1996. *Análise estratigráfica de depósitos pleistocênicos no Médio Vale do Rio Paraíba do Sul (SP/RJ)* [M.Sc. dissertation]. Rio de Janeiro: Universidade Federal do Rio de Janeir, 141 p.

Catuneanu O. 2006. *Principles of Sequence Stratigraphy*. Amsterdam: Elsevier, 375 p.

Dalrymple R.W., Choi K. 2007. Morphologic and facies trends through the fluvial-marine transition in tide dominated depositional systems: a schematic framework for environmental and sequence stratigraphic interpretation. *Earth-Science Reviews*, **81**(3-4):135-174. https://doi.org/10.1016/j.earscirev.2006.10.002

Fernandes A.C.S., Borghi L.F., Carvalho I.S. 1992. Icnofósseis de artrópodes na Formação Resende (Bacia de Resende, RJ). *Anais da Academia Brasileira de Ciências*, **63**(1):96-97.

Fillion D., Pickerill R.K. 1990. Ichnology of the Upper Cambrian? to Lower Ordovician Bell Island and Wabana groups of eastern Newfoundland, Canada. *Palaeontographica Canadiana*, **7**:1-119.

Frey R.W., Pemberton S.G. 1984. Trace Fossil Facies Models. In: Walker R.G. (Ed.). *Facies Models*. 2. ed. Tulsa: American Association of Petroleum Geologists. P. 189-207.

Gowland S., Taylor A.M., Martinius A.W. 2018. Integrated sedimentology and ichnology of Late Jurassic fluvial point-bars – facies architecture and colonization styles (Lourinhã Formation, Lusitanian Basin, western Portugal). *Sedimentology*, **65**(2):400-430. https://doi.org/10.1111/sed.12385

Guedes E., Heilbron M., Vasconcelos P.M., Valeriano C.M., Almeida J.C.H., Teixeira W., Thomaz Filho A. 2005. K-Ar and Ar/Ar ages of dikes emplaced in the onshore basement of Santos Basin, Resende area, SE Brazil: implications for the South Atlantic opening and Tertiary reactivation. *Journal of South American Earth Sciences*, **18**(3-4):371-382. https://doi.org/10.1016/j.jsames.2004.11.008

Gugliotta M., Flint S.S., Hodgson D.M., Veiga G.D. 2016. Recognition criteria, characteristics and implications of the fluvial to marine transition zone in ancient deltaic deposits (Lajas Formation, Argentina). *Sedimentology*, **63**(7):1971-2001. https://doi.org/10.1111/sed.12291

Hasiotis S.T. 2007. Continental ichnology: fundamental processes and controls on trace fossil distribution. In: Miller W. (ed.). *Trace Fossils: Concepts, Problems, Perspectives*. Amsterdam: Elsevier. p. 268-284.

Hasiotis S.T., Mitchell C.E. 1993. A comparison of crayfish burrow morphologies: Triassic and Holocene fossil, paleo-and neoichnological evidence, and the identification of their burrowing signatures. *Ichnos*, **2**(4):291-314. https://doi.org/10.1080/10420949309380104

Hasui Y., Carneiro C.D.R., Coimbra A.M. 1975. The Ribeira Folded Belt. *Revista Brasileira de Geociências*, **5**(4):257-266. https://doi.org/10.25249/0375-7536.1975257266

Heilbron M., Pedrosa-Soares A.C., Campos Neto M.C., Silva L.C., Trouw R.A.J., Janasi V.A. 2004. Província Mantiqueira. In: Mantesso-Neto V., Bartorelli A., Dal Ré Carneiro C., Brito Neves B.B. (Eds.). *Geologia do Continente Sul-Americano – Evolução da Obra de Fernando Flávio Marques de Almeida*. São Paulo: Beca. p. 203-235.

Krapovickas V., Ciccioli P.L., Mángano M.G., Marsicano C.A., Limarino C.O. 2009. Paleobiology and paleoecology of an arid–semiarid Miocene South American ichnofauna in anastomosed fluvial deposits. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **284**(3-4):129-152. https://doi.org/10.1016/j.palaeo.2009.09.015

Lima M.R.D., Amador E.D.S. 1985. Análise palinológica de sedimentos da Formação Resende, Terciário do estado do Rio de Janeiro. *Coletânea de Trabalhos Paleontológicos*, **27**:371-378.

MacEachern J.A., Stelck C.R., Pemberton S.G. 1999. Marine and Marginal Marine Mudstone Deposition: Paleoenvironmental Interpretations Based on the Integration of Ichnology, Palynology and Foraminiferal Paleoecology. In: Bergaman K.M., Snedden J.W. (Eds.). *Isolated Shallow Marine Sand Bodies: Sequence Stratigraphic Analysis and Sedimentological Interpretation*. Amsterdam: Society for Sedimentary Geology Special Publication, v. 64, p. 205-225.

Martinsen O.J., Ryseth A., Helland Hansen W., Fleshe H., Torkildsen G., Idill S. 1999. Stratigraphic Base Level and Fluvial Architecture: Ericson Sandstone (Campanian), Rocky Springs Uplift, SW Wyoming, USA. *Sedimentology*, **46**(2):235-263. https://doi.org/10.1046/j.1365-3091.1999.00208.x

Melo M.S., Riccomini C., Hasui Y., Almeida F.F.M., Coimbra A.M. 1985. Geologia e Evolução do Sistema de Bacias Tafrogênicas Continentais do Sudeste do Brasil. *Revista Brasileira de Geociências*, **15**(3):193-201. https://doi.org/10.25249/0375-7536.1985193201

Miall A.D. 1996. *The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis and Petroleum Geology*. Heidelberg: Springer-Verlag Incorporation, 582 p.

Miall A.D. 2014. *Fluvial Depositional Systems*. Berlin: Springer International Publishing, 323 p.

Motta M.C., Araújo-Júnior H.I., Menezes M.N., Trifilio L.H.M.S. 2023. Ichnology and sedimentological aspects of the Floriano Formation (Miocene of the Resende Basin), southeast of Brazil. *Revista Brasileira de Paleontologia*, **26**(3):172-182. https://doi.org/10.4072/rbp.2023.3.03

Nascimento D.L., Netto R.G., Indicatti R.P. 2021. Neoichnology of mygalomorph spiders: Improving the recognition of spider burrows in the geological record. *Journal of South American Earth Sciences*, **108**:103178. https://doi.org/10.1016/j.jsames.2021.103178

Negrão A.P., Mello C.L., Ramos R.R.C., Sanson M.S.R., Louro V.H.A., Bauli P.G. 2020. Tectonosedimentary evolution of the Resende and Volta Redonda basins (Cenozoic, Central Segment of the Continental Rift of Southeastern Brazil). *Journal of South American Earth Sciences*, **104**:102789. https://doi.org/10.1016/j.jsames.2020.102789

Netto R.G. 2020. O paradigma das icnofácies e icnofábricas. In: Sedorko D., Francischini H. (Eds.). *Icnologia: interações entre organismos e substrates*. Curitiba: CRV, p. 91-106.

Netto R.G., Rossetti D.F. 2003. Ichnology and salinity fluctuations: a case study from the Early Miocene (Lower Barreiras Formation) of São Luís Basin, Maranhão, Brazil. *Revista Brasileira de Paleontologia*, **6**:5-18.

Nichols G.J., Fisher J.A. 2007. Processes, facies and architecture of fluvial distributary system deposits. *Sedimentary Geology*, **195**(1-2):75-90. https://doi.org/10.1016/j.sedgeo.2006.07.004

Pearson N.J., Gingras M.K. 2006. An ichnological and sedimentological facies model for muddy point-bar deposits. *Journal of Sedimentary Research*, **76**(5):771-782. https://doi.org/10.2110/jsr.2006.070

Pemberton S.G., Frey R.W. 1982. Trace fossil nomenclature and the *Planolites* and *Palaeophycus* dilemma. *Journal of Paleontology*, **56**(4):843-881.

Ramos K.S., Netto R.G., Sedorko D. 2021. Termite nests in eolian backshore settings: An unusual record throughout the Quaternary in the Neotropical realm. *Palaeontologia Electronica*, **24**(1):a15. https://doi.org/10.26879/1146

Ramos K.S., Netto R.G., Sedorko D., Nascimento D.L. 2022. Insect trace fossils as indicators of climatic conditions during the uppermost Pleistocene deposits in southern Brazilian Atlantic coast. *Quaternary Research*, **111**:1-12.

Ramos R.R.C., Mello C.L., Sanson M.S.R. 2006. Revisão estratigráfica da bacia de Resende, Rift Continental do Sudeste do Brasil, Estado do Rio de Janeiro. *Geociências,* **25**(1):59-69.

Rangel C.C., Carneiro L.M., Bergqvist L.P., Oliveira É.V., Goin F.J., Babot M.J. 2019. Diversity, affinities and adaptations of the basal sparassodont Patene (Mammalia, Metatheria). *Ameghiniana*, **56**(4):263-289.

Rangel C.C., Carneiro L.M., Oliveira É.V. 2023a. Systematics, dental specialization and paleoecology of Silvenator gen. nov., a small carnivorous metatherian (Mammalia, Sparassodonta) from the Paleogene Itaboraí Basin. *Journal of South American Earth Sciences*, **128**:104461. https://doi.org/10.1016/j.jsames.2023.104461

Rangel C.C., Carneiro L.M., Tejedor M.F., Bergqvist L.P., Oliveira É.V.A. 2023b. A Reassessment of Nemolestes (Mammalia, Metatheria): Systematics and evolutionary implications for Sparassodonta. *Journal of Mammalian Evolution*, **30**(3). https://doi.org/10.1007/s10914-023-09663-7

Ratcliffe B.C., Fagerstrom J.A. 1980. Invertebrate lebensspuren of Holocene floodplains: their morphology, origin and paleoecological significance. *Journal of Paleontology*, **54:** 614-630.

Rebata L.A., Gingras M.K., Räsänen M.E., Barberi M. 2006. Tidal-channel deposits on a delta plain from the Upper Miocene Nauta Formation, Marañón Foreland Subbasin, Peru. *Sedimentology*, **53**(5):971-1013. https://doi.org/10.1111/j.1365-3091.2006.00795.x

Reineck H.E. 1963. Sedimentgefüge im Bereich der südlichen Nordsee. *Abhandlungen der Senckenbergischen Naturforschenden Gesellschaft*, **505**:1-138.

Riccomini C. 1989. *O Rift Continental do Sudeste do Brasil* [Doctoral Thesis]. São Paulo: Programa de Pós- graduação em Geociências, Universidade de São Paulo, 256 p.

Riccomini C., Sant'Anna L.G., Ferrari A.L. 2004. Evolução Geológica do Rift Continental do Sudeste do Brasil. In: Mantesso-Neto V., Bartorelli A., Dal Ré Carneiro C., Brito Neves B.B. (Eds.). *Geologia do Continente Sul-Americano – Evolução da Obra de Fernando Flávio Marques de Almeida*. São Paulo: Beca, p. 383-405.

Richter K.W., Bosetti E.P., Siqueira I., Sedorko D. 2023. Trace fossils from Furnas formation (Paraná Basin) reveal a marine depositional environment. *Journal of South American Earth Sciences*, **128**:104475. https://doi.org/10.1016/j.jsames.2023.104475

Rosa P.A.D.S., Ruberti E. 2018. Nepheline syenites to syenites and granitic rocks of the Itatiaia Alkaline Massif, Southeastern Brazil: new geological insights into a migratory ring Complex. *Brazilian Journal of Geology*, **48**(2):347-372. https://doi.org/10.1590/2317-4889201820170092

Savrda C.E., Blanton-Hooks A.D., Collier J.W., Drake R.A., Graves R.L., Hall A.G., Wood H.A. 2000. *Taenidium* and associated ichnofossils in fluvial deposits, Cretaceous Tuscaloosa Formation, eastern Alabama, southeastern USA. *Ichnos*, **7**(3):227-242. https://doi.org/10.1080/10420940009380162

Sedor F.A., Oliveira É.V., Silva D.D., Fernandes L.A., Cunha R.F., Ribeiro A.M., Dias E.V. 2017. A New South American Paleogene Land Mammal Fauna, Guabirotuba Formation (Southern Brazil). *Journal of Mammalian Evolution*, **24**(1):39-55. https://doi.org/10.1007/s10914-016-9364-7

Sedorko D., Alessandretti L., Warren L.V., Verde M., Rangel C.C., Ramos K.S., Netto R.G. 2020. Trace fossils from the Upper Cretaceous Capacete Formation, Sanfranciscana Basin, Central Brazil. *Annales Societatis Geologorum Poloniae*, **90**(3):247-260. https://doi.org/10.14241/asgp.2020.15

Sedorko D., Francischini H. 2020. *Icnologia*: interações entre organismos e substrates. Curitiba: CRV, 672 p.

Sedorko D., Nascimento D.L., Carmona N.B., Netto R.G., Rangel C.C., Ramos K.S., Alessandretti L. 2024. Neoichnological analysis of mole cricket burrows: implications of substrate moisture changes on preservation and morphology. *Palaios*, **39**(1):21-32. https://doi.org/10.2110/palo.2023.028

Sedorko D., Netto R.G., Savrda C.E., Assine M.L., Tognoli F.M.W. 2017. Chronostratigraphy and environment of Furnas Formation by trace fossil analysis: Calibrating the lower Paleozoic Gondwana realm in the Paraná Basin (Brazil). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **487**:307-320. https://doi.org/10.1016/j.palaeo.2017.09.016

Seilacher A. 1953. Studien zur palichnologie. I. Uber die methoden der palichnologie. *Neues Jahrbuch fur Geologie und Palaontologie*, **96**:421-452.

Thomaz Filho A., Rodrigues A.L. 1999. O alinhamento de rochas alcalinas Poços de Caldas-Cabo Frio (RJ) e sua continuidade na cadeia Vitória-Trindade. *Brazilian Journal of Geology*, **29**(2):189-194.