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Article

TRACE FOSSIL ANALYSIS IN THE MIOCENE PINDAMONHANGABA FORMATION, TAUBATÉ BASIN, BRAZIL

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ABSTRACT – The Taubaté Basin comprises continental deposits formed within the central segment of the Continental Rift of Southeastern Brazil. The paleontological record of this basin is limited to the lacustrine deposits of the Tremembé Formation, with rare fossil evidence from other units. The Pindamonhangaba Formation, likely of Miocene age, was deposited in a meandering fluvial system during a post-rift phase. While its sedimentological and stratigraphic aspects are well-documented, trace fossils have not been described in this basin. Trace fossil analysis offers valuable insights into paleoenvironmental reconstructions, as they are generally preserved in situ and reflect the behavior of tracemakers, which is controlled by paleoecological parameters. Consequently, trace fossil studies are essential for interpreting paleoenvironmental conditions concurrent with or subsequent to sediment deposition. This study aims to characterize the ichnoassociations of the Pindamonhangaba Formation using a paleoecological approach. A 33-meter-thick section in Taubaté City, composed predominantly of mud-rich deposits with pedogenic features interbedded with sandy channel deposits, reveals diverse trace fossils. These include *Skolithos, Taenidium,* and *Palaeophycus* in sandstones; *Skolithos*, *Palaeophycus, Beaconites,* and *Vondrichnus* in pedogenized mudstones; and rhizoliths. The ichnological record reflects the dominance of *Scoyenia* ichnofacies (composed of *Skolithos, Palaeophycus, Taenidium*, and *Beaconites*), indicating a transition from subaqueous to subaerial conditions, and a single level with of the *Termitichnus* ichnofacies (*Vondrichnus, Beaconites*), indicating a greater paleoecological stability in paleosols, likely influenced by lateral changes in depositional settings.

Keywords: *Scoyenia* ichnofacies, *Termitichnus* ichnofacies, meandering river, *Taenidium*, *Vondrichnus*.

INTRODUCTION

Ichnology plays a crucial role in the reconstruction of paleoenvironments, as trace fossils are generally preserved in situ (Buatois & Mángano, 2011). This in situ preservation allows trace fossil analysis to reflect the depositional processes active during or immediately after sediment deposition (Sedorko & Francischini, 2020). Additionally, trace fossils are produced abundantly by soft-bodied organisms, which are rarely preserved as body fossils, thus providing a record of the fauna interacting with the substrate without the taphonomic biases related to skeletal preservation (Bromley, 1996). Some continentals or even marine units have their faunal composition solely known by the trace fossil content (*e.g.*, Sedorko *et al*., 2017, 2020, 2024).

Despite the extensive application of ichnology in sedimentological analyses, the majority of ichnological studies have focused on marine successions, which is also the case for the Brazilian basins. Ichnological studies on continental successions, however, have gained substantial improve worldwide (*e.g.*, Hembree & Blair, 2016; Buatois *et al*., 2020.; Srivastava *et al*., 2024; Das *et al*., 2025), which also have been crucial for understanding how the continental fauna responded to paleoenvironmental and paleoclimatic changes (Genise, 2017; Ramos *et al*., 2021, 2022; Nascimento *et al*., 2022). In this context, ichnological information can serve as a valuable tool for refining sedimentological and stratigraphic interpretations.

The Taubaté Basin has been well-studied in terms of sedimentological and facies analysis (Suguio & Vespucci, 1985; Riccomini, 1989). Regarding the paleontological record of the basin, the lacustrine Tremembé Formation is rich in vertebrates, with brief mentions to simple burrows (Bergqvist & Ribeiro, 1998; Couto-Ribeiro *et al*., 2005), while the meandering systems represented by the Pindamonhangaba Formation only have records of phytoliths (Praxedes *et al*., 2010). Garcia *et al*. (2014) suggested a Miocene age for this unit, mostly based on stratigraphic correlations. There is a notable scarcity of ichnological studies regarding the Taubaté Basin, without any description of trace fossils for the Pindamonhangaba Formation. Therefore, this study aims to conduct an ichno-sedimentological analysis of the meandering deposits from the Pindamonhangaba Formation, providing paleodepositional and paleoenvironmental interpretations.

GEOLOGICAL SETTING

The Continental Rift of Southeastern Brazil (CRSB) is a regional structure that developed during the Paleogene, forming an elongated depression approximately 900 km long and up to 70 km wide between Tijucas do Sul (PR) and the vicinity of Macaé (RJ; Figure 1). The CRSB contains several basins: the Curitiba Basin (western segment), the São Paulo, Taubaté, Resende, and Volta Redonda basins (central segment), and the Macacu and Itaboraí basins. Although facies relationships and paleoenvironmental interpretations of these basins are well understood (*e.g*., Amador, 1975; Amador & Castro, 1976; Melo *et al*., 1985; Suguio & Vespucci, 1985; Riccomini, 1989; Ramos *et al*., 2006; Negrão *et al*., 2020), studies on ichnocoenoses are rare, being concentrated in Resende and Volta Redonda basins (*e.g*., Fernandes *et al*., 1992; Sedorko *et al*., 2024, 2025), but with mentions to trace fossils in Tremembé Formation (Taubaté Basin; Bergqvist & Ribeiro, 1998).

The Taubaté Basin comprises the Resende, Tremembé, São Paulo, Itaquaquecetuba, and Pindamonhangaba formations. The first three units, forming the Taubaté Group, are related to active rifting. The Resende Formation represents alluvial fan systems associated with braided rivers. The Tremembé Formation is characterized by an upward-deepening lacustrine setting. The São Paulo Formation is composed of meandering fluvial deposits. The Itaquaquecetuba Formation is represented by fluvial braided systems. The Pindamonhangaba Formation represents a post-rift meandering fluvial system (Riccomini, 1989; Carvalho *et al*., 2011).

MATERIAL AND METHODS

In this study, sedimentary facies and trace fossils of the Pindamonhangaba Formation were analyzed in an outcrop close to the Oswaldo Cruz Road at Taubaté Municipality, São Paulo State (23°3’32.54” S, 45°33’28.84” W; WGS84). The facies analysis followed Miall (1996), focusing on the texture, geometry, composition, and primary sedimentary structures, along with a systematic survey of the ichnological attributes. The sedimentological section was measured and represented at a 1:20 scale to record detailed stratigraphic information, where each sedimentary layer was examined for in situ trace fossils.

Descriptions of the trace fossils adhered to ichnotaxonomic criteria established by Bromley (1996). The amount of bioturbation (AB) was assessed using a linear scale proposed by Knaust (2012), ranging from 1 (0–20%) to 5 (80–100%). The trace fossil types were identified and recorded to interpret ichnoassociations and paleoenvironmental conditions within the Pindamonhangaba Formation. Data collection included sedimentary facies characteristics, facies associations, and bioturbation features, providing a foundation for reconstructing depositional processes and paleoenvironments specific to this post-rift sequence.

RESULTS

Facies and trace fossils

The studied outcrop (Figure 2; Table 1) is composed of pedogenized lutitic facies (facies S and M), that exhibits pedogenic features, interbedded with sandy deposits (facies Sm and St) and conglomeratic layers (facies Ct and Cm). The lower half of the sedimentary profile records fining upward successions with predominance of medium to coarse, stratified sandstones and conglomerates at the base overlapped by fine sandstones and bioturbated mudstones. The upper half of the profile exhibits coarse to medium-grained, stratified sandstones intercalated with stratified conglomerates, with rare lutitic layers, recording the sedimentation in the main channel.

The high bioturbation intensity prevents the ichnospecific identification. The sandy deposits (Sm and St facies) are characterized by the common occurrence of simple, passively filled, unbranched vertical trace fossils, predominantly attributed to *Skolithos* (Figure 3A). The simple, horizontal, unbranched traces with a discrete wall are attributed to *Palaeophycus* (Figure 3B). Subordinately, in the sandstone facies, the meniscated, unwalled burrows are identified as *Taenidium* (Figure 3C). Trace fossils in sandstone facies exhibit a range of colors, from dark red to white, and are often distinguished from the surrounding matrix by their well-defined walls.

The lutitic lithofacies (M and S facies) display a slightly greater ichnodiversity, featuring both vertical and horizontal trace fossils (*i.e*., *Skolithos* and *Palaeophycus*), alongside other morphologies, mostly *Taenidium* and *Beaconites*. At a single level (~7.5 m of the section; Figure 2A) it occurs two oblate chambers interconnected by an unbranched burrow, exiting from one point on the periphery structure and filled by a structureless sediment, identified as *Vondrichnus* (Figure 3D).

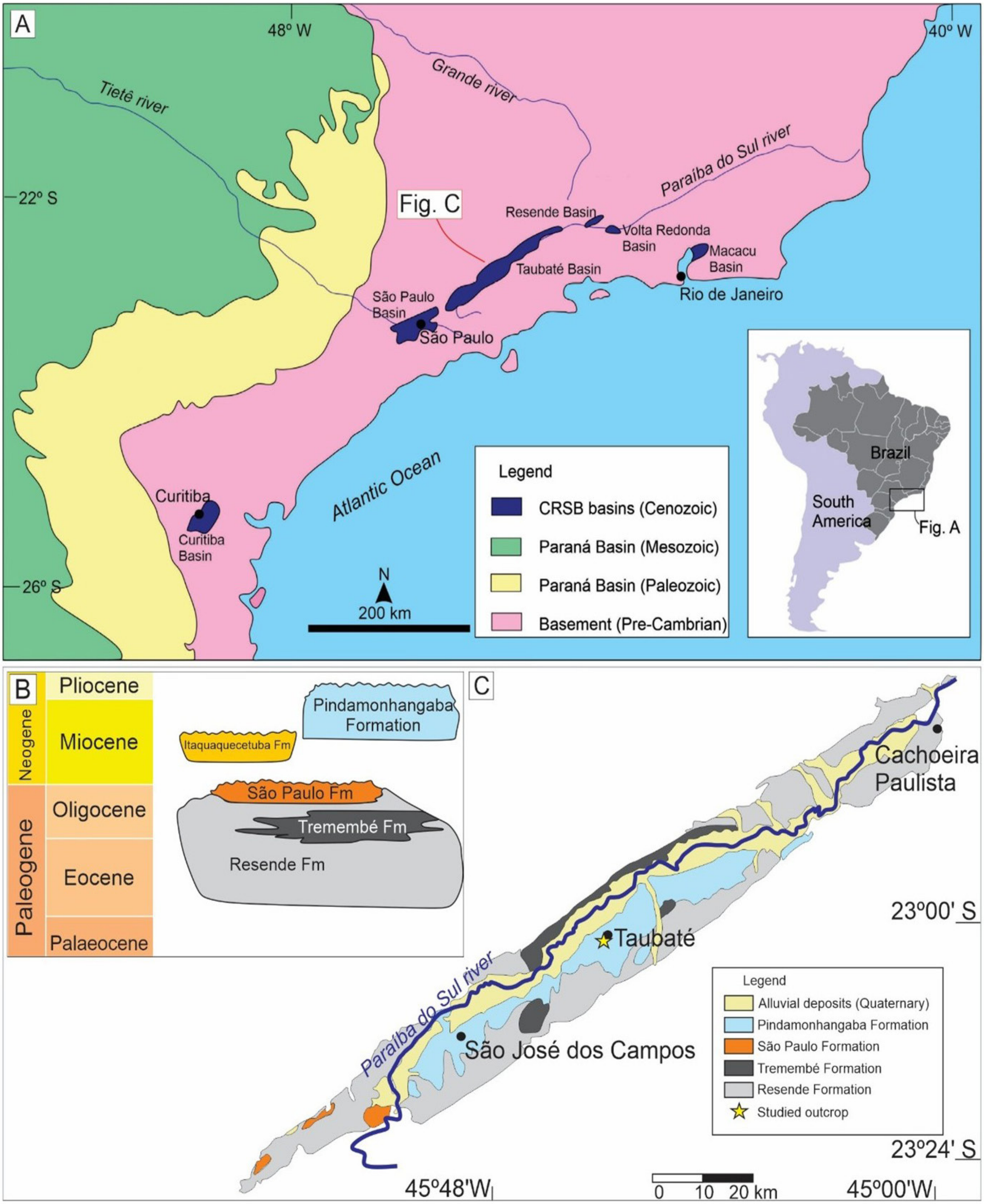

Figure 1. Geological setting of the study area**. A**, geological map of the Continental Rift of Southeastern Brazil (**CRSB**) highlighting the Taubaté Basin. **B**, stratigraphic chart of the Taubaté Basin (Riccomini *et al*., 2004). **C**, geological map of Taubaté Basin with the studied outcrop in the Pindamonhangaba Formation at Taubaté Municipality.

Most recurrent are meniscated trace fossils, reaching high bioturbation densities (AB = 4; Figure 2A). These traces are meniscated burrows with well-defined walls, identified as *Beaconites* (Figure 3E). At some levels, *Beaconites* occurs concentrated in rhizohaloes, with unwalled burrows identified as *Taenidium* and simple sub horizontal burrows identified as *Palaeophycus* (Figure 3F). Besides rhizohaloes (Figure 2F), rhizocretions (Figure 2G) and root casts (Figure 3G) are widely distributed throughout the section, particularly within the Sm, S, and M facies. *Beaconites* also occurs associated with a vertical, slightly sinuous, sub-circular, sharp-walled burrow, with 6 cm in diameter and 26 cm in length, with a slight enlargement in the direction of the rounded bottom. The filling is structureless and composed of poorly sorted coarse sand, distinct from the surrounding matrix.

Finally, conglomeratic facies (Ct and Cm) devoid of trace fossils were recorded, with a single exception at approximately 29 m in the section, where *Skolithos* was identified (Figure 2).

Ichnocoenoses

Based on the recurrence of ichnoassociations in the facies, three ichnocoenoses were identified. The *Skolithos* ichnocoenosis is the most recurrent and is characterized by the dominance of *Skolithos*, associated with *Palaeophycus*, with sparse occurrences of *Taenidium*. It occurs in sandstone or conglomeratic beds, rarely at lutitic levels. The *Beaconites* ichnocoenosis occurs in high densities (AB = 3–4) in lutitic intervals and sparsely in sandstones. *Palaeophycus*, *Taenidium*, and crustacean burrows (large burrows) are subordinate trace fossils. Finally, the *Vondrichnus* ichnocoenosis is dominated by *Vondrichnus* and

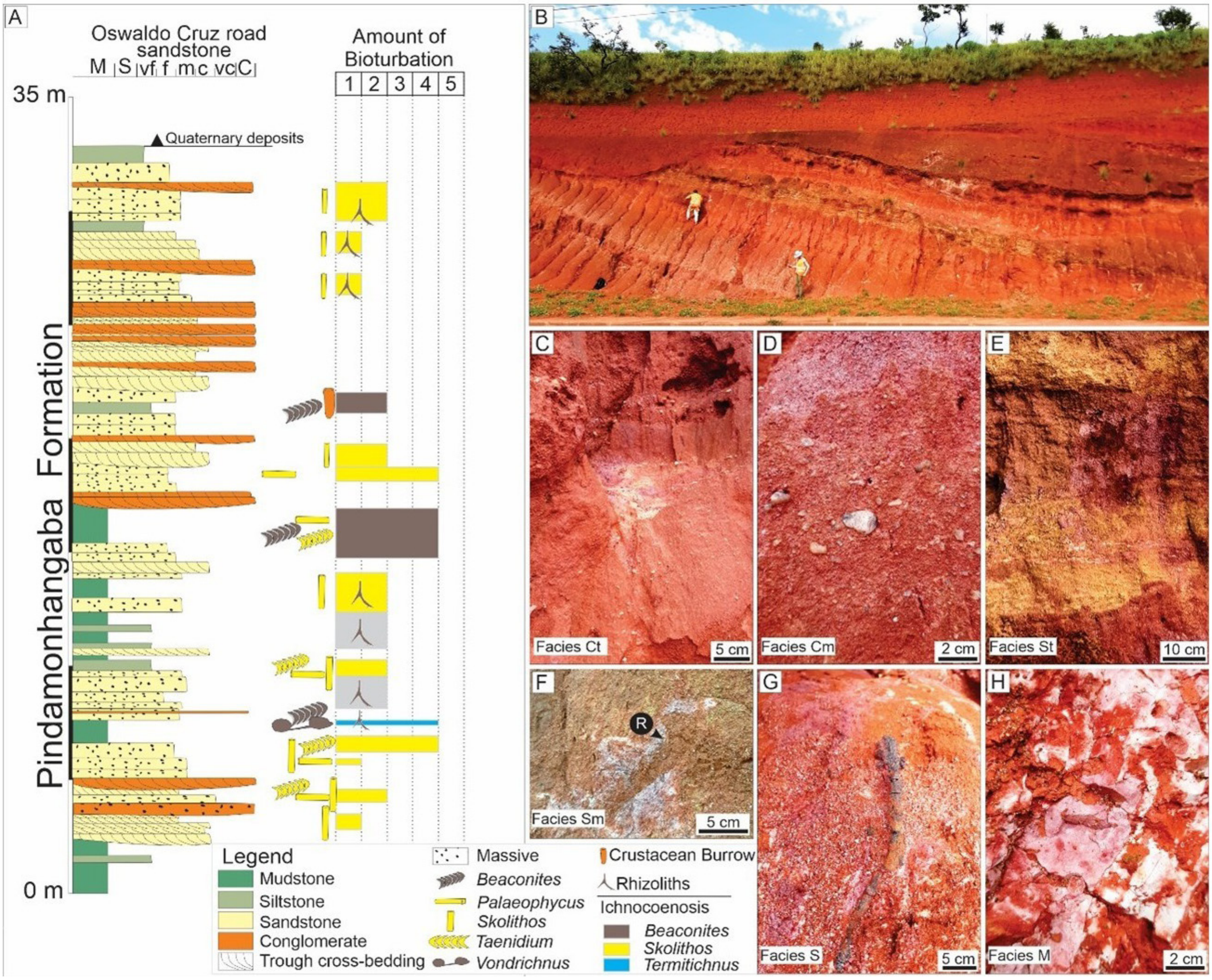

Figure 2. Sedimentological features of the outcrop studied of Pindamonhangaba Formation. **A**, sedimentological log, levels with trace fossils and iats Amount of Bioturbation; light gray is highlighting levels with only rhizoliths. **B**, general view of the studied outcrop; note the channel-cut and fill features in the middle-upper part of the outcrop. **C**, conglomerate with trough cross-stratification (Facies Ct). **D**, massive conglomerate (Facies Cm). **E**, sandstone with trough cross-stratification (Facies St). **F**, massive sandstone (Facies Sm); note the white rizohaloes (R). **G**, siltstone (Facies S), note the rhizocretion. **H**, mudstone (Facies M).

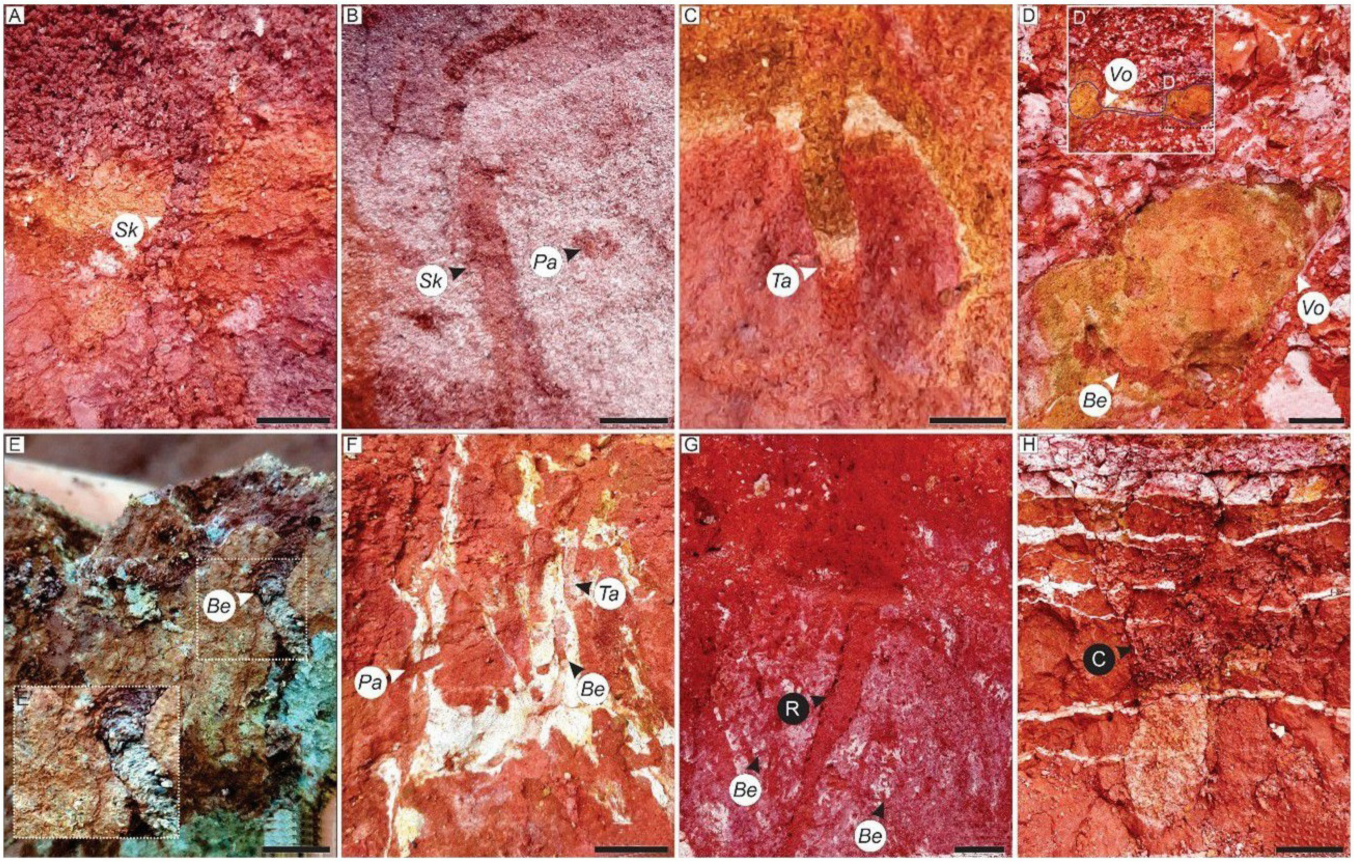

Figure 3. Trace fossils of the outcrop studied of Pindamonhangaba Formation. **A–C**, *Skolithos, Palaeophycus,* and *Taenidium* in sandstone facies, characterizing the *Skolithos* ichnocoenosis. **D**, *Vondrichnus* and *Beaconites* in mudstone characterizing the *Vondrichnus* ichnocoenosis; observe the drawing of *Vondrichnus* in the highlighted box. **E–H**, *Beaconites, Palaeophycus*, *Taenidium*, and a crustacean burrow in lutitic facies (S and M facies) characterizing the *Beaconites* ichnocoenosis. **Abbreviations:** ***Sk***, *Skolithos*; ***Pa***, *Palaeophycus*; ***Ta***, *Taenidium*; ***Be***, *Beaconites*; ***Vo***, *Vondrichnus*; **R**, Rhizoliths; **C**, Crustacean burrow. Scale bars: A–D, F = 20 mm; E = 10 mm; G–H = 50 mm.

Table 1. Facies and trace fossils from studied succession.

Code	Facies	Description	Trace fossils	Interpretation	Figure
Ct	Conglomerate with trough cross-stratification	Fine- to coarse-grained paraconglomerates with a dark red sandy matrix and a framework made up of quartz grains and lithoclasts, and through cross-stratification and a lenticular geometry	*Skolithos*	High-energy fluvial currents within a channel	2C
Cm	Massive Conglomerate	Fine- to coarse-grained conglomerates with a dark red sandy matrix and a framework made up of quartz grains and lithoclasts with tabular geometry	-	Fast deposition by high-energy currents within a channel	2D
St	Sandstone with cross-stratification	Fine- to very coarse-grained sandstone, yellow to red in color, with channeled cross-stratification and occasional clay intraclasts, and tabular to lenticular geometry	*Skolithos, Palaeophycus,* and *Taenidium*	Deposition by high-energy currents within a meandering river channel, with frequent erosion and reworking	2E
Sm	Massive sandstone	Very fine to very coarse sandstone, yellow, red, and off-white in color with a massive structure, and tabular to lenticular geometry	*Palaeophycus, Skolithos, Taenidium,* and Rhizoliths	Deposition by low- to moderate-energy fluvial currents within a channel	2F
S	Massive siltstone	Siltstone with a grayish color, and a massive structure and tabular geometry	*Beaconites, Taenidium, Palaeophycus, Skolithos,* and Rhizoliths	Deposition in a low-energy, overbank environment	2G
M	Massive mudstone	Mudstone with a gray, purple and red color, a massive structure and tabular geometry	*Beaconites, Taenidium, Palaeophycus, Skolithos, Vondrichnus,* and Rhizoliths	Deposition in a low-energy, floodplain environment	2H

Beaconites, with subordinated *Palaeophycus*, occurring in high density (AB = 4). Rhizoliths are present in small quantities at the base of the section and gradually increase in abundance above 10 m. They are best preserved and most prominent in the lutitic intervals, where they can occur as rhizocretions.

DISCUSSION

The facies are dominated by fine to medium-grained sandstones interbedded with massive and occasional laminated claystones and siltstones, with sporadic occurrences of conglomerates, and pebbly sandstones, which can contain intraclasts of clay and erosive contacts. The fine-grained deposits suggest low-energy depositional conditions, such as overbank deposits (Nichols & Fisher, 2007). In contrast, the sandstones and conglomerates levels indicate more energetic conditions, likely linked to the disruption of marginal dykes and channels. This facies distribution is indicative of a meandering river system, as also described by Riccomini *et al*. (2004) for Pindamonhangaba Formation. This depositional scenario is further supported by the here reported trace fossils, as discussed below.

The presence of *Skolithos*, *Taenidium*, and *Palaeophycus* in sandstone facies, which define the *Skolithos* ichnocoenosis, indicates deposition under predominantly high-energy hydrodynamic conditions (Nascimento *et al*., 2022; Sedorko *et al*., 2024), such as within active channels or crevasse splays in a meandering fluvial system (Figure 4). Colonization in these

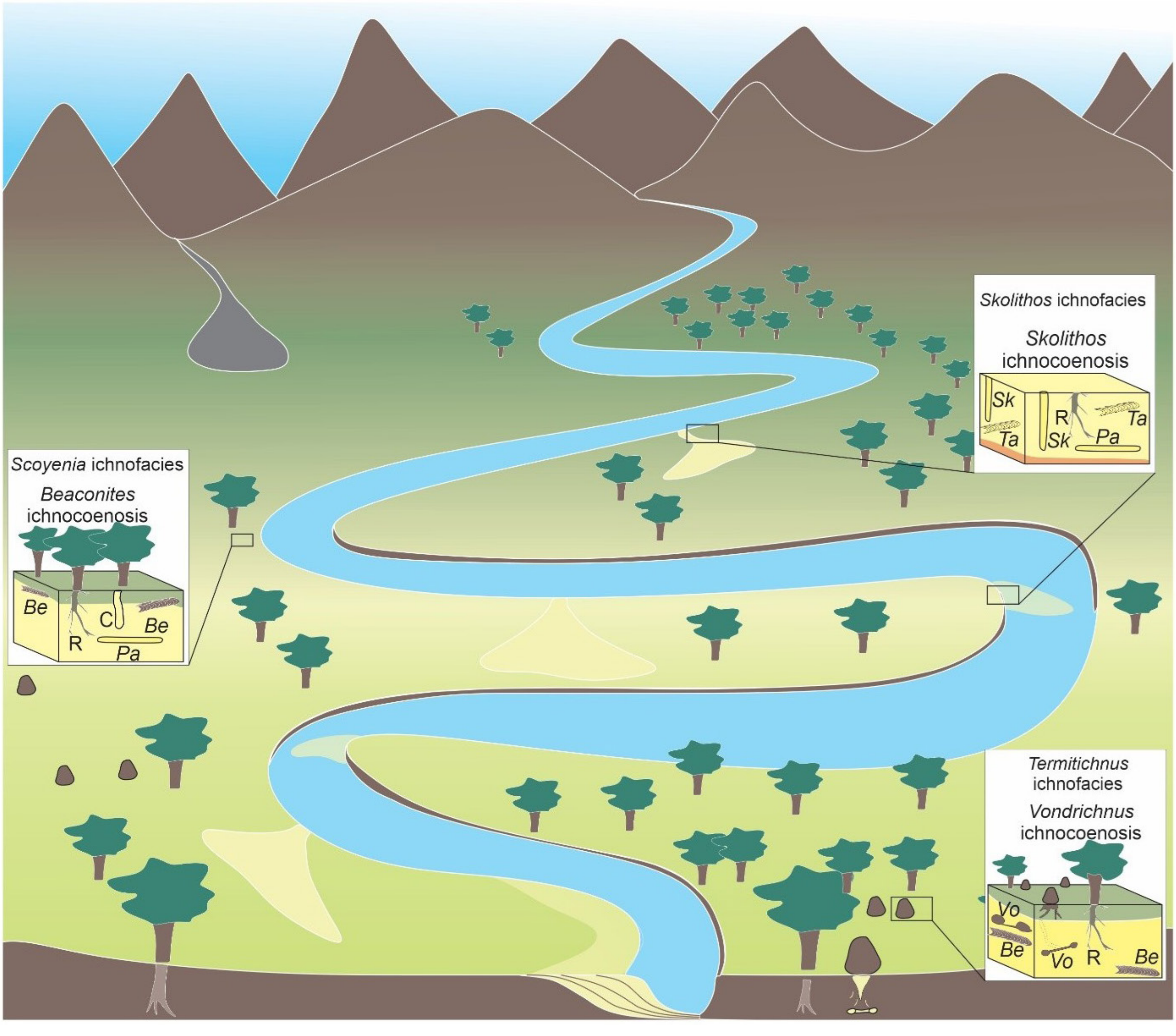

Figure 4. Inferred depositional scenario represented by the trace fossils in the meandering fluvial Pindamonhangaba Formation, Taubaté Basin. **Abbreviations:** ***Be***, *Beaconites*, **C**, crustacean burrow; ***Pa***, *Palaeophycus*; **R**, rhizoliths; ***Sk***, *Skolithos;* ***Ta***, *Taenidium*; ***Vo***, *Vondrichnus.*

settings likely occurred during brief episodic intervals of reduced energy, allowing opportunistic organisms to settle on the substrate (Sedorko *et al*., 2025). The limited bioturbation reflects rapid sediment accumulation, interrupted by short periods of stability (Savrda *et al*., 2000; Buatois & Mángano, 2004). Additionally, *Taenidium* suggests phases of slower sedimentation, representing colonization of substrates in abandoned channels prior to subsequent high-energy flooding events (Nascimento *et al*., 2022). Thus, *Skolithos* ichnocoenosis suggests colonization of sand bars, and local levels with *Taenidium* likely reflect colonization of exposed bars (Buatois *et al*., 1998; Buatois & Mángano, 2007; Minter *et al*., 2007).

The presence of insect-produced trace fossils, particularly *Vondrichnus*, provides evidence for paleosol development, as termite nests and galleries are typically constructed in sediments exposed to air, even in the absence of other pedogenic indicators (Genise, 2017). The association of rhizohaloes with the *Vondrichnus* layer further supports the interpretation of paleosol formation. The occurrence of *Beaconites* with well-defined walls suggests overall dry substrate conditions, reflecting colonization under subaerial exposure (Graham & Pollard, 1982). Termite-dominated trace fossil assemblages, such as those of the *Termitichnus* ichnofacies, are often linked to forested substrates in warm, humid climates (Grassé, 1986). However, termite nests also occur in non-forested tropical regions, including both humid and arid environments like the Pantanal (central-western Brazil), the Namib Desert (Namibia), and the subtropical grasslands of the Pampa in Rio Grande do Sul (Ramos *et al*., 2021). Though less frequent, they are also observed in vegetated frontal dunes within the active rear zone of Lagoon-Barrier Systems IV, where water sources are accessible (Ramos *et al*., 2021). Termites require moisture and vegetation for survival and adapt in arid regions by constructing horizontal tunnels near the surface to collect plant material and vertical tunnels to access deeper, moister soil (Ramos *et al*., 2021). These nests indicate social behavior and larval care (Genise, 2017). Therefore, the presence of *Termitichnus* in the section reflects a prolonged period of non-deposition and suggests wetter, warmer conditions during the formation and colonization of these paleosols.

Similarly, lutitic levels with the *Beaconites* ichnocoenosis, including crustacean burrows and rhizoliths, reflect extended exposure and the development of paleosols (Figure 4). The local abundance of rhizoliths in these paleosols suggests periods of relatively high-water tables (Kraus & Hasiotis, 2006). Root decomposition contributes organic matter for soil development and serves as a significant food source for soil macrofauna, as evidenced by some levels with rhizohaloes being colonized by invertebrates (Figure 3F). The crustacean burrow attribution was based on the general morphology and dimensions. Considering that *Camborygma litonomos* has chambers and multiple shafts, *Capayanichnus* has an L-shape and distinctive surface ridges, and *Loloichnus* has a thick lining, it is classified simply as a crustacean burrow (Hasiotis & Mitchell, 1993; Bedatou *et al*., 2008; Melchor *et al*., 2010). This ichnocoenosis can be associated with the *Scoyenia* ichnofacies (Buatois & Mángano, 2004, 2007).

CONCLUSIONS

The integration of ichnological and sedimentological data highlights the coexistence of three ichnofacies for the Pindamonhangaba Formation (Miocene, Taubaté Basin): *Skolithos*, *Termitichnus*, and *Scoyenia* ichnofacies. The *Skolithos* ichnofacies is associated with high-energy channel or crevasse splay deposits, reflecting rapid sedimentation with brief colonization windows. The *Termitichnus* ichnofacies indicates prolonged subaerial exposure under warm and moist conditions, with episodes of soil stabilization and vegetation growth. Finally, the *Scoyenia* ichnofacies, marked by *Beaconites*, rhizoliths, and crustacean burrows, represents a transitional environment with moderate energy, extended exposure, and paleosol formation in overbank settings.

The presence of the ichnogenus *Vondrichnus* provides an important record of social insect colonization in the RCSB Basin during the Miocene. The integration of sedimentological and ichnological evidence corroborates a dynamic meandering fluvial system characterized by channel deposits (*Skolithos* ichnofacies), subaerially exposed paleosols with termite activity (*Termitichnus* ichnofacies), and transitional overbank environments (*Scoyenia* ichnofacies). Future correlations with contemporaneous basins (Resende, Volta Redonda, and Curitiba basins) may provide a more comprehensive understanding of the Miocene paleoclimate.

DATA AVAILABILITY STATEMENT

The authors confirm that the data supporting the findings of this study are available within the article.

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AUTHOR CONTRIBUTIONS

Victória Ramiro Coelho Goulart, Mariano Verde, Marcelle Tostes Manhães, Claudio Limeira Mello, Daniel Carvalho West, Kimberly Silva Ramos, Lethicia Carlos da Silva Ferreira, Daniel Sedorko: writing – original draft, editing, investigation, formal analysis, data curation. Victória Ramiro Coelho Goulart, Marcelle Tostes Manhães, Daniel Carvalho West, Lethicia Carlos da Silva Ferreira, Daniel Sedorko: visualization. Victória Ramiro Coelho Goulart, Daniel Sedorko: writing – review, formal analysis, data curation, conceptualization. Daniel Sedorko: resources. All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

DECLARATION OF AI USE

We have not used AI-assisted technologies to create, review, or any part of this article.

ETHICS

This work did not require ethical approval, collecting licenses, or previous authorizations.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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