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Guest Editors

Rodrigo S. Horodyski & Hermínio Araújo Jr.

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Cover image: Artistic impression of the small cynodont *Irajatherium hernandezi*. Artwork by Márcio L. Castro (from Pretto et al. 2024, this issue).

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Journal of the Geological Survey of Brazil

Introduction to the special issue on "Brazilian fossiliferous sites with paleobiological importance"

Invited Editors

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Abstract

To enhance our understanding of Brazilian paleontological heritage, we have launched the special edition titled "Brazilian Fossiliferous Sites with Paleobiological Importance". Seven manuscripts have been accepted and published in Vol. 7 SI2 (2024). Recognizing our fossil heritage is essential for the scientific and cultural advancement of Brazil. We strongly encourage paleontologists to continuously publish papers on our rich fossiliferous deposits.

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1. Introduction

The Brazilian paleontological heritage is a vital component of the scientific and cultural identity of our country. Its preservation and study is not only essential for the advancement of science but also for the development of a culture that values natural history and promotes a harmonious coexistence between humans, their history and the environment.

The scientific importance of this heritage lies in its ability to provide data on deep time, the evolution of life, climate and environmental changes, and the processes that have shaped Brazilian extant ecosystems. Through paleontological research, we can better understand how species have adapted or become extinct in response to climate changes, which is crucial for addressing the environmental challenges posed by the current climatic crisis and planetary emergence.

The Brazilian basins preserve a wealth of fossil specimens with significant value for science and culture in Brazil. Highlighting them is the first step for decision-making on protection, valorization and utilization. This special volume comes to fill a gap regarding the identification of paleontological sites with paleobiological significance in Brazil, emphasizing their contribution for promoting the paleontological record as a source of scientific and cultural improvement in our country.

2. Content of the Special Issue

For this special volume, seven high-quality contributions were accepted for publication. These articles focused on

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paleontological sites dated from different periods of the Phanerozoic and from different regions of the country (Fig. 1).

Carvalho et al. (2024) present notable advancements in understanding the palaeobiodiversity of the Iapó and Vila Maria formations (Rio Ivaí Group) by the Três Barras Farm section with Ordovician-Silurian age. The fossil record is composed of mollusks, brachiopods, ostracods, acritarchs and cryptospores.

Epifânio et al. (2024) highlight the Triassic Passos das Tropas outcrop complex, with exceptional preservation fossil plants of *Dicroidium* Flora, in addition to important evidence of insect-plant interactions. The authors emphasize the significance of preserving and protecting fossil sites, the valorization of the geoheritage of Santa Maria and the global importance of contributing additional data to understand the biota of the Gondwanan Triassic.

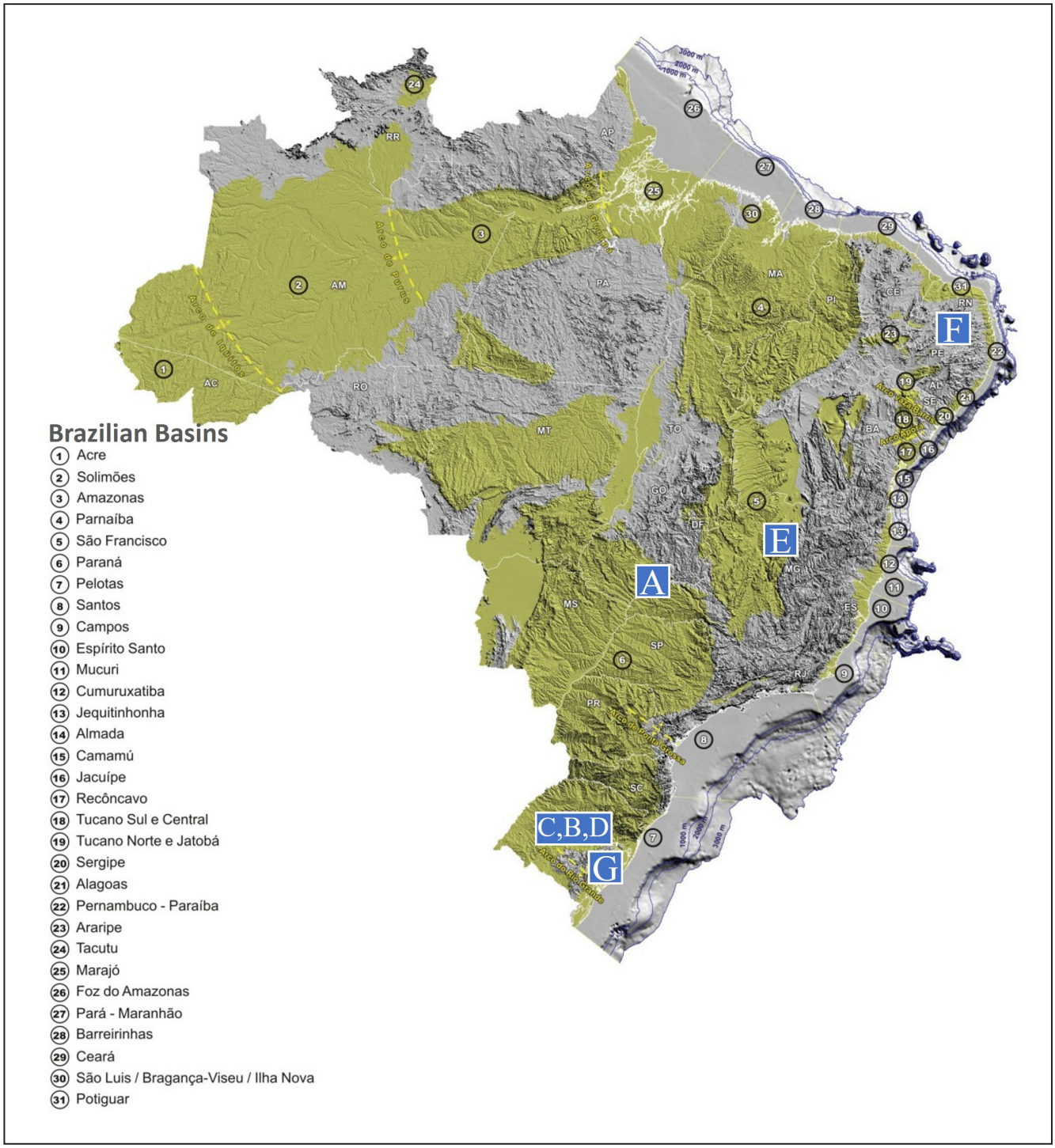

Figure 1. Map of Brazilian sedimentary basins with occurrences of fossiliferous sites (blue squares) with paleobiological importance from the papers published in this special volume (adapted from Milani et al. 2007). (A) Três Barras Farm section (Carvalho et al. 2024); (B) Passo das Tropas site (Epifânio et al. 2024); (C) Bica São Tomé fossil site (Pinheiro and Da-Rosa 2024); (D) Linha São Luiz Geosite (Pretto et al. 2024); (E) Pripiri Geosite (Sanchez et al. 2024); (F) Oligocene-Miocene Boa Vista Basin outcrop in Paraíba State (Silva et al. 2024); (G) Quaternary sites of the southern coast of Rio Grande do Sul state (Lopes et al. 2024).

The Lower Triassic Bica São Tomé site, presented by Pinheiro and Da-Rosa (2024), has become a key-outcrop for understanding the Triassic recovery after the Late Permian Mass Extinction. Notably, recent explorations at the outcrop have yielded more than two hundred specimens, including holotypes and representative samples of significant Early Triassic taxa.

The Mesozoic Linha São Luiz Geosite is one of the richest fossil assemblages known in southern Brazil, whose fossil-bearing strata is composed of micro to macrovertebrates (dinosaurs, pterosauromorphs, cynodonts and lepidosauromorphs), invertebrates (insects, clam shrimp), plants (primitive conifers and paleosols), and trace fossils. Pretto et al. (2024) discuss the geoconservation strategies being implemented at the site to protect this crucial glimpse into the Brazilian Mesozoic.

Sanchez et al. (2024) analyzed the Quiricó Formation in the Sanfranciscana Basin, revealing a rich paleoasis with diverse vertebrates, microfossils, and paleobotanical content. Recent findings from the Pripiri Geosite in Minas Gerais include potential archosaur fragments and novel microfossil taxa, shedding light on ecological resilience under extreme climatic conditions. The study emphasizes Pripiri's national importance for geodiversity and geoheritage, supporting initiatives for geoconservation and socio-economic development in Coração de Jesus.

Silva et al. (2024) investigate the plant fossil record of the Boa Vista Basin in Paraíba State, Brazil, revealing a volcanic-sedimentary sequence from the Oligocene-Miocene boundary. The Campos Novos Formation contains diverse fossil material, including 200 specimens of leaves and silicified wood, primarily from tropical to subtropical plant families. This assemblage highlights ecological affinities with both humid and dry environments, providing insights into the region's paleoclimate and supporting geological age data.

Finally, Lopes et al. (2024) examine geoheritage records related to Quaternary sea level and environmental changes along the southern coast of Rio Grande do Sul State, Brazil. The region hosts significant fossil records from marine and terrestrial faunas, found in deposits ranging from the continental shelf to coastal lagoons. While most sites remain unthreatened, conservation efforts, including surveys and educational initiatives, aim to enhance public awareness and protect these valuable fossil locations.

Acknowledgements

This thematic issue was only possible with the editorial collaboration of Prof. Dr Evandro Klein, Editor-in-Chief of the Journal of the Geological Survey of Brazil. We thank all researchers who submitted manuscripts for this volume. We are also warmly grateful to many colleagues who reviewed the manuscripts. Rodrigo S. Horodyski thanks to CNPq (grant nº 310970/2022-9) and FAPERGS (grant nº 21/2551-0002043-1); and Hermínio I. Araújo Júnior thanks to CNPq (grant nº 305576/2021-6) and FAPERJ (grant nº E-26/201.371/2021).

Authorship credits

Author	A	B	C	D	E	F
RSH						
HIAJ						

A - Study design/ Conceptualization **B** - Investigation/ Data acquisition
C - Data Interpretation/ Validation **D** - Writing
E - Review/Editing **F** - Supervision/Project administration

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Geological heritage of the Três Barras Farm section, Ordovician-Silurian record in the Paraná Basin, Brazil

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Abstract

The Três Barras Farm section is an outcrop located at the northern edge of the Paraná Basin, in Midwest Brazil. Rocks from the Ordovician-Silurian period are found in this section, represented by the Iapó and Vila Maria formations of the Rio Ivaí Group, which lie directly on the crystalline basement. Devonian rocks of the Furnas Formation are also visible at the top of the section. Although the first fieldwork was conducted there in 1985, the site has been visited by multiple generations of researchers, often for paleontological studies. The fossil record in this section includes invertebrates such as mollusks and brachiopods, mineralized microfossils like ostracods, and palynomorphs such as acritarchs and cryptospores. Analyses conducted up until the 2000s suggested a Lower Silurian age for the complete strata of the Vila Maria Formation, with no invertebrate fossils reported. However, since then, knowledge about the Rio Ivaí Group and the Três Barras Farm section has advanced. Recent studies have challenged the previously assigned Silurian age, with fossil ostracods and brachiopods indicating a Hirnantian age for the upper Iapó and lower Vila Maria formations. Recent palynological research has also reported the presence of palynomorphs in the Iapó Formation for the first time, supporting interpretations of a post-glacial paleoenvironment. Despite these advances, significant knowledge gaps remain regarding the palaeobiodiversity of the Iapó and Vila Maria formations, particularly considering recent discoveries at the Três Barras Farm. This site, located in a remote area, preserves the transition of Late Ordovician strata to Early Silurian ones, enabling studies on Lower Paleozoic speciation and on the impact of a major glaciation on the biota. Preservation measures include sharing directions and mapping routes to the section, as well as raising awareness among the non-scientific community about its importance.

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1. Introduction

The Ordovician (485.4 My - 443.8 My) is known for its rising palaeobiodiversity. Many fossil invertebrates such as graptolites, conodonts, and brachiopods are distinctive from this period. Palynomorphs like chitinozoans and acritarchs are as biostratigraphically useful as invertebrates (Delabroye and Vecoli 2010). While the Ordovician-Silurian (O-S) boundary is recognized by a mass extinction event related to a global glaciation, which led to the death of about 72% of marine genera (Stanley 2016), the Early Silurian (443.8 My - 433.4 My) fossil record shows again an increase in diversity and the thriving of new biological species.

Many Ordovician-Silurian fossiliferous sites in Gondwana exhibit these diversity patterns and have been specially studied in the search for palynomorphs and fossil invertebrates. This is the case for Ordovician chitinozoans from the Central Andean Basin, northwest Argentina. In this area, researchers have found chitinozoans from Tremadocian (Early Ordovician) to Hirnantian (Late Ordovician) layers, which have helped the

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recognition of Time Slices and determination of the age of such assemblages (Puente and Rubinstein 2007). These studies also have palaeogeographic importance since chitinozoan zones are recognized worldwide.

Likewise, well-preserved brachiopods are found in the Hirnantian (Late Ordovician, 445.2 My - 443.8 My) and Rhuddanian (Early Silurian, 443.8 My - 440.8 My) strata in the Argentine Precordillera (Benedetto 1986; Benedetto and Cocks 2009). The fossil record showed similarity to the assemblages recovered in different paleocontinents, such as Laurentia and Baltica, supporting the widespread distribution of these organisms during the Late Ordovician and Early Silurian. More recently, Benedetto et al. (2013) proposed a sea connection between South America and North Africa based on the shared occurrence of brachiopod taxa of the Late Ordovician *Hirnantia* fauna.

Although there is extensive literature on the Ordovician-Silurian record from northern Argentina and surrounding areas in South America, more is needed about the assemblages in higher paleolatitudes, such as the one recovered from the O-S sedimentary layers in Brazil. The O-S rocks collectively known as the Rio Ivaí Group represent the oldest strata of the Paraná Basin, Brazil, and outcrop at its north, northwestern, and southeastern borders (Assine et al. 1994; Milani et al. 2007).

The study of the Rio Ivaí Group began in the late 1940s, with the first formal description of a Pre-Devonian geologic unit in the Paraná Basin (Maack 1947). Some of the O-S outcropping sites have a long research history, which dates back to the work of Faria (1982) at the north margin of the basin. This paper aims to present the study history of the Três Barras Farm section, a significant site of the Ordovician-Silurian strata at the northern border of the Paraná Basin.

This work addresses the historic paleontological discoveries at the Três Barras Farm section and how they contributed to advancing the chronobiostratigraphic positioning of the Rio Ivaí Group. It introduces present-day location maps indicating the coordinates and an updated lithostratigraphic profile with the positioning of the fossiliferous occurrences identified to date. Ultimately, it considers the vulnerability aspects and suggests preservation measures for this important O-S paleontological section.

2. The Rio Ivaí Group

The Paraná Basin is the largest sedimentary basin of South America, comprising almost 1.4 million km². It occupies the territories of mid-southern Brazil, eastern Paraguay, northeastern Argentina, and northern Uruguay, with its axis oriented towards NNE-SSW. The volcano-sedimentary sequence ranges from the Ordovician to the Cretaceous and it is composed of six allostratigraphic units, the oldest one being with the Rio Ivaí Group of Ordovician-Silurian age (Milani et al. 2007) (Fig. 1).

Three units compose the Rio Ivaí Group: the Alto Garças Formation (Upper Ordovician), the Iapó Formation (Upper Ordovician), and the Vila Maria Formation (Upper Ordovician/

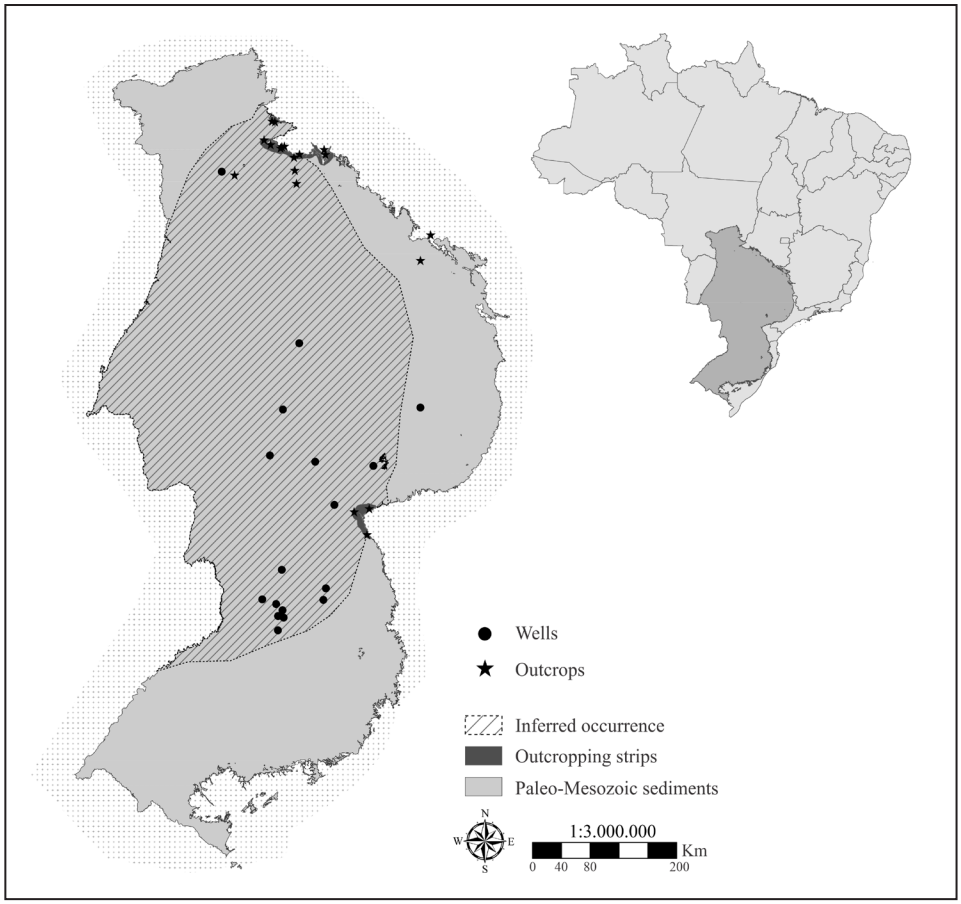

Figure 1. Simplified geologic map of the Paraná Basin in Brazil. The outcropping strips of the Rio Ivaí Group are represented in dark grey, at the northern and southeastern borders of the basin. The inferred occurrence in based on the isopach map (Milani el al. 1995).

Lower Silurian) (Assine et al. 1994; Adôrno et al. 2016). The age of these units was obtained through the radiometric and palynological study of the Vila Maria Formation (Gray et al. 1985; Grahn et al. 2000; Mizusaki et al. 2002) and lithostratigraphic correlation of the O-S units with the Paraguayan portion of the Paraná Basin (Assine and Soares 1989; Assine et al. 1994).

The Rio Ivaí Group represents the first transgressive-regressive cycle of the Paraná Basin (Assine et al. 1994; Milani et al. 2007). The oldest unit, the Alto Garças Formation, comprises white to reddish conglomerates at its base, with quartz pebbles and feldspathic sandy matrix, and predominantly conglomeratic sandstones at its top. Its thickness is variable, although no values greater than thirty meters were found, and the vertical profile shows ascending fining-up. Medium to fine sandstones with hummocky cross-stratification can be found at the uppermost layers, suggesting coastal marine conditions (Assine et al. 1994). This unit does not occur at the Três Barras Farm section.

Despite its wide geographic distribution, the Iapó Formation rarely exceeds a twenty-meter thickness and has a discontinuous record. The unit comprises reddish diamictites and conglomerates at its base, often intercalated with sandstones. These beds occasionally exceed ten meters. In complete sections, the upper portion exhibits mudstones or shales with dropstones. The presence of dropstones suggests that these are glacial or glacially-influenced sediments (Assine et al. 1994, 1998).

The Iapó and Vila Maria formations are often observed in gradational contact, and the contact between them is generally characterized as transitional. The Vila Maria Formation shows fossiliferous grey shales at its base, which may be present as mudstones in some localities. These beds show no dropstones. The upper portion is defined by fine, well-sorted, muscovite-bearing sandstones and siltstones, which present cross-stratification and wave-generated truncated lamination, indicating a marine depositional environment (Assine et al. 1994).

These formations outcrop at different localities at the northern border of the Paraná Basin, in midwest Brazil. Various sections have been reported since the 1980s when Faria (1982) first described the Vila Maria Formation and studied what are now classical sites of the Ordovician-Silurian interval in the Paraná Basin. The Três Barras Farm section is one of these classical sites (Figs. 2-3) that has been revisited and analyzed by different generations of researchers over the decades. It is located on the private property called Três Barras Farm, south of Bom Jardim de Goiás town and west of Piranhas town by the unpaved road GO-188 and then by an unnamed road that connects Piranhas to Bom Jardim de Goiás.

The Três Barras Farm section (UTM coordinates: zone 22 K, 382877 E and 8181679 N, datum WGS84) is 26.5 meters thick, in which the Iapó Formation represents the first 6.95 meters, laying directly over the crystalline basement. The Alto Garças Formation cannot be found at this outcrop. The basal portion of the section is composed of conglomerates

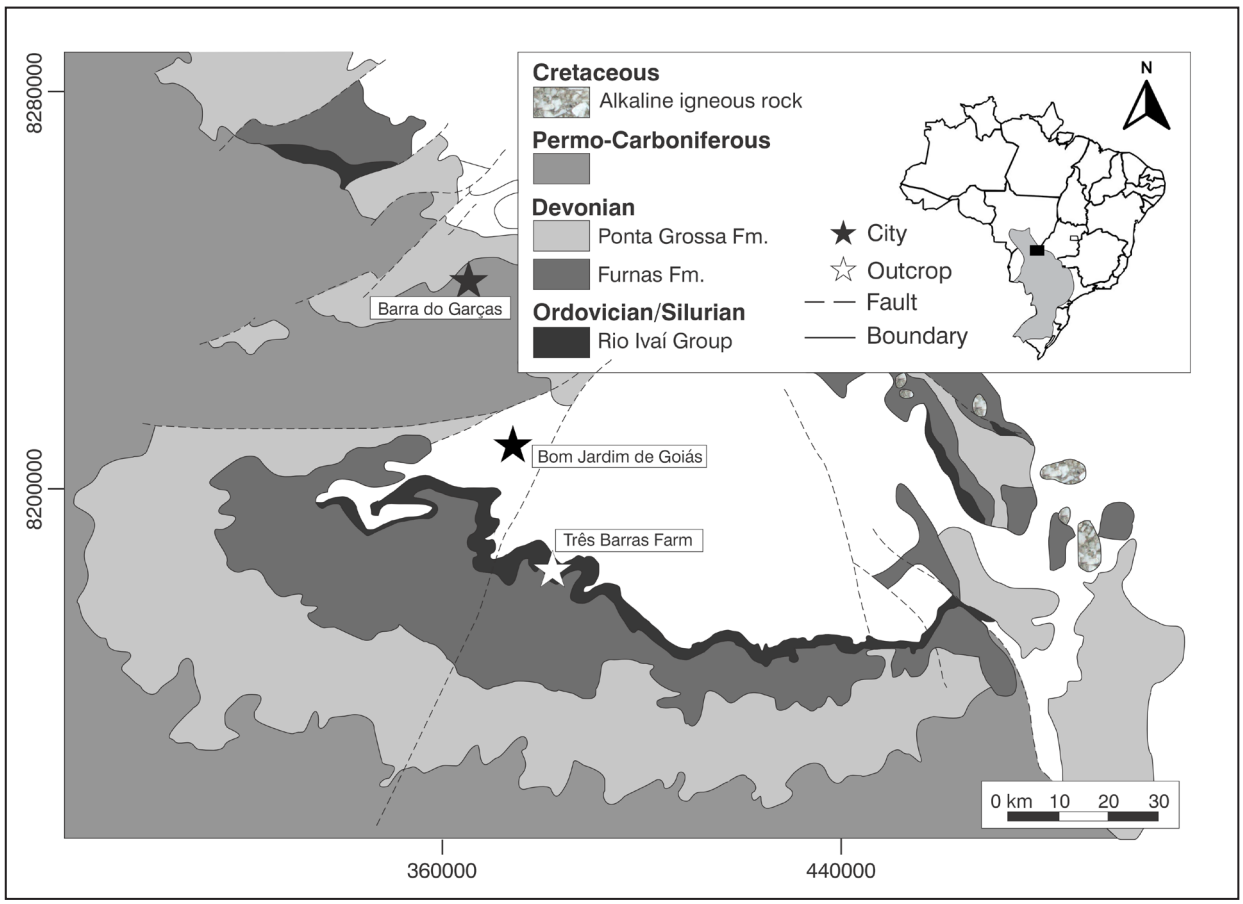

Figure 2. Geological map of the northern border of the Paraná Basin. The white star indicates the Três Barras Farm section (adapted from Adôrno et al. 2016).

with siltstone lenses at 2.6 meters from the base, followed by a package of sandstones with conglomeratic levels between 2.6 and 6.4 meters and shales with dropstones up to 6.95 meters. The Vila Maria Formation overlays the Iapó unit and comprises three primary lithologies. The first 4.5 meters are represented by fossiliferous dark shales, followed by a 6-meter-package of muscovite-bearing siltstone. The last 9 meters are represented by fine pinkish sandstones, where trace fossils can occasionally be found. The Furnas Formation is a Devonian unit that overlays the Vila Maria Formation in disconformity. The rocks from the Iapó and Vila Maria formations at Três Barras Farm are found along the banks of a stream, from where they were collected (Fig. 3).

3. Três Barras Farm: The research history

The Três Barras Farm section is in Bom Jardim de Goiás, state of Goiás, midwest Brazil. It was first described by Gray et al. (1985), who reported the first palynomorphs (acritarchs, cryptospores, and prasinophytes) of the Rio Ivaí Group, recovered from the Vila Maria Formation. The section was later visited by Mizusaki et al. (2002), Zabini et al. (2019, 2021), Rodrigues et al. (2022), and Gonçalves et al. (2022).

The original description of the Três Barras Farm portrayed the Vila Maria Formation as a fourteen-meter-thick unit that overlaid the crystalline basement. Its basal diamictites were superposed by fossiliferous dark shales, reddish siltstones, and pinkish sandstones (Gray et al. 1985). Whitish, coarser sandstones overlaid the upper layers, indicating the basal sequence of the much more studied Furnas Formation, of Devonian age and fluvial origin (Fig. 4a). Although researchers agree on the marine origin of the Vila Maria Formation, its age continues a question of debate.

Previous authors proposed a Silurian age to the complete Vila Maria sequence based on the trace fossil record. The ichnospecies *Arthrophycus alleghaniensis* (Harlan 1831) was documented in the upper siltstones of the Vila Maria Formation and the lowermost Furnas Formation layers (Burjack and Popp 1981). This trace fossil is often associated with the foraging of arthropods or worms. The contact between the Vila Maria and Furnas units was originally thought to be transitional, which led authors to assume a Llandovery (Lower Silurian) age to these strata (Burjack and Popp 1981; Faria 1982). Later authors questioned the validity of such a statement, arguing that in other localities *A. alleghaniensis* is also recorded in the Ordovician, and its upper stratigraphic limit is uncertain (Gray et al. 1985).

Gray et al. (1985) published the first palynological study of the Rio Ivaí Group, with samples from the Três Barras Farm section. The microfossils were recovered from the grey fossiliferous shales, a low-diversity assemblage dominated by the acritarchs *Leiosphaeridia* spp. and *Dictyotidium* sp., which together represented 94% of the specimens. Cryptosopores tetrad and dyads were also found – this plant spore assemblage corresponded to an assemblage zone also documented in different localities such as interior North America, Czech Republic, and North and South Africa, placing the Brazilian Paraná Basin in a relevant position in the paleogeographic debate of the Early Silurian. The palynological research suggested a Llandovery age based on the assemblage composition, the size range, and the mean size of the tetrads (Gray et al. 1985).

Decades later, Mizusaki et al. (2002) adopted the lithological column proposed by Gray et al. (1985) and conducted a new palynological study with dark shale samples from the Três Barras Farm outcrop. Their results presented a low-diversity acritarch-prasinophyte assemblage, yet a much-diversified cryptospore record, composed of ten genera and twenty species of tetrads and dyads. This work documents the first occurrence of *Laevolancis divellomedium* (Chibrikova) Burgess and Richardson, 1991, an important criterion to distinguish Early Silurian assemblages from Late Ordovician ones (Mizusaki et al. 2002).

The authors also performed a pioneer radiometric analysis from shale samples, presenting integrated radiometric and palynological dating that indicated a Lower Silurian age.

Figure 3. Rocks from the Rio Ivaí Group outcrop along the banks of a stream at the Três Barras Farm section. a. The authors work in the section searching for fossil invertebrates. b. Dark shales from the base of the Vila Maria Formation compose the creek's banks that form after the Três Barras waterfall, which gives the section its name.

The Rb-Sr isochron result (435.9 ± 7.8 Ma) was considered the depositional age of the Vila Maria Formation, which was consistent with the cryptospore Sub-zone identification, dated Rhuddanian to Early Aeronian (Mizusaki et al. 2002). However rich these results proved, the knowledge of the Rio Ivaí Group and the Três Barras Farm would evolve substantially in the following years.

Adôrno (2014) provided a new description of the section in their unpublished dissertation. Their main contribution was reporting that the Iapó Formation also outcropped at Três Barras Farm (Fig. 4b). Fossil invertebrate occurrences were then reported in this section by Zabini et al. (2021), who recorded five different *taxa* in both Iapó and Vila Maria formations, including ostracods, mollusk bivalves, and brachiopods.

Juvenile specimens of the ostracod *Satiellina paranaensis* Adôrno and Salas (2016) were found pyritized and articulated, all individuals of the ostracod *Harpabollia* sp. were replaced by pyrite, while specimens of the bivalve *?Paleoneilo* sp. were found in life position. Considering these taphonomic signatures, the Três Barras Farm section fossil assemblage

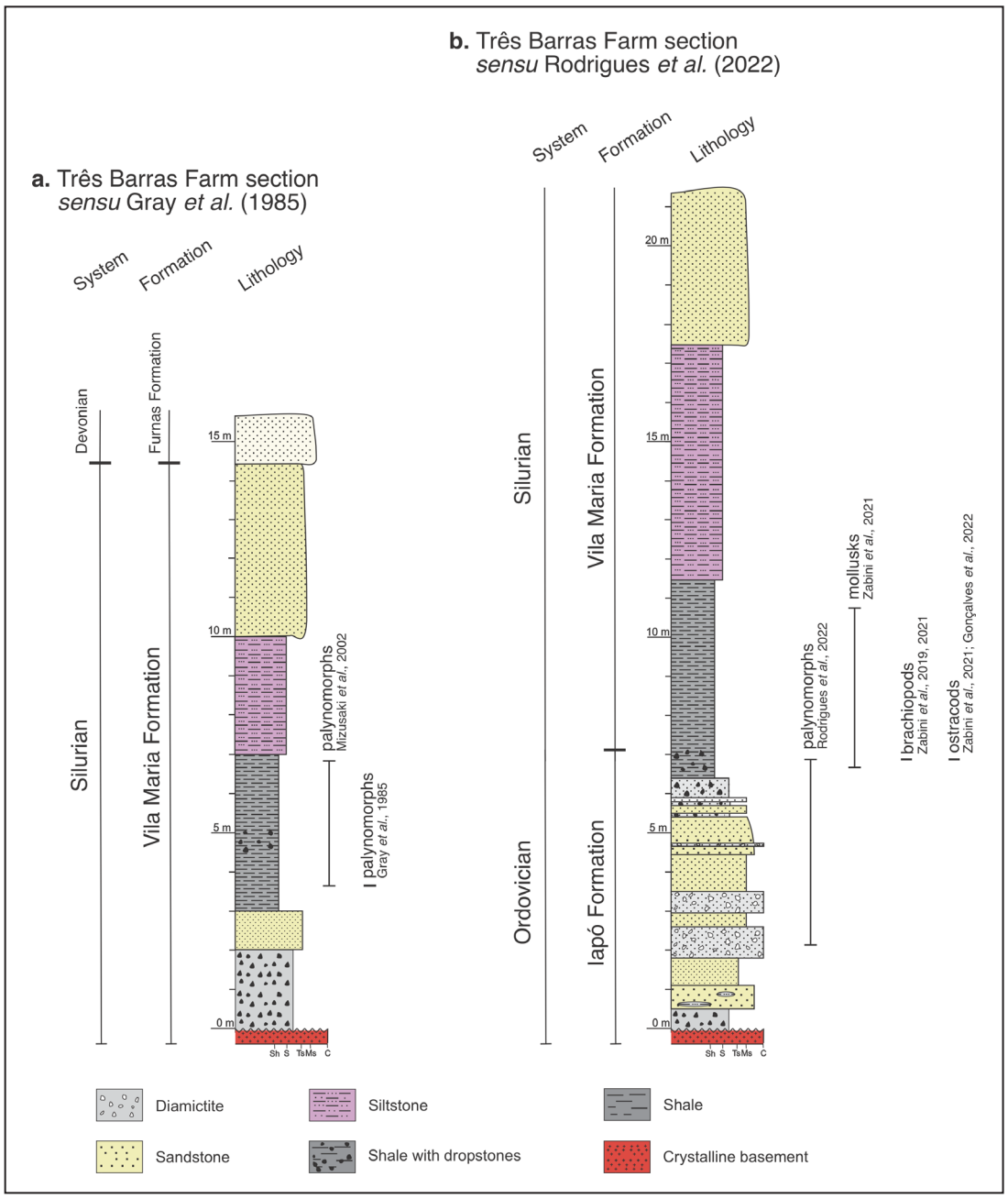

Figure 4. Stratigraphic profiles of the Três Barras Farm section proposed by different authors. a. Gray et al. (1985) described this outcrop for the first time and identified only the Vila Maria Formation of the Rio Ivaí Group. The Furnas Formation (Devonian) was not fully represented. Mizusaki et al. (2002) adopted their vertical profile. b. Rodrigues et al. (2022) developed a complete vertical profile in line with what had previously been produced by Zabini et al. (2019, 2021) and Gonçalves et al. (2022). The upper sandstones of the Vila Maria Formation were not represented. Once the transition from the Iapó to the Vila Maria formations is gradual, no exact division between the Ordovician and Silurian strata is represented.

was considered autochthonous to parautochthonous. The environmental conditions could be anoxic, and individuals were probably not subjected to high-energy conditions post-mortem. The discinid brachiopod *Kosoidea australis* Zabini and Furtado-Carvalho (2019) and an unidentified rhynchonelliform (calcitic) brachiopod were also reported (Zabini et al. 2021).

In yet another argument on the age of the Iapó and Vila Maria formations, the ostracod species was assigned as a strong indicator of the Hirnantian age since the genus *Satiellina* (Vannier 1986) was only recorded in Ordovician strata, and never in Silurian ones (Adôrno et al. 2016). Researchers also affirmed that the palynomorph assemblages reported previously by Gray et al. (1985) and Mizusaki et al. (2002) (Table 1) did not record any age-diagnostic species (Adôrno et al. 2016).

In addition to that, the discinid brachiopod *K. australis* found in the section was also referred to as an element that pointed to the Hirnantian age (Zabini et al. 2019, 2021), once the genus *Kosoidea* Havlíček and Mergl (1988) was recorded in the Hirnantian layers of the Soom Shale, Cedarberg Formation of Cape Basin in South Africa (Bassett et al. 2009). The discinid species was found at shales with dropstones, the uppermost layers of the Iapó Formation at Três Barras Farm (Zabini et al. 2019, 2021).

The ostracod species *Harpabollia harparum* (Troedsson 1918), considered an indicator of the Hirnantian in Baltica (Truuver and Meidla 2015), was recovered from the shales with dropstones of the Iapó Formation at the Três Barras Farm, strongly suggesting the Hirnantian age to the upper layers of the Iapó unit (Gonçalves et al. 2022). Its association with *K.* australis and *S. paranaensis* reinforces the hypothesis that these fossil invertebrates might indicate the Hirnantian in the Rio Ivaí Group strata.

Rodrigues et al. (2022), working at this same outcrop, recognized a palynomorph assemblage essentially composed of cryptospores and acritarchs that corroborated the paleoenvironmental interpretations previously proposed (Assine et al. 1998; Zabini et al. 2021). The researchers recorded an assemblage composed of 17 cryptospore species and 12 species of acritarchs and prasynophytes, the first record of palynomorphs from the Iapó Formation. These *taxa* were also observed in localities such as China, Estonia, Canada, and Argentina, corroborating the cosmopolitan nature of the Late Ordovician palynoflora and the early radiation of land plants in Gondwana. The terrestrial input, seen by the increase in cryptospores, is recorded at the top of the Iapó Formation, signaling the ice melting and proximity to the land (Rodrigues et al. 2022).

Since the first work in the Três Barras Farm section in the 1980s, much of the knowledge regarding its vertical profile (Fig. 4), the fossil record, and the units of the Rio Ivaí Group evolved. Table 1 presents all the fossil *taxa* recovered at the Três Barras Farm. New evidence indicates that some strata are Hirnantian, fossil invertebrates point to an offshore setting, and palynological data corroborates the post-glacial paleoenvironment. Although rich, these results do not answer all the questions regarding the topic. New studies could provide more information regarding the fossil record and the geological setting at the Três Barras Farm.

Table 1. Fossil *taxa* recorded in the Três Barras Farm section.

Biological Group	*Taxon*	Formation		Reference					
		Iapó	Vila Maria	Gray et al., 1985	Mizusaki et al., 2002	Zabini et al., 2019	Zabini et al., 2021	Rodrigues et al., 2022	Gonçalves et al., 2022
Acritarch	*?Dictyotidium* sp.		x	x	x				
	Diexallophasis sp.		x	x	x				
	Dorsennidium sp.	x						x	
	Elektoriskos pogonius			x					
	Eupoikilofusa sp.		x		x				
	Eupoikilofusa striata	x						x	
	Evittia cf. *E. dentificulata*	x						x	
	Helosphaeridium sp.	x						x	
	Leiosphaeridia sp.			x					
	Leiosphaeridia sp. A	x						x	
	Leiosphaeridia sp. B	x						x	
	Lophosphaeridium sp. A	x						x	
	Lophosphaeridium sp. B	x						x	
	?*Multiplicisphaeridium* sp.		x	x	x				
	Multiplicisphaeridium irregulare	x						x	
	?*Pterospermella* sp.		x	x	x				

continue

Table 1. Fossil taxa recorded in the Três Barras Farm section (continued)

Biological Group	*Taxon*	Formation		Reference					
		Iapó	Vila Maria	Gray et al., 1985	Mizusaki et al., 2002	Zabini et al., 2019	Zabini et al., 2021	Rodrigues et al., 2022	Gonçalves et al., 2022
	Villosacapsula cf. *setosapellicula*	x						x	
	Veryhachium sp.			x					
	Veryhachium lairdii group	x						x	
	Veryhachium trispinosum group	x						x	
	Visbysphaera n. sp.			x					
Brachiopoda	*Kosoidea australis*	x	x			x	x		
	Rhynchonelliformea	x	x				x		
Crypstospores	*Abditusdyadus laevigatus*		x		x				
	Dyads			x					
	Dyadospora murusdensa	x	x		x			x	
	Dyadospora murusattenuata	x	x		x			x	
	Gneudaspora divellomedia	x						x	
	Imperfectotriletes patinatus		x		x				
	Imperfectotriletes vavrdovae	x	x		x			x	
	Laevolancis divellomedia		x		x				
	Laevolancis chibrikovae	x						x	
	Nodospora rugosa		x		x				
	Pseudodyasdospora laevigata	x	x		x			x	
	Pseudodyasdospora petasus	x	x		x			x	
	Rimosotetras problematica	x	x		x			x	
	Rugosphaera sp. A	x						x	
	Rugosphaera cerebra	x						x	
	Segestrespora laevigata	x	x		x			x	
	Segestrespora membranifera		x		x				
	Segestrespora rugosa	x	x		x			x	
	Sphaerasaccus glabellus		x		x				
	Tetrahedral tetrad			x					
	Tetrahedraletes			x					
	Tetrahedraletes grayae	x						x	
	Tetrahedraletes medinensis	x	x		x			x	
	Tetraplanarisporites laevigatus	x						x	
	Velatitetras anatoliensis		x		x				
	Velatitetras laevigata	x	x		x			x	
	Velatitetras retimembrana		x		x				
	Velatitetras rugosa	x	x		x			x	
Fungi	*Tortotubus protuberans*	x						x	
Mollusca	?*Cuneamya* sp.		x				x		
	?*Paleoneilo* sp.		x				x		
Ostracoda	*Harpabollia harparum*	x					x		x
	Satiellina paranaensis	x					x		
Prasynophyte	*Tasmanites* sp. B	x						x	

4. Investigation potential

The age of the Iapó and Vila Maria formations has been debated since their proposition and the paleontological record plays a prominent role in this discussion, often yielding new insight. The recent findings of probable Hirnantian species raise questions about the alleged consensus that the Vila Maria Formation was entirely deposited during the Silurian (Burjack and Popp 1981; Faria 1982; Gray et al. 1985; Mizusaki et al. 2002) – rather, data point that the upper Iapó and lower Vila Maria strata are Ordovician.

In this sense, searching for other fossil organisms is paramount in determining the age of the formations. Several fossil groups are typical of the Hirnantian, such as conodonts, chitinozoans, graptolites, and brachiopods (Delabroye and Vecoli 2010). Rhynchonelliform brachiopods were reported at the Três Barras Farm section (Zabini et al. 2021), which creates an opportunity for future research on Hirnantian brachiopods. Similarly, Rodrigues et al. (2022) published the first palynomorph record from the Iapó Formation; studying these organisms in the Iapó and Vila Maria formations could provide valuable information regarding the paleoenvironment.

Furthermore, the Três Barras Farm section preserves a unique record of the Lower Paleozoic once the Late Ordovician strata transition to Early Silurian layers in this locality, documenting one of the most remarkable events in the history of the Earth. Existing research has not yet faced this topic in depth, and there is few literature comparing the fossil fauna and flora from the Hirnantian layers with the ones from Llandovery layers in Três Barras Farm. Such a study could shed light on the current understanding of speciation and the impacts of a major glaciation in a high-latitude community.

The fossil diversity at the Três Barras Farm section is also noteworthy; more than forty *taxa* have already been discovered (Table 1) and there are more to describe. Zabini et al. (2021) reported the occurrence of mollusk bivalves whose identification still needs improvement. In their unpublished work, Adôrno (2014) mentions gastropod specimens in the Vila Maria strata at Três Barras Farm who lack proper taxonomical study.

New fossil *taxa* recovered were compared to those reported in different, coeval basins. Adôrno et al. (2016) reported ostracods similar to the ones found in the north of Africa, while Zabini et al. (2019) described a new species whose genus also occurs in Hirnantian strata in South Africa. Likewise, Gonçalves et al. (2022) reported the Hirnantian *Harpabollia harparum*, which is also found in the Argentinean Precordillera and Baltica, and the cryptospore assemblage published by Rodrigues et al. (2022) is similar to the ones reported in China, Estonia, and Argentina. A comparative study between faunas could help elucidate the connection between ancient oceans and seas.

The fossil record at Três Barras Farm section has not yet been comprehensively researched. There are still some gaps concerning the age of the units, the fossil diversity, and the relationship between the record seen in Paraná Basin and coeval basins. Facing the amount of work that still needs to be done, this paper also aims to draw attention to the scientific questions that could be explored at the Três Barras Farm and, hopefully, call up researchers willing to explore them.

5. Recommended preservation and educational measures

The Três Barras Farm section is located in Bom Jardim County, within a private property named Três Barras Farm. The study site comprises the ravine of a small drainage, and access to the outcrop is difficult. The roads built within the property are seasonal and usually change annually. Valuable measures to keep this section available for future research are sharing directions to the site with the scientific community and mapping alternative routes coming from the different state and federal roads that cross the region.

The site is isolated and does not pose many risks or pressures related to human occupation or infrastructure projects. Preventive measures should be evaluated to avoid degradation of the area, or even banning access for researchers. In that regard, one recommended preservation measure would be to raise awareness among the owners of the Três Barras Farm, informing them about the scientific relevance that the site has and encouraging them to maintain access for researchers who wish to access the outcrop in search of developing new research projects. An effective approach to that is sharing results (e.g. images of fossil specimens, publications) with the local community and reporting on what was discovered and produced from the work on the site.

Once the site is located in a remote area, it may be subject to inaccessibility or degradation caused by natural hazard events (e.g. floods, landslides). Although protection measures for the outcrop would be unavailable in cases like this, alternative sites could be explored, such as the parastratotype section of the Vila Maria Formation, located a few kilometers away in a neighbor farm.

For these measures to be taken, there is a need for research that appraises the geological and paleontological heritage that the Três Barras Farm section represents. Much about the Gondwana and the Ordovician-Silurian interval can still be discovered from studies in this outcrop.

6. Final Remarks

The Três Barras Farm section is a geosite with high potential for the scientific community with a special interest in paleontological investigation. The presented information was defined based on field works and the current geological knowledge. This section needs to be known not only for the promotion of new paleontological discoveries but also for the preservation of the site. The Três Barras Farm outcrop revealed that the study area offers variability and diversity of interest, namely sedimentological, stratigraphic, paleontological, and geomorphological, so that combined with other important sites nearby such as the type-section and the parastratotype section of the Vila Maria Formation, has great interest. In terms of scientific evaluation and degree, this section is representative and has national and international relevance.

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Authorship credits

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A - Study design/ Conceptualization **B** - Investigation/ Data acquisition
C - Data Interpretation/ Validation **D** - Writing
E - Review/Editing **F** - Supervision/Project administration

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The Passo das Tropas outcrop complex and the *Dicroidium* Flora in southern Brazil

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Abstract

The *Dicroidium* flora, composed of different genera of fossil plants, has its first records dating back to the Permian, expanded significantly in diversity in the Triassic, occupying several regions of the Gondwanan territory, becoming a biostratigraphic landmark for the Triassic. In Brazil, this paleoflora is found in the sedimentary rocks of the Santa Maria region, state of Rio Grande do Sul, in locations close to the Passo das Tropas Creek, an informal type section of the Passo das Tropas Member, of the Santa Maria Formation. Pioneering studies on the subject in the region began in 1952, at the Passo das Tropas outcrop, which described the first records of the *Dicroidium* flora. Over the years, different outcrops were found in this region, which also revealed this paleoflora, such as: "Dom Antônio Reis" outcrop, "Zenir Aita" outcrop and "Espuma" outcrop, where several paleontological collections were carried out. In addition to plant fossils, fish scales and insect wings were recorded in these outcrops. However, these outcrops were totally or partially buried due to the urbanization process in the city of Santa Maria and its surroundings, making further studies impossible. This article presents a historical and stratigraphic review, compiling the work carried out in the last 70 years on the outcrops of the Passo das Tropas Member and presents a new fossil site, the outcrop called Estância dos Montes. A total of 125 specimens were recovered from the Estância dos Montes outcrop, belonging to *Dicroidium odontopteroides*, D. *zuberi*, D. *lancifolium*, *Umkomasia* sp., *Pteruchus* sp., *Neocalamites* sp. and seeds. The fossils presented in this work come from a paleontological rescue carried out at the Estância dos Montes outcrop and are currently deposited in the Paleontological Collection of the Laboratório de Estratigrafia e Paleobiologia of the Universidade Federal de Santa Maria. Not only the importance of preserving and protecting fossil sites and their contents is highlighted, but also the uniqueness of these fossils for the valorization of the regional heritage of Santa Maria and the global relevance of adding more data to understand the biota during the Gondwanan Triassic.

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1. Introduction

The *Dicroidium* Flora is a phytoassembly found throughout the Gondwana supercontinent in the Triassic period, composed of several genera, such as *Neocalamites*, *Cladophlebis*, *Tetraptilon*, *Dicroidium*, *Ginkgoites* and *Williamsonia* (Guerra-Sommer et al. 1985; Da-Rosa et al. 2009) and others. These plants play a crucial role as biostratigraphic markers for the Triassic, as they make up a group of plants that had their origins in the Permian, and persisted and diversified after the great extinction that marks the transition to the Mesozoic Era (Kerp et al. 2006).

The studies of the *Dicroidium* Flora in Santa Maria - Brazil began in 1952 by Gordon and Brown at the outcrop known as Passo das Tropas, a place where several fossil records of plants, insects, fish and conchostracans were collected. Over

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the years, other outcrops were described for the locality and generated important works on geology (Bortoluzzi 1974), or on the description and characterization of the *Dicroidium* Flora (Bortoluzzi 1975; Guerra-Sommer et al. 1985).

Passo das Tropas is the name of a creek that runs southwestwards from the city of Santa Maria, in which some outcrops were found (Gordon Jr. and Brown 1952; Bortoluzzi 1974). Those rocks proved to be highly fossiliferous, so they were described as part of the Santa Maria Formation, namely the Passo das Tropas Member (PTM) (Andreis et al. 1980). The area described in this contribution represents part of the undescribed type section of PTM (Fig. 1).

The aim of this work is to provide a comprehensive historical context of the fossiliferous outcrops of Passo das Tropas in Santa Maria, due to its paleobiogeographic importance and relevance in the fossil record. Additionally, this research presents a new fossiliferous locality in this geological unit, which contains new records of *Dicroidium* Flora.

2. Material and methods

The present study initiated with a historical compilation of geological and fossiliferous papers in the analyzed area. Those contributions allowed recognizing that different outcrops were prospected along the last 70 years, after the opening of the road to the city of São Sepé, circa 55 km south of Santa Maria. The area was designated as the type section of the Passo das Tropas Member, lower part of the Santa Maria Formation (but see 4. Stratigraphic context), although never formally and fully described. So, here we provide a stratigraphic context for those outcrops, presenting a new finding, namely the Estância dos Montes outcrop which is geologically and paleontologically presented here.

During the years 2020 to 2022, 125 fossil specimens were collected in Estância dos Montes outcrop, corresponding to plant fossils, in a paleontological rescue project related to the construction of a residential project in the area. These fossil plants were collected using paleontological tools such as: hammer, brush, chisel and pickaxe, with stratigraphic control within the geological profile. The outcrop called Estância dos Montes corresponds to part of the construction of a residential project in the area, located at the geographical coordinates 29°44'26.15"S, 53°47'28.61"W.

Regarding the curatorial work, the fossil plants were registered and stored in the Paleontological Collection of the Laboratório de Estratigrafia e Paleobiologia (Stratigraphy and Paleobiology Lab) at the Universidade Federal de Santa Maria, under the acronym UFSM. Numbers range from UFSM12163 to UFSM12286 (12 = paleobotanical collection). They were then mechanically prepared using needles, spatulas and brushes. The samples were analyzed using a SteREO ZEISS Discovery V12 stereomicroscope at the Laboratório de Paleobotânica e Evolução Ambiental (Paleobotany and Environmental Evolution Lab), of Universidade do Vale do Taquari, Univates. Photographs of the frond specimens were taken with camera CANON SX50 HS and processed in Adobe Photoshop, while the photographs of the smaller samples were taken with Canon EOS Rebel T5i using a Sigma DG Macro 105mm 1:2.8 and processed in Adobe Photoshop Lightroom. A morphoanatomical comparison was made with other specimens of the *Dicroidium* Flora, namely the Espuma outcrop (Cenci 2013; Barboni and Dutra 2015), deposited at the paleontological collection of the Museu de História Geológica do Rio Grande do Sul (MHGEO) at the Universidade do Vale do Rio dos Sinos.

3. Historical context

Although the first paleobotanical records for Rio Grande do Sul were made by Friedrich Sellow, between 1823 and 1825 (Marchiori et al. 2018), in relation to the silicified trunks of Mata and São Pedro do Sul, the first references of the genus Dicroidium Gothan 1912 for Brazil were carried out by Gordon Jr. and Brown (1952), when there were no Geology schools in the country, and much of the geological research was carried out by foreign researchers. With the aggregation of professors at the Federal University of Rio Grande do Sul, to create the School of Geology, Brazilian researchers began to carry out their research in the national territory. Thus, Irajá Damiani Pinto, in 1956, described a fossil insect for the same location described by Gordon Jr., on the road that connected Santa Maria to São Sepé, close to the Passo das Tropas creek (Pinto 1956). In the same location, another fossil insect was described in 1974, being the only insect records published to date for the Santa Maria Formation (Pinto and Ornellas 1974). In addition to these fossils, fishes (Lima et al. 1984; Perez and Malabarba 2002; Richter and Toledo 2008) and conchostracans (Gallego 1996) were also described.

In 1974, Carlos Alfredo Bortoluzzi carried out a geological survey in the municipality of Santa Maria, finding several fossil outcrops and presenting a geological section (Fig. 2A) (Bortoluzzi 1974). Many of those outcrops were lost, due to urban growth (Da-Rosa 2004), namely the “Parque Dom Antônio Reis” and “Escola Zenir Aita”. This work allowed the recognition of different plant impressions, in a first work of international relevance (Bortoluzzi 1975), with the description of two forms of Dicroidium: D. odontopteroides (Morris) Gothan 1912 and D. zuberi (Szajnocha) Archangelsky 1968. Subsequently, Margot Guerra-Sommer and various collaborators carried out important work on the Dicroidium Flora in southern Brazil, including demonstrating its biostratigraphic importance (e.g. Guerra-Sommer et al. 1985; Guerra-Sommer et al. 1999a, b; Guerra-Sommer and Klepzig 2000).

After several years without collection records, a new outcrop was discovered near the Passo das Tropas outcrop at the end of the 2000s. It was named the 'Espuma outcrop' because it resulted from the rupture of a sewer gallery, likely mixed with industrial waste, which caused foam to form at the site, giving the outcrop its name. On this outcrop, insect wings and insect-plant interactions were recorded (Cenci 2013; Cenci and Adami-Rodrigues 2017), as well as ginkgophytes, ginkgo fertile organs and leaves (Barboni and Dutra 2015) (Fig. 2B). Unfortunately, this outcrop was buried, making further paleontological explorations impossible.

In 2009, the Brazilian Commission of Geological and Paleontological Sites (SIGEP) proposed the preservation of the Passo das Tropas outcrop, with online dissemination (Da-Rosa et al. 2009), and subsequent printed publication (Da-Rosa et al. 2013). This proposition was based on a map of the fossiliferous sites of Santa Maria, produced in 2000 (Da-Rosa 2004), and later incorporated into the thematic map of the Santa Maria Urban Development Master Plan, in its initial version. This thematic map allowed the Municipality of Santa

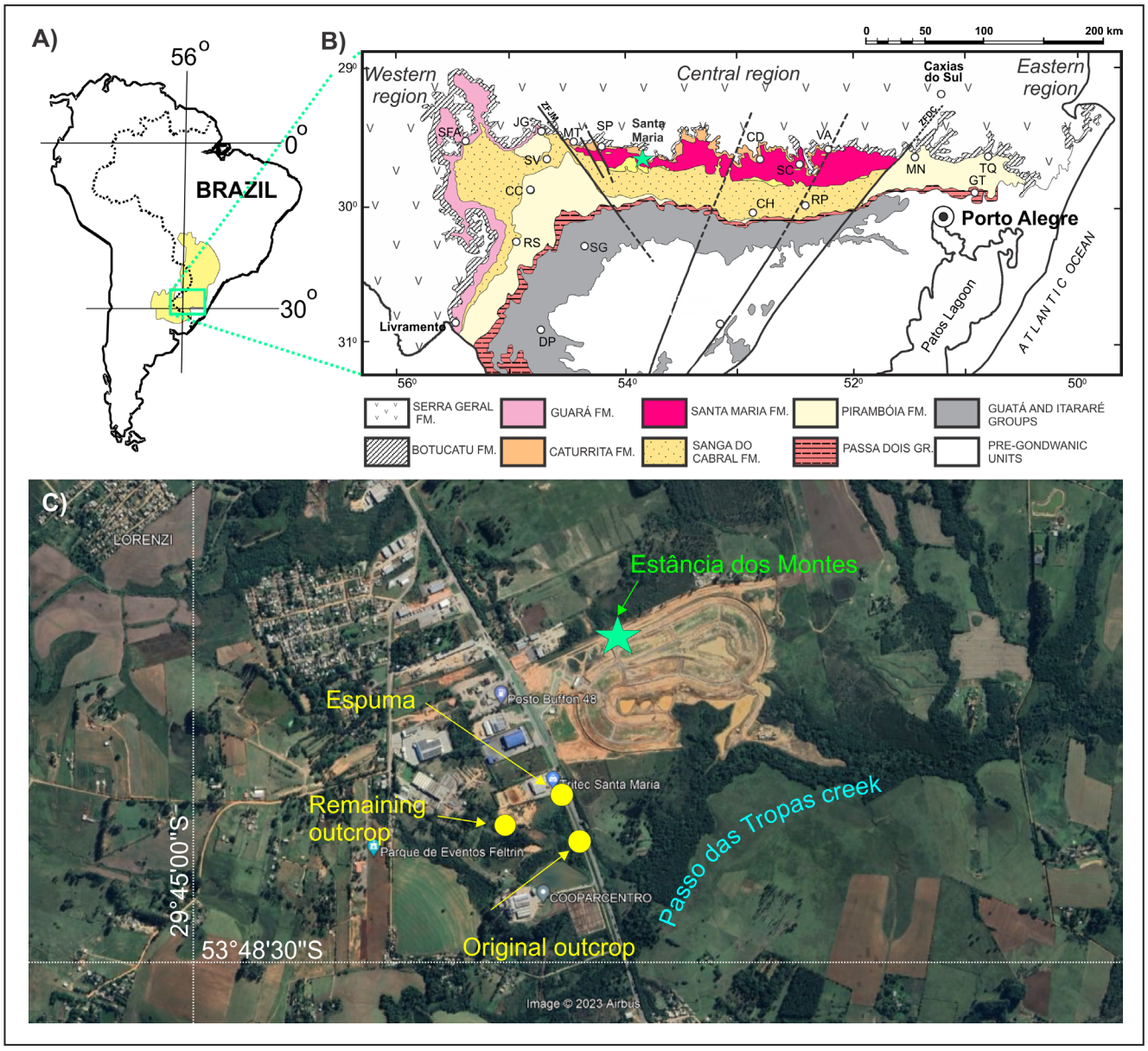

FIGURE 1. Location of studied outcrops. A) Paraná Basin (in yellow), in the context of South America. B) Simplified geological map of the central region of the state of Rio Grande do Sul, focusing on Mesozoic lithologies. C) Satellite image with location of the outcrops mentioned in the text (image taken from Google Earth Pro). Modified from Da Rosa (2015).

Maria to control and monitor existing fossil sites in the urban area, and promote their preservation through environmental licensing of residential and industrial enterprises.

To summarize the historical context of the geological and paleontological information of the Passo das Tropas area, we provide a graphical summary (Fig. 3).

4. Stratigraphic context

The stratigraphic framework of the Paraná Basin was defined in the beginning of the 20th century, with the report on the coal basins of southern Brazil (White 1988), the result of which became internationally known as the White Column (Orlandi Filho et al. 2006). However, the existing stratigraphic column in Serra do Rio do Rastro, state of Santa Catarina, does not record the Triassic rocks only outcropping in the state of Rio Grande do Sul. So, the first record of Triassic rocks and fossils was only in the second half of the 20th century, initially in a undefined form (Gordon Jr. and Brown 1952), then as “Santa Maria beds” (Bortoluzzi and Barberena 1967), as part of the Rosário do Sul Formation (Gamermann 1973).

Considering geological studies in the city of Santa Maria, it was possible to recognize an individualized and mapable sedimentary package, recording sandstones with intraclasts and intraformational conglomerates (“Passo das Tropas beds”), at the base of reddish mudstones (“Alemoa beds”) (Figure 4 of Bortoluzzi 1974). At that time, the “Passo das Tropas beds” only recorded leaf imprints and invertebrate remains, while the “Alemoa beds” provided a plethora of vertebrate fauna (Huene 1942; Colbert 1970). Later, Andreis et al. (1980) elevated this unit to the status of Rosário do Sul Group, divided into the Sanga do Cabral (Early Triassic), Santa Maria (Middle to Upper Triassic) and Caturrita (Upper Triassic) formations. The Santa Maria formation, by its turn,

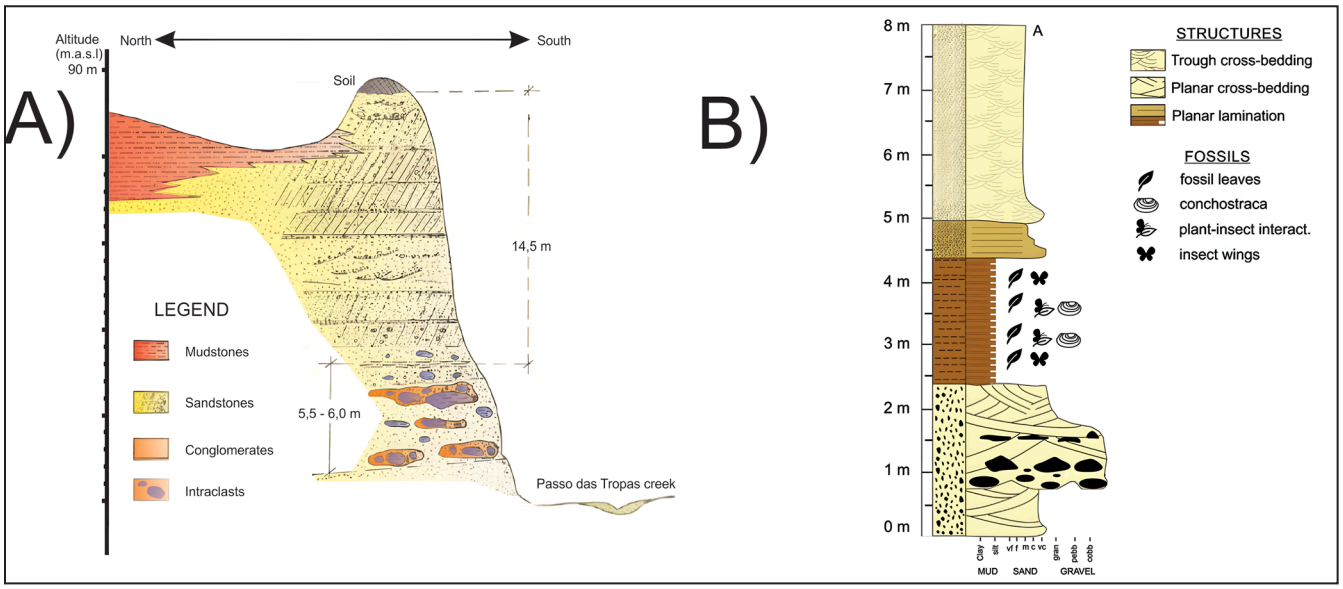

FIGURE 2. Geological profiles of the (A) Passo das Tropas area (redrawn from Bortoluzzi, 1974); and (B) the "Espuma" outcrop (adapted from Barboni & Dutra 2015).

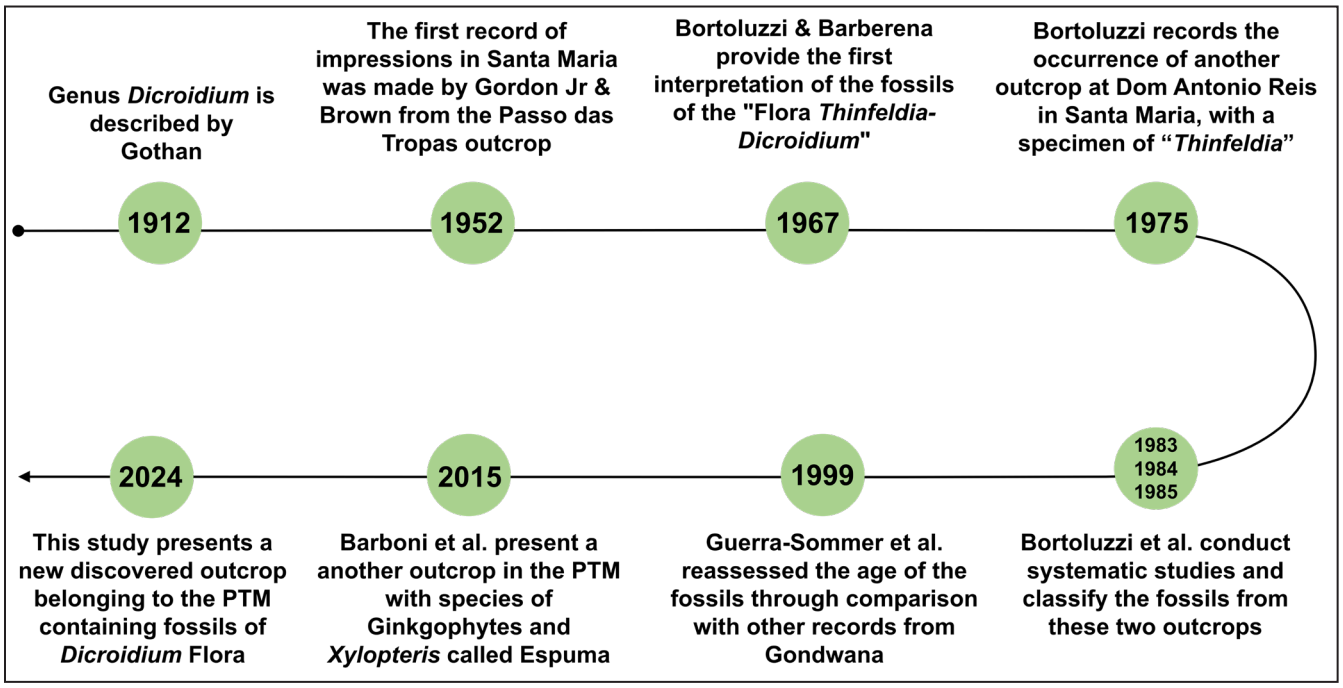

FIGURE 3. Timeline referring to publications and paleontological findings about the *Dicroidium* Flora in the Passo das Tropas Member in Santa Maria, RS.

was divided into a "basal" Passo das Tropas Member and an "upper" Alemoa Member.

The recognition of Middle to Upper Triassic beds along an W-E outcrop belt in Rio Grande do Sul State (Wildner et al. 2008; Da-Rosa 2015), with different assemblage zones (AZ) of vertebrate fossils (Barberena 1977; Schultz et al. 2020), recorded in different post-depositional structural blocks (Da-Rosa and Faccini 2005) showed that there is a more intricate stratigraphic framework. For example, considering the whole Paraná Basin, (Milani et al. 1998) assigned all Triassic rocks to his Gondwana II Supersequence, while Zerfass et al. (2003) recognized two second-order supersequences, namely Sanga do Cabral and Santa Maria. The Sanga do Cabral Supersequence stands for the homonymous formation, whilst the Santa Maria Supersequence congregated the Santa Maria and Caturrita formations, although there was a discussion if the "Mata Sandstone" should or not be included (Faccini 2000). Presently, the Santa Maria Supersequence is divided into four third-order sequences, namely the Pinheiros-Chiniquá, Santa Cruz, Candelária and Mata (Horn et al. 2014), corresponding the first three of them to the deposition of sandstones and mudstones, thus provoking a misuse of the name "Passo das Tropas Member" or "Passo das Tropas sandstones". Although all sandstones are considered as Passo das Tropas Member, we consider that each AZ sandstone must have its own name.

After the geological and hydrostratigraphic characterization of different sandstones in the vicinities of Santa Maria, Wankler et al. (2007) recognized the Sarandi and São Valentim units, respectively linked to the *Hyperodapedon* and *Dinodontosaurus* Assemblage Zones. Considering that the sandstones of the Santa Cruz Sequence outcrop at the Schmitt sand quarry, south of the city of Venâncio Aires, here in we call this the Schmitt unit. Therefore, the Passo das Tropas Member of the Santa Maria Formation is constituted by the São Valentim (late Ladinian? - early Carnian), Schmitt (early Carnian) and Sarandi (late Carnian) units.

The present work provides the location and geological profile of a new outcrop (Fig. 4), the Estância dos Montes, from which a number of leaf imprints and reproductive organs will be described afterwards. In addition, we compiled the geological profiles of the remaining outcrops of the Sarandi unit of the Passo das Tropas Member, at the vicinity of the Passo das Tropas creek, south of Santa Maria, to present a paleoenvironmental reconstruction. The Estância dos Montes outcrop stands for an artificial exposure due to excavation to the implementation of the homonymous residential plan, in which there is a two-meter thick sedimentary package, with a 50 cm mudstone bed, embedded in medium to fine sandstones.

5. Paleontological description

A total of 125 samples of plant fossils were collected at the Estância dos Montes outcrop and these records correspond to impressions of leaves and fronds, reproductive organs and seeds. Some of the plants have been recognized to a more inclusive level, by their anatomical characteristics. First, the plants were identified as belonging to the genus *Dicrodium* due to the constant presence of dichotomized fronds with forked rachis in addition to pinnate and bipinnate specimens, also due to the venation being odontopteroid and alloptéroid. Then, in this preliminary description of the fossils, three species of *Dicroidium* were initially identified: *Dicroidium lancifolium, Dicroidium zuberi, Dicroidium odontopteroides*; reproductive organs fragments: *Pteruchus* sp. and *Umkomasia* sp.; and as a representative of Equisetales, *Neocalamites* sp. (Fig. 5).

Thus, the preliminary taxonomic analysis of fossil plants from the Estância dos Montes outcrop shows the presence of the following taxa:

Division Spermatophyta
Class Pteridospermopsida
Order Corystospermales
Family Corystospermaceae
Genus Dicroidium Gothan 1912

Dicroidium lancifolium (Morris) Gothan 1912 (Fig. 5A).
Referred materials: UFSM12259

One specimen showed observable diagnostic morphological characteristics corresponding to species *Dicroidium lancifolium*, highlighting the presence of pinnate fronds, lanceolate leaflets with a broad base and acute apex, opposite leaflets at the base of the frond becoming alternate from the median to the apical part, entire margin, alloptéroid venation, as described Gottan (1912) and visualized in the UFSM12259 specimen (Fig. 5A). This same species was recorded from the Triassic deposits of the Passo das Tropas by Guerra-Sommer and Klepzig (2000).

Division Spermatophyta
Class Pteridospermopsida
Order Corystospermales
Family Corystospermaceae
Genus *Dicroidium* Gothan 1912.

Dicroidium zuberi (Szajnocha) Archangelsky 1968 (Fig. 5B).
Referred materials: UFSM12276, UFSM12222, UFSM12232, UFSM12252, UFSM12260, UFSM12250, UFSM12258, UFSM12164, UFSM12165, UFSM12165, UFSM12165, UFSM12260, UFSM12252, UFSM12173, UFSM12281, UFSM12271, UFSM12220, UFSM12166, UFSM12221, UFSM12208, UFSM12284, UFSM12282.

There were a total of 22 specimens that showed observable diagnostic morphological characteristics corresponding to species *Dicroidium zuberi*, highlighting the presence of bipinnate fronds, equidimensional rhomboid pinnules with obtuse apex, slightly lobed margin, subopposed secondary rachis becoming alternate in the median part to the apex, odontopteroid venation (Archangelsky 1968) and visualized in the UFSM12222 specimen (Fig. 5B). This same species was recorded from the Triassic deposits of the Passo das Tropas by Guerra-Sommer et al. (1999b).

Division Spermatophyta
Class Pteridospermopsida
Order Corystospermales
Family Corystospermaceae
Genus *Dicroidium* Gothan 1912.
Dicroidium odontopteroides (Morris) Gothan 1912 (Fig. 5D)

Referred materials: UFSM12175, UFSM12244, UFSM12277, UFSM12224, UFSM12163, UFSM12215, UFSM12207, UFSM12262, UFSM12209, UFSM12176, UFSM12256, UFSM12242, UFSM12242, UFSM12167, UFSM12174, UFSM12170, UFSM12171, UFSM12224.

There were a total of 18 specimens that showed observable diagnostic morphological characteristics corresponding to species *Dicroidium odontopteroides*, highlighting the presence of fronds are pinnate, base pinnae wider than long, pinnae opposite to subopposite, apex rounded, margin entire, odontopteroid venation, as described Gothan (1912), and visualized in the UFSM12163 specimen (Fig. 5D). This same species was recorded from the Triassic deposits of the Passo das Tropas outcrop by Bortoluzzi et al. (1985), Guerra-Sommer et al. (1999b) and Da-Rosa et al. (2013).

Division Spermatophyta
Class Pteridospermopsida
Order Corystospermales
Family Corystospermaceae
Genus *Pteruchus* Thomas 1933
Pteruchus sp. (Fig. 5E)
Referred materials: UFSM12266, UFSM12246

Two specimens showed observable diagnostic morphological characteristics corresponding to *Pteruchus*

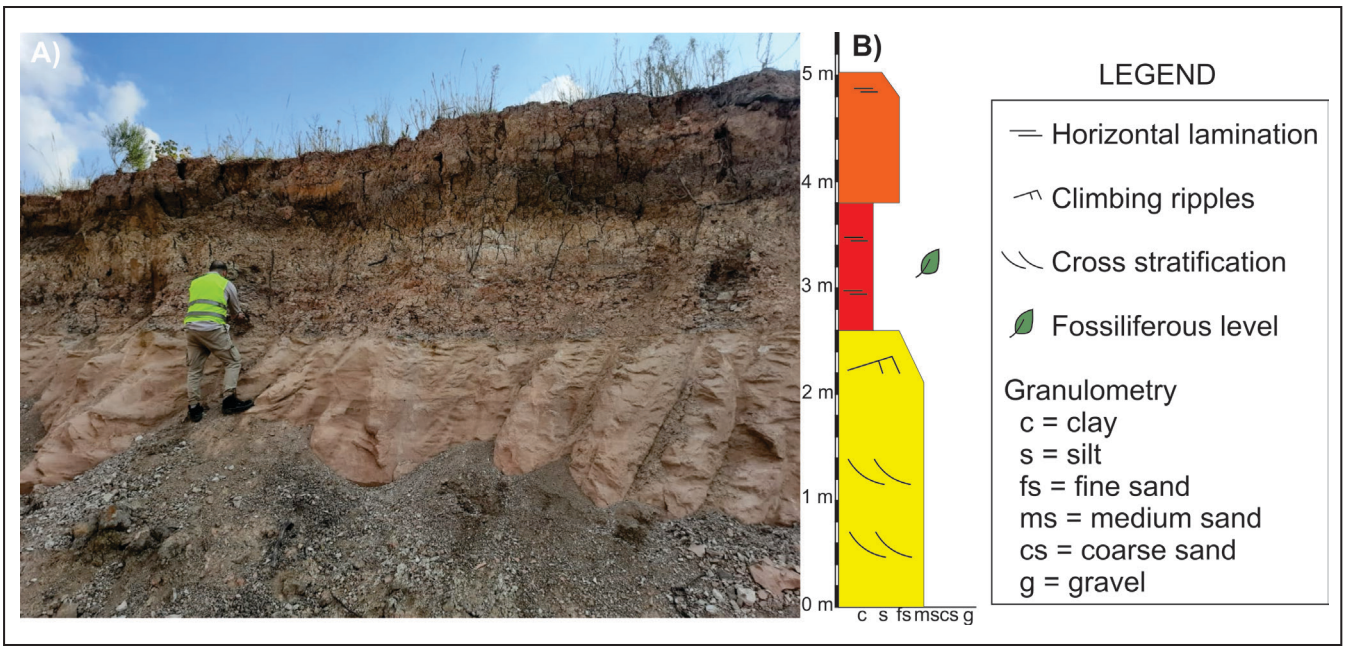

FIGURE 4. Estância dos Montes outcrop. (A) General view of the artificial exposure; (B) Geological profile, with indication of the fossiliferous level.

sp., the pollen organs consisting of naked axes with short microsporophylls, arranged in a subopposite to alternating pattern. Corystosperm pollen organs are assigned to the genus (Taylor and Taylor 2009). Due to the scarcity of specific diagnostic elements, it was only possible to identify these specimens to genus level. UFSM12266 specimen (Fig. 5E). This same genus was recorded from the Triassic deposits of the Passo das Tropas by Pinto (1956), Bortoluzzi and Barberena (1967) and Guerra-Sommer et al. (1999b).

Division Spermatophyta
Class Pteridospermopsida
Order Corystospermales
Family Corystospermaceae
Genus Umkomasia Thomas 1933

Umkomasia sp. (Fig. 5G)
Referred materials: UFSM12251

There were thirty specimens that showed observable diagnostic morphological characteristics corresponding to *Umkomasia* sp., highlighting the presence of ovulate cupules, uni-ovulate, recurved and isolated, roundly shaped with wrinkled surface. Due to the scarcity of specific diagnostic elements, it was only possible to identify these specimens to genus level. This same genus was recorded from the Triassic deposits of the Espuma outcrop by Barboni and Dutra (2015).

Division Pteridophyta
Class Sphenopsida
Order Equisetales
Family Apocalamitaceae
Genus *Neocalamites* T. Halle 1908
Neocalamites sp. (Fig. 5C)
Referred materials: UFSM12274

Only one specimen showed morphological characteristics associated with *Neocalamites* sp. with fragments of thallus with continuous striae, preserved as impression, secondary thalli and leaves not preserved. Due to the scarcity of specific diagnostic elements, it was only possible to identify this specimen to genus level. This same genus was recorded from the Triassic deposits of the Passo das Tropas by Guerra-Sommer et al (1999b) and Da-Rosa et al. (2013).

It was possible to make a taxonomic identification of 61 specimens to at least genus level from the Estância dos Montes outcrop, it. The other specimens (64 in total) represent fragments plant fossils with poorly preserved or inconsistent morphological characteristics, making their identification unfeasible. The paleontological material presented here represents only the first studies carried out on fossils from this new fossiliferous locality. Therefore, a detailed paleofloristic composition of the Estância dos Montes outcrop will be presented elsewhere shortly, as well as associated paleoecological and paleoenvironmental information.

6. Discussion

6.1. Stratigraphy

The Estância dos Montes outcrop is a new outcrop, as explained before, consisting of a sedimentary section composed of a 2 m thick bed of cross-bedded, medium sandstones below a 50 cm thick laminated or massive, reddish to purple mudstone. Leaf imprints can be found all over the fine-grained lithology, but preferentially when they are covered with a purple coloration. This outcrop may not resist the urbanization of the residential area, thus its description and interpretation, as well as correlation with nearby outcrops is urgent.

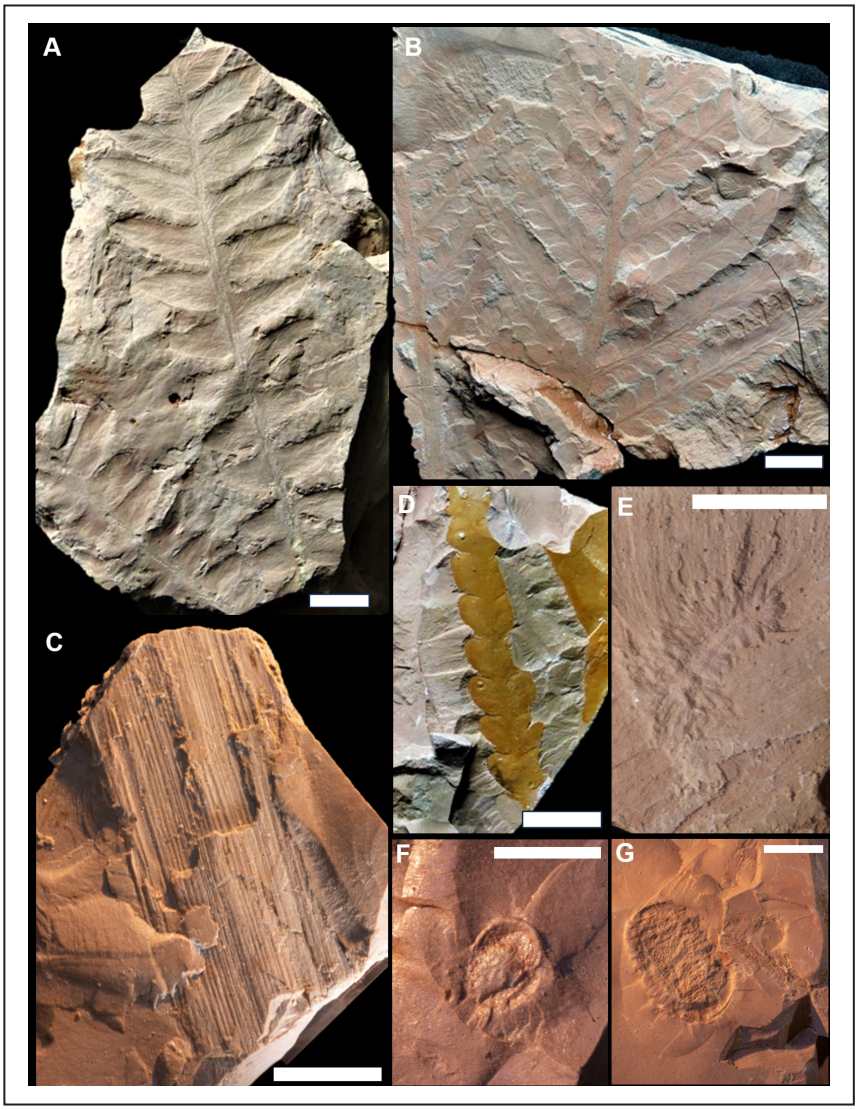

FIGURE 5. Floristic elements belonging to the *Dicroidium* Flora collected in Estância dos Montes outcrop. A) *Dicroidium lancifolium*; B) *Dicroidium zuberi*; C) *Neocalamites* sp.; D) *Dicroidium odontopteroides*; E) *Pteruchus* sp.; F) Seed; G) *Umkomasia* sp. Scale 1 cm.

The Sarandi unit of the Passo das Tropas Member at the studied area is constituted by the Estância dos Montes, "Espuma", the Passo das Tropas and the remaining outcrops of the never described type section. Here we provide a simplified correlation of these outcrops, aiming to construct its paleoenvironmental reconstruction (Fig. 6).

Medium-grained lithologies may have constituted the original outcrop, as they can be hardly seen in the margins of the road, although covered with vegetation. It is difficult to consider it in a geological section, but here we consider them as part of the channel complex of a meandering system. This interpretation corroborates the stratigraphic characterization of Faccini et al. (2003) and the petrographic analysis of Garcia et al. (2003). An unpublished geophysical analysis in the area, with ground penetrating radar (GPR) by the Universidade do Vale do Rio dos Sinos (UNISINOS) team, also stands for channel seams with interbedded floodplain deposits (Garcia et al. 2003).

The remaining outcrop is an abandoned sand quarry, in which a N-S wall reveals fine sandstones in decimeter thick beds that end in millimeter thick mudstone beds, in a sigmoidal shape ("epsilon structures"), interpreted as lateral accretion of a meandering system. Lateral to these lithologies, but stratigraphically above them, there is a laterally restricted, circa 10 m wide, lens of purple mudstones finely interbedded with fine sandstones, interpreted as a lacustrine deposit of an abandoned channel.

The "Espuma" outcrop shows multiple millimetric mudstone layers, embedded in medium sandstones. These lithologies may represent a more extensive lacustrine deposition in an abandoned channel. The Estância dos Montes outcrop also records the same lithologies, representing the same environment.

In the proposed simplified geological section (Fig. 6), the studied outcrops stand for small and lateral variations of a meandering fluvial system, with its channel and lateral accretion deposits, cross cutting the floodplain and abandoned channels.

6.2. Fossil remains

The results found align with the estimates presented in the studies of Bortoluzzi et al. (1985), indicating a significant

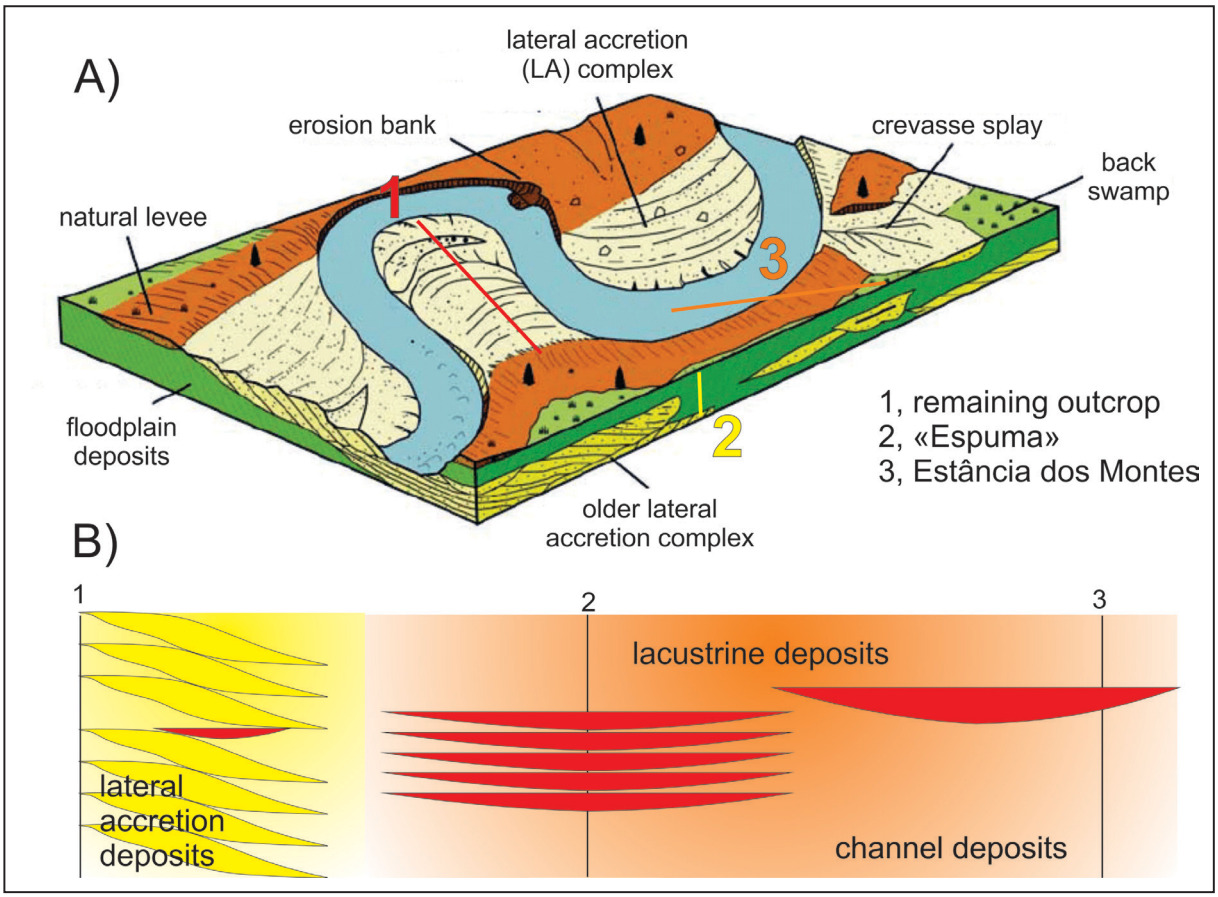

FIGURE 6. Paleoenvironmental reconstruction of the Sarandi unit of the Passo das Tropas Member. (A) Block diagram of a meandering river, with location of studied outcrops; (B) Simplified geological section and interpretation.

abundance of D. zuberi, followed by D. odontopteroides, whereas D. lancifolium has limited sampling. It's worth noting the substantial sampling of Umkomasia Thomas 1933 found in this outcrop. Accordingly, Da-Rosa et al. (2009) suggested that the presence of more developed limb pinnae and the occasional occurrence of reduced limb pinnae are part of a floodplain taphoflora resulting from a river system alternating between xerophilic and humid environments.

The genus Dicroidium stands out as the predominant representative of the Triassic taphofloras around the world. According to the classification of Petriella (1981), Dicroidium Gothan 1912 belongs to the order Corystospermales, division Pteridospermophyta, a clade composed of extinct land plants, popularly called “seed ferns”. Dicroidium can be found in the Gondwana territories: Antarctica, Australia, Arabian Peninsula, Índia, Southern Africa, South America (Fig 7.).

For this genus, the main morphological characteristic consists of the presence of a forked frond, often unipinnate, bipinnate or tripinnate, with a delta-shaped leaf contour with an inverted base. The pinnae are generally bifurcated into two straight or slightly curved rachis with a variable angle and are supported by the petiole, which has a straight shape. In addition, the pinnae can have their apex with a very acute to obtuse shape and entire or divided leaf margins, venetian odontopteroid or alopteroid (Guerra-Sommer et al. 1999a).

During the Permian, the genus Dicroidium already inhabited small parts of Gondwana, and shared territory with the main floristic representative of this period, Glossopteris Flora (Kerp et al. 2006). At the end of the Permian, the planet went through the largest mass extinction event, massively extinguishing marine organisms and strongly affecting terrestrial life. In this event, records of Glossopteris disappeared, however, Dicroidium persisted, resisting even after such an environmental imbalance (Kerp et al. 2006). After the decline of the Glossopteris Flora, the niches became vacant, enabling the expansion of Dicroidium and migration through Gondwana, which populated the territory during the Triassic for around 50 million years (Mays and McLoughlin 2019).

The Lower Triassic is marked by the recovery of fauna and flora after the Permo-Triassic extinction, while later periods are characterized by the warming of the planet, the Greenhouse effect (Guerra-Sommer and Cazzulo-Klepzig 2007). The high temperature on the continents with the combination of intense rainfall events led to the migration and colonization of Dicroidium across Gondwana (Kerp et al. 2006). Concomitantly, the intense rains from the Carnian event led to an increase in the diversity of shapes and an increase in the abundance of species of the genus Dicroidium during the Middle Triassic and Late Triassic (Bomfleur and Kerp 2010).

Therefore, the discovery of a new outcrop, such as the Estância dos Montes outcrop, which contains fossiliferous material related to the Dicroidium Flora, is a new and valuable opportunity to obtain more information about the Triassic ecosystems of Gondwana and also to obtain data that will help to understand the factors that led to the evolution and subsequent extinction of this flora.

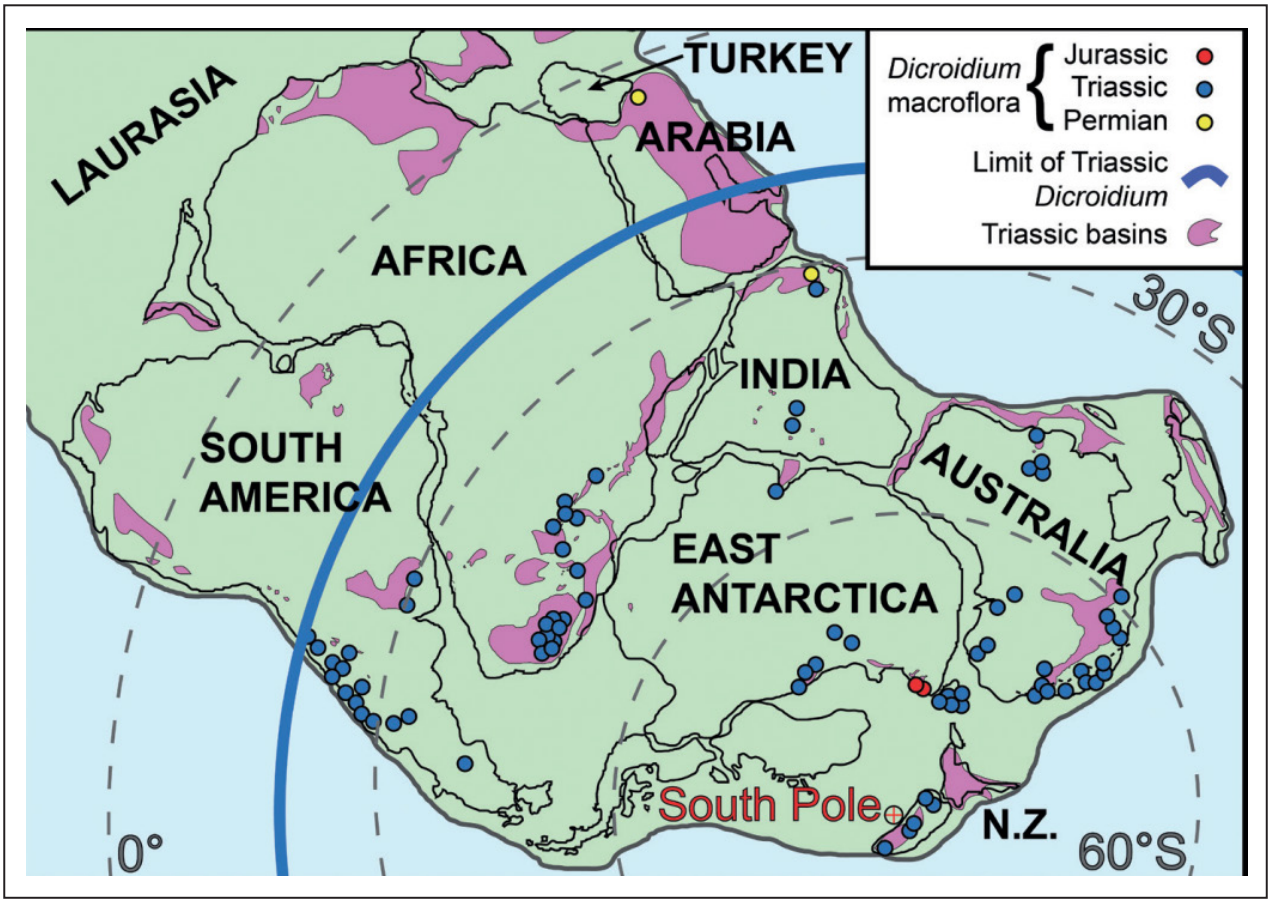

FIGURE 7. Distribution of the *Dicroidium* Flora around Gondwana (Mays and Mc Loughlin 2019).

Furthermore, when considering the entire Brazilian territory, the Triassic deposits, especially at the Passo das Tropas Member, appear in the southern region of Brazil in a well represented way. As previously mentioned, unfortunately the poor management of paleontological heritage and adequate inspection regulations for the protection of these deposits throughout history in Brazil and also in Rio Grande do Sul state, a large part of the locations that contained deposits with Dicroidium Flora were completely destroyed, which further reinforces the importance of the new discovery and the potential for paleontological studies of global importance of this new outcrop in the territory Brazilian.

7. Conclusions

Based on the data presented here, it is possible to state that:

- A new outcrop with fossil leaf imprints belonging to the *Dicroidium* Flora, Estância dos Montes outcrop, is described for the municipality of Santa Maria, state of Rio Grande do Sul/ Brazil.
- The presence of *Dicroidium lancifolium*, *Dicroidium zuberi*, *Dicroidium odontopteroides*, *Neocalamites* sp., *Pteruchus* sp., *Umkomasia* sp. and seed was diagnosed in this new fossiliferous locality.
- The Triassic deposits of southern Brazil, especially in the Santa Maria region, hold important paleontological records of the *Dicroidium* Flora, which require protection and/or conservation measures.
- The Passo da Tropas Member holds a unique and important record of the *Dicroidium* Flora in southern Brazil, and although it has been explored by different authors over time, it has potential for new studies, especially paleoenvironmental and paleoecological ones.

Acknowledgments

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Authorship credits

Author	A	B	C	D	E	F
NME						
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LE						

A - Study design/ Conceptualization **B** - Investigation/ Data acquisition
C - Data Interpretation/ Validation **D** - Writing
E - Review/Editing **F** - Supervision/Project administration

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The Bica São Tomé fossil site, Paraná Basin, Rio Grande do Sul, Brazil: A unique window to the dawn of the Mesozoic Era

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Abstract

The Early Triassic is pivotal for understanding the recovery and diversification of post-extinction biotas, marking the initial emergence or early diversification of many modern life forms. This phase holds dual significance as it establishes the groundwork for contemporary biodiversity evolution and provides crucial insights into managing present ecological challenges. Focused efforts on the Sanga do Cabral Formation in the Paraná Basin unveil a critical opportunity for studying Early Triassic vertebrates in South America, offering a unique perspective on Western Gondwana's biotic recovery after the End-Permian Mass Extinction. Here, we review the geology and fossil record of the most important fossiliferous outcrop of the Sanga do Cabral Formation, the Bica São Tomé Fossil Site. Prospections at the outcrop have already recovered over two hundred specimens, including holotypes and representative materials of important Early Triassic taxa. Our review aims to demonstrate the relevance of the site and highlight strategies for its preservation. The site includes an unusual representation of archosauromorphs, although its content is dominated by procolophonids. Among the known localities of the Sanga do Cabral Formation, the Bica São Tomé Fossil Site stands out for the unique presence of well-preserved specimens in articulation, such as the nearly complete skeleton of the archosauromorph *Teyujagua paradoxa*. Even so, most of the record is dominated by fragmentary and reworked specimens. The Bica São Tomé site stands as a beacon for understanding Lower Triassic ecosystems in Latin America, presenting an unparalleled opportunity for Mesozoic exploration in Brazil. The Sanga do Cabral Formation, with its wealth of fossil evidence, promises to enrich our understanding of the Early Triassic period and its significance in shaping modern biodiversity.

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1. Introduction

The path traversed by life in the course of evolution has, at times, been marked by profound revolutions triggered by geological phenomena. Such was the case with the End-Permian Extinction (EPE), an event that led to the decimation of alarming proportions of continental and marine biotas (Erwin 2008). The impact of the EPE on ecosystems resulted in a revolution in the macroevolutionary history of lineages, so that all current living organisms descend from some of the few survivors of the EPE.

The early moments of the Triassic period thus mark the beginning of the recovery and diversification of post-EPE biotas. This is an event of utmost significance for two reasons. Firstly, the Early Triassic biotic recovery laid the foundation for what we now know as modern life (Romano et al. 2020). Secondly, and no less important, understanding mass extinctions and life's recovery under conditions of profound environmental stress is crucial for managing the current ecological crisis (Payne and Clapham 2012).

The Triassic was a pivotal moment in the history of continental life, and many of the groups that now populate terrestrial ecosystems, such as birds, turtles, crocodiles, lizards, lissamphibians and mammals have their origins or initial diversification consolidated in this period (e.g. Simões et al. 2018). The Triassic marks the beginning of the Mesozoic

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Era (the "Age of Reptiles"), during which dinosaurs eventually became dominant in terrestrial communities (Chen and Benton 2012; Benton and Wu 2022).

Despite their relevance, the initial stages of the Triassic remain relatively underexplored, largely due to significant biases in collection and geographic representation. Our understanding of Early Triassic vertebrates is predominantly derived from a limited number of fossil deposits, concentrated mainly in South Africa, Russia, and China (e.g. Benton et al. 2004; Botha and Smith 2006; Benton and Twitchett 2003). The sparse record adds to the natural scarcity of fossils due to the decline in diversity following the extinction event.

In this context, the Sanga do Cabral Formation (SCF) in the Paraná Basin emerges as a crucial opportunity for the recovery of fossil vertebrates from the Lower Triassic. In fact, the SCF is the only Lower Triassic unit with informative paleontological content from South America, offering a unique perspective on the biotic recovery of the Early Triassic in Western Gondwana (Dias-da-Silva et al. 2017).

Given its evident relevance, it seems strange that so little effort has been dedicated to systematic paleontological prospecting in the SCF since the first reports of fossil specimens in the 1980s (see Schultz et al. 2020). Three main factors may be hypothesized to explain this apparent lack of interest: First, it is not easy to find informative fossils in SCF outcrops. Its deposition resulted from harsh fluvial environments, inhospitable to biological remains (Xavier et al. 2023). SCF fossils are usually found as fragmentary remains, with obvious evidence of transport and reworking, and complete/articulated specimens are exceptionally rare findings. In second place, the productivity and aesthetic appeal of fossils from the overlying Santa Maria and Caturrita formations have eclipsed the SCF record, which has been revealed as the "ugly duckling" of the Brazilian Triassic. A third important factor is related to the distance from productive localities to large urban centers, such as the Rio Grande do Sul state capital, Porto Alegre. Consequently, there has been a significant increase in prospecting within the SCF following the establishment and strengthening of research groups in smaller cities, such as the Laboratório de Paleobiologia at the Universidade Federal do Pampa (Paleobio Unipampa, São Gabriel, RS) and the Laboratório de Estratigrafia e Paleobiologia at the Universidade Federal de Santa Maria (LEP, Santa Maria, RS).

Although the first formal reports of SCF tetrapods were made by Barberena et al. (1981), the first valid nominal taxon described for this unit was *Sangaia lavinai* (Dias-da-Silva et al. 2006a). It is important to note that two separate *Procolophon* species, "*P. pricei*" and "*P. brasiliensis*," were erected by Lavina (1983) and Cisneros and Schultz (2002), respectively. However, these were later synonymized to *P. trigoniceps* by Cisneros (2008). A boost in the research on SCF fossil faunas occurred through the discovery and description of new fossil sites (Da-Rosa et al. 2009; Dias-da-Silva and Da-Rosa 2011) and the growing interest of a few research groups, notably the Paleobio Unipampa the LEP (UFSM). These efforts resulted in the recovery of hundreds of new specimens (most of which are still undergoing triage and preparation) and the description of several new taxa. These include the early archosauromorphs *Teyujagua paradoxa* and *Elessaurus gondwanoccidens* (Pinheiro et al. 2016; De-Oliveira et al. 2020), the procolophonid *Oryporan insolitus* (Pinheiro et al. 2021), and the temnospondyls *Tomeia witecki* and *Kwatisuchus rosai* (Eltink et al. 2017; Pinheiro et al. 2024).

Pivotal to these new discoveries are the systematic collection efforts concentrated on particularly productive SCF sites. This is the case with the Bica São Tomé fossil site in São Francisco de Assis, Brazil (Fig. 1). In its initial report (Da-Rosa et al. 2009), the Bica São Tomé site has already demonstrated an unusual abundance of fossil yields, especially when compared to other SCF localities. The site is also the only SCF locality where fairly complete and articulated specimens have been found (e.g., Pinheiro et al. 2016, 2020; De-Oliveira et al. 2020, 2024). Additionally, four of the six nominal taxa described for the SCF originate from this site (see below). Consequently, the Bica São Tomé site has instigated a revolution in our understanding of the South American Early Triassic, emerging as one of the most relevant localities for Mesozoic research in this continent. In this work, we review the geology and fossil content of this unique locality with the aim of highlighting its significance for understanding the early Mesozoic Era in western Gondwana and proposing potential strategies for its preservation.

2. Comments on the surface exposure of the Sanga do Cabral Formation

Although the Sanga do Cabral Formation (SCF) was designated based on outcrops surrounding the city of Rio Pardo, in the eastern portion of the Triassic exposure in the central region of Rio Grande do Sul State, the fossiliferous sites are primarily situated in the western portion, between the cities of Santa Maria and São Francisco de Assis. There is also a segment of outcrops along the road to Santana do Livramento, and likely extending into Uruguay, prompting Dias-da-Silva et al. (2017) to regard the Buena Vista Formation in that country as part of the Sanga do Cabral Supersequence (Zerfass et al. 2003). However, paleomagnetic data from that formation suggest it predates the Permian-Triassic boundary (Ernesto et al. 2020).

Most of the retrieved fossils from the SCF are fragmentary and/or disarticulated, originating from scattered outcrops in Rio Grande do Sul State, southern Brazil (Table 1). Ramal Abandonado (also referred to as Catuçaba, Campo da Pedra, or Dilermando de Aguiar) likely represents the earliest recognized fossiliferous exposure of the SCF. It comprises a series of exposures of sheet sandstones and conglomerates encased within fine orange sandstones, situated along an abandoned railroad. This outcrop yielded fragmentary specimens of procolophonids, including a partial skull identified as "*Procolophon pricei*," as well as temnospondyl dermal bones (Lavina 1983; Lavina and Barberena 1985). Empedrado is an exposure located along road BR 158, exhibiting a similar lithological composition of sheet sandstones/conglomerates embedded in fine orange sandstones, albeit displaying post-depositional fracturing and dyke intrusion, likely associated with the separation of South America and Africa during the onset of the Gondwana breakup. São José da Porteirinha and Cabeceira do Raimundo, also situated along BR 158, exhibit limited lateral expression. Fazenda dos Melos, identified during the geological mapping of the Quarta Colônia Geopark (Zerfass et al. 2008), presents a notable exposure, although no fossils have been recovered thus far. Rincão dos Weiss represents another known outcrop, located adjacent to a rural

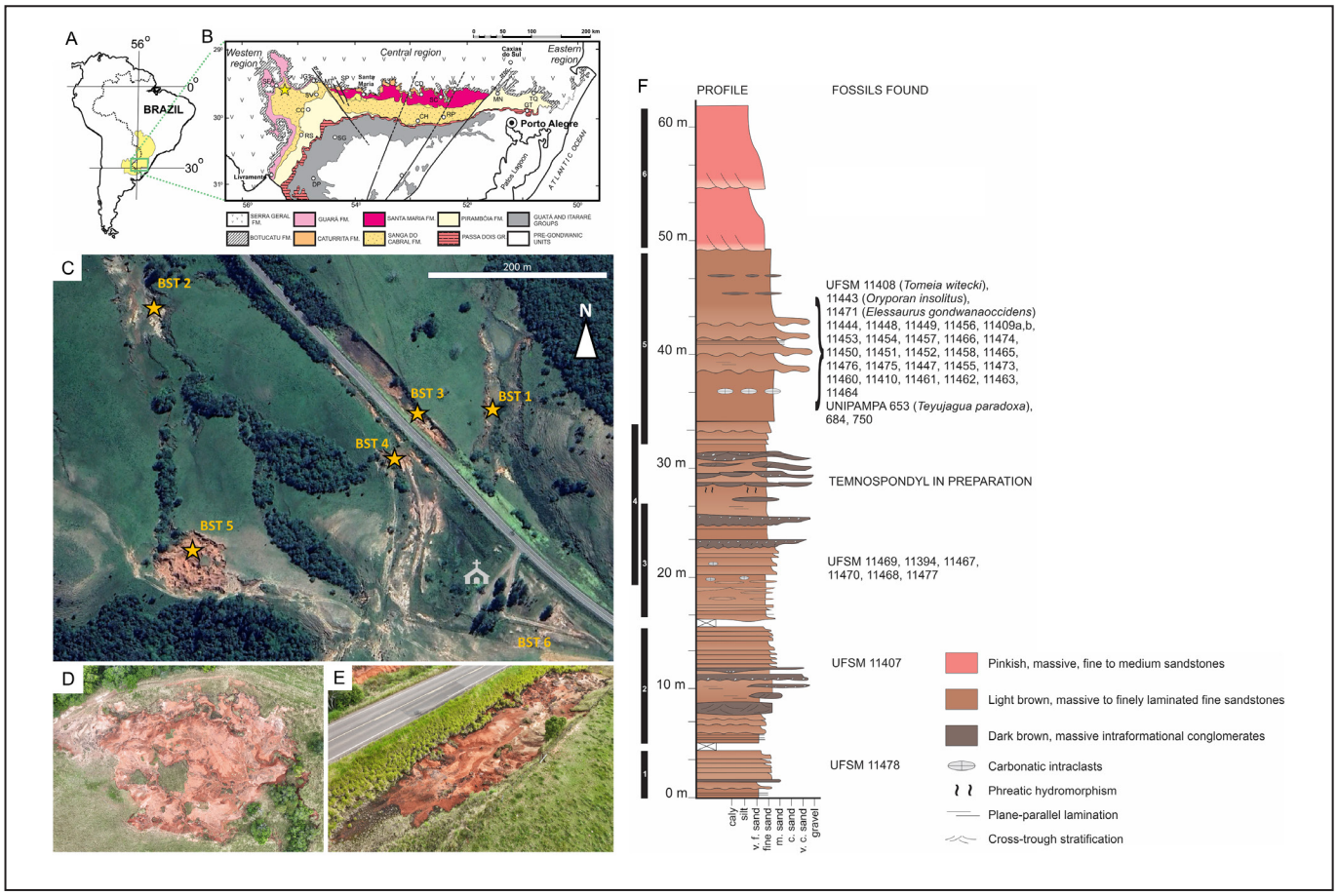

Figure 1. Location and geology of the Bica São Tomé fossil site. A, the Paraná Basin in the context of South America; B, simplified geological map of sedimentary units of Rio Grande do Sul State, southern Brazil. C, aerial image detailing the location Bica São Tomé exposures (image from Google Earth Pro); D, aerial image of outcrop BST 5, the most productive exposure of Bica São Tomé fossil site; E, aerial image of BST 3, other productive exposure of the Bica São Tomé fossil site; F, composite geological section of the 6 outcrops of the Bica São Tomé fossil site, indicating the occurrence of published fossil specimens. The black numbered bars next to the geological section indicate the outcrops BST 1-6. Church symbol: former location of the Saint Thomas Jesuitic Mission, ca. 1632 AD.

road near the city of Mata, primarily yielding fragmentary procolophonid remains. A series of small outcrops in the vicinity of Morro do Cruzeiro in Cachoeira do Sul yielded temnospondyl remains described as *Sangaia lavinai* (Dias-da-Silva et al. 2006a). The SCF spans at least 30 m, exhibiting a gradual lithological transition from sheet sandstones/conglomerates embedded in fine orange sandstones to finer lithologies at the top, although a comprehensive description is warranted. Lastly, the exploration of new outcrops led to the discovery of Bica São Tomé (Da-Rosa et al. 2009), Côrte, and Granja Palmeiras (Dias-da-Silva and Da-Rosa 2011), significantly enriching the fossil record of the SCF. This last site is the type locality of the temnospondyl *Kwatisuchus rosai*, a recently described taxon for the SCF (Pinheiro et al. 2024).

Considering the scattered outcrops and the characteristic fragmentary nature of SCF fossils, Bica São Tomé (Fig. 1) emerges as a unique and significant site for understanding Early Triassic Gondwanan diversity. Notably, the site stands out as the most productive locality within the SCF in terms of fossil yield.

3. Site characterization, geology and age

The Bica São Tomé is situated within the escarpments of a hill, adjacent to road RS 241, linking the cities of São Francisco de Assis and São Vicente do Sul in Rio Grande do Sul State, Southern Brazil (Fig. 1, 2). It encompasses six outcrops, with most situated along the roadside and two within privately owned areas (Da-Rosa et al. 2009). The predominant vegetation consists of open fields utilized for agricultural activities, interspersed with isolated clusters of trees. The exposure of fossiliferous rocks is attributed to road excavation activities or erosional processes within the private areas, likely influenced by extensive cattle grazing.

The name of the fossil site derives from a water fountain (Bica) with religious significance dedicated to Saint Thomas (São Tomé). In fact, a Jesuit mission was founded there on June 13th, 1632, named “Redução Jesuítica São Thomé”, agglomerating more than 400 indigenous people till 1838, when it was abandoned prior to the incursions of pillage soldiers from the center of Brazil (Cohen and Colombo 2015).

The six outcrops were arranged in a composite stratigraphic section exhibiting a predominance of orange fine sandstones, interspersed with lenses of intraclastic conglomerates (Da-Rosa et al. 2009). A detailed geological profile (Fig. 1) delineates the following:

Outcrop BST 1. situated within a private area, constitutes the basal segment of the composite profile, characterized by approximately three meters of massive, very fine orange sandstones.

Table 1. Known fossiliferous outcrops of the Sanga do Cabral Formation.

Outcrop	Municipality	Fossils	References
Ramal abandonado (also Catuçaba or Dilermando de Aguiar)	Dilermando de Aguiar	"*Procolophon pricei*", temnospondyl dermal bones	Lavina 1983; Lavina and Barberena 1985
Empedrado	Dilermando de Aguiar	Procolophonid jaw, undescribed fragments	
São José da Porteirinha	Dilermando de Aguiar	Indeterminate fragments	
Cabeceira do Raimundo	Santa Maria	Procolophonid fragments	Da-Rosa 2004
Fazenda dos Melos	Restinga Seca	Indeterminate remains	Zerfass et al. 2008
Morro do Cruzeiro	Cachoeira do Sul	Sangaia lavinai	Dias-da-Silva et al. 2006a
Rincão dos Weiss	Jaguari	Procolophonid and temnospondyl fragments	
São Vicente do Sul	São Vicente do Sul	Indeterminate fragments	
Trevo para Cacequi	São Vicente do Sul	Indeterminate fragments	
Côrte	Rosário do Sul	Indeterminate fragments	
Granja Palmeiras	Rosário do Sul	Fish, procolophonid, temnospondyl and archosauriform frgments, *Kwatisuchus rosai*	Dias-da-Silva and Da-Rosa 2011; Pinheiro et al. 2024
Bica São Tomé	São Francisco de Assis	Procolophonid, temnospondyl and archosauriform fragments, *Teyujagua paradoxa*, *Tomeia witecki*, *Elessaurus gondwanaoccidens*, *Oryporan insolitus*	Da-Rosa et al. 2009; Eltink et al. 2017; Pinheiro et al. 2016, 2021; De-Oliveira et al. 2020

Outcrop BST 2. spans both sides of RS 241, positioned at the northwesternmost side, featuring two small cliffs preserving a limited number of fragmentary fossils within lenses of intraformational conglomerates embedded in trough cross-bedded fine orange sandstones.

Outcrop BST 3. located 200 meters southeastwards from the previous outcrop, along the northern margin of the road, exhibits a coarsening upward succession of fine orange sandstones interspersed with medium sandstone levels, carbonate concretions, and lenses of intraformational conglomerates, housing a sparse collection of fragmentary fossils.

Outcrop BST 4. extends southwards from the preceding outcrop, showcasing a maximal coarsening trend with abundant conglomeratic lenses, evidence of phreatic hydromorphism (manifested as lateral discoloration levels), yet yielding few fragmentary fossils.

Outcrop BST 5. situated within a private area, features an erosional escarpment displaying at least four beds of fining upward fine to medium orange sandstones, adorned with carbonate nodules. Notably, two of these beds exhibit the highest productivity in fossil preservation, yielding the majority of retrieved fossils.

Outcrop BST 6. records medium pink sandstones with trough cross-bedding, attributable to the Guará Formation (Upper Jurassic).

The only SCF nominal taxon with a precise and undisputed correlation to other, better temporally anchored sedimentary basins is the parareptile *Procolophon trigoniceps* (see below). The presence of this species enables a reliable correlation of the SCF with the *Lystrosaurus declivis* Assemblage Zone of the South African Karoo Basin (Katberg Formation) (Botha and Smith 2020). In well-described, complete sections of the Katberg Fm., the first remains of *P. trigoniceps* occur 116 m above the Permo-Triassic boundary (Botha and Smith 2006). This correlation, along with the temporal range of other taxa (from a more inclusive taxonomic perspective), indicates a late Induan/Olenekian age for the SCF. It is worth noting, however, that absolute dating of the SCF is already underway. Furthermore, the apparently highly time-averaged SCF assemblage may suggest the possibility of wide temporal gaps between fossil elements present in different sedimentary facies, thus necessitating an in-depth taphonomic assessment of the SCF. For a more detailed account of the SCF biostratigraphy, please refer to Dias-da-Silva et al. (2017).

4. Taphonomic remarks

Fossils collected from the Bica São Tomé Fossil Site are divided into two distinct modes of preservation, associated with different sedimentary facies and differing in numerical representativeness. The most common occurrences are characterized by isolated, disarticulated bone elements (especially vertebrae, mandibular fragments, and long bones) in varying degrees of fragmentation. These occurrences are usually associated with intraformational conglomerate levels. The common preservation of fragile structures might indicate, according to Holz and Souto-Ribeiro (2000), the pre-fossilization and reworking of elements sharing these taphonomic signatures.

Much more rarely, some specimens show moderate to high degrees of articulation. These include vertebral sequences, limbs, or skeletal portions in varying degrees of completeness (e.g., *Elessaurus gondwanoccidens* - De-Oliveira et al. 2020) (Fig. 3, F, H). A single occurrence of a skull associated with a reasonably complete postcranium is known—the holotype of the archosauromorph *Teyujagua paradoxa* (De-Oliveira et al. 2024) (Fig. 3, C, E). Articulated or semi-articulated specimens are normally associated with fine sand facies, sometimes preserved as cores of carbonate concretions (see Dias-da-Silva et al. 2017).

The different modes of preservation and the possibility of reworking of specimens recovered from conglomeratic levels highlight the potential for substantial time averaging at the fossil site. An accurate assessment of this temporal dimension requires a more in-depth taphonomic study.

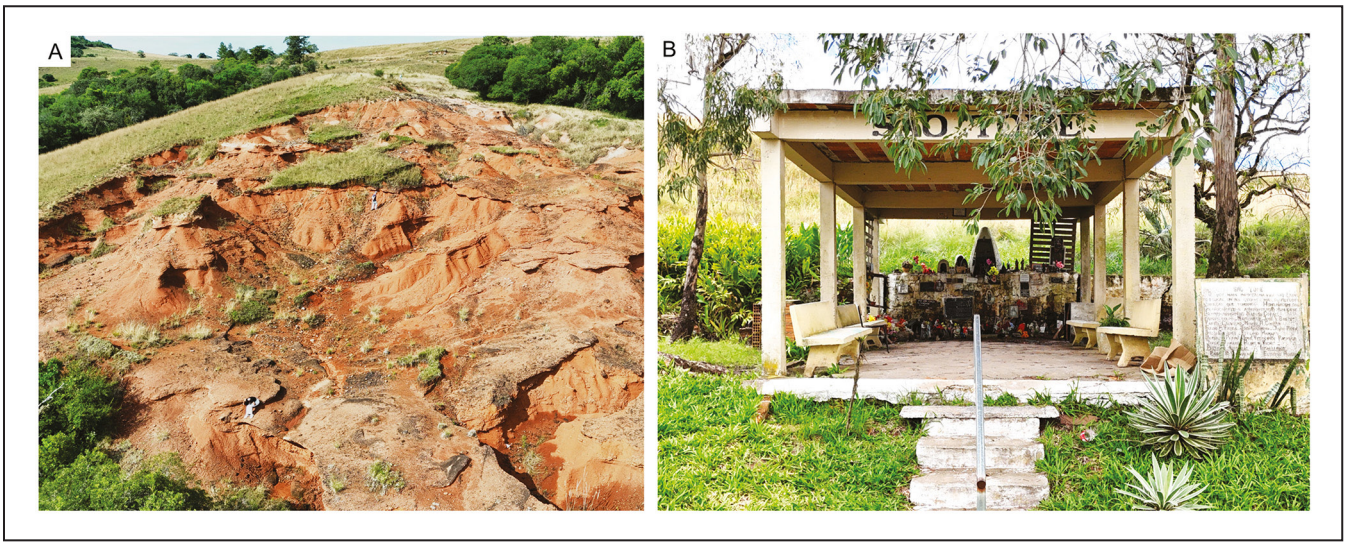

Figure 2. Bica São Tomé fossil site. A, aerial view of outcrop BST 5, exposing the most fossiliferous layers of the locality; B, Sanctuary in honor of Saint Thomas, a water fountain area suitable for picnics and camping.

5. Fossil content

The first fossils from the Bica São Tomé site were presented alongside the formal introduction of the locality by Da-Rosa et al. (2009). At that time, the authors illustrated and preliminarily described numerous fossils belonging to Temnospondyli, Procolophonidae, Cynodontia, and Archosauromorpha. It is worth noting that specimens presented as Cynodontia were reevaluated by Dias-da-Silva et al. (2017) as belonging to Procolophonoidea. Among the materials reported by Da-Rosa et al. (2009), only *Procolophon trigoniceps* was identified at the specific level. Some of the materials presented by the authors were further described in posterior contributions, and Da-Rosa et al. (2009) already recognized the uniqueness of the Bica São Tomé site due to the quality of preservation and the occurrence of articulated elements.

Given that the Bica São Tomé site is a recent addition to the Brazilian Triassic, systematic and exhaustive collections at the locality are relatively recent, and the collection effort intensified from the year 2016. Although the locality already boasts hundreds of recovered specimens (mostly fragmentary), the materials that have been sorted, prepared, and identified are scarce compared to those still waiting for preparation. Therefore, this review will focus on those specimens that have already been formally presented and described for the site.

5.1 Temnospondyli

The temnospondyls are the most diverse group of non-amniote tetrapods in Paleozoic and Mesozoic ecosystems, with a large stratigraphic range that spans from the Carboniferous until nowadays (when considering that lissamphibians belong to the clade) (Schoch 2013). The main adaptive radiation of temnospondyls occurred in the aftermath of the End-Permian Extinction, and the group is one of the major components of Early Triassic continental ecosystems (Romano et al. 2020).

Although bone fragments of Temnospondyli are not rare occurrences at the Bica São Tomé site, few materials have been formally reported for the site. Many collected specimens still require preparation, identification, and formal presentation.

The first materials belonging to the clade for the site were presented by Da-Rosa et al. (2009). These are specimens UFSM 11408, UFSM 11447, UFSM 11455, UFSM 11451, UFSM 11450, UFSM 11473, UFSM 11477. Da-Rosa et al. (2009) highlighted the relevance of specimen UFSM 11408. In this initial article, the material was illustrated as a sequence of cranial bones found in association, some of them showing fitting surfaces.

The same specimen (UFSM 11408) was formally presented as a new species of temnospondyl by Eltink et al. (2017). It consists of a partial skull, represented by its posterior portion, along with several fragmented cranial roof bones and jaw fragments (Fig 3, A). The animal was named *Tomeia witecki* and was recovered as belonging to the Capitosauroidea, one of the major stereospondyl lineages that diversified during the Triassic. Approximately ten years after the discovery of the holotype of *T. witecki*, a cranial fragment was found near the location where the first material was discovered. After laboratory preparation, it became evident that, surprisingly, this second piece fits perfectly with the holotype, being attributable to the same specimen. The holotype of *T. witecki*, including new anatomical information contributed by the new material, is undergoing reassessment and study.

5.2 Procolophonoidea

Procolophonoidea is a fairly diverse group of parareptiles, exclusively composed of small-sized animals. Among Parareptilia, procolophonoids were the only clade to survive the EPE, indicating a pulse of diversification in the Early Triassic (Modesto et al. 2001). Within procolophonoids, the taxon with the most abundant and geographically well-distributed records is undoubtedly the procolophonid *Procolophon trigoniceps*. This species is abundantly represented in outcrops of the Sanga do Cabral Formation, being the primary biostratigraphic proxy for the unit and enabling its correlation with other Lower Triassic strata worldwide (see Dias-da-Silva et al. 2017).

Da-Rosa et al. (2009) attribute several cranial and mandibular materials recovered from the Bica São Tomé site to *Procolophon trigoniceps* (UFSM 11409a, UFSM 11443,

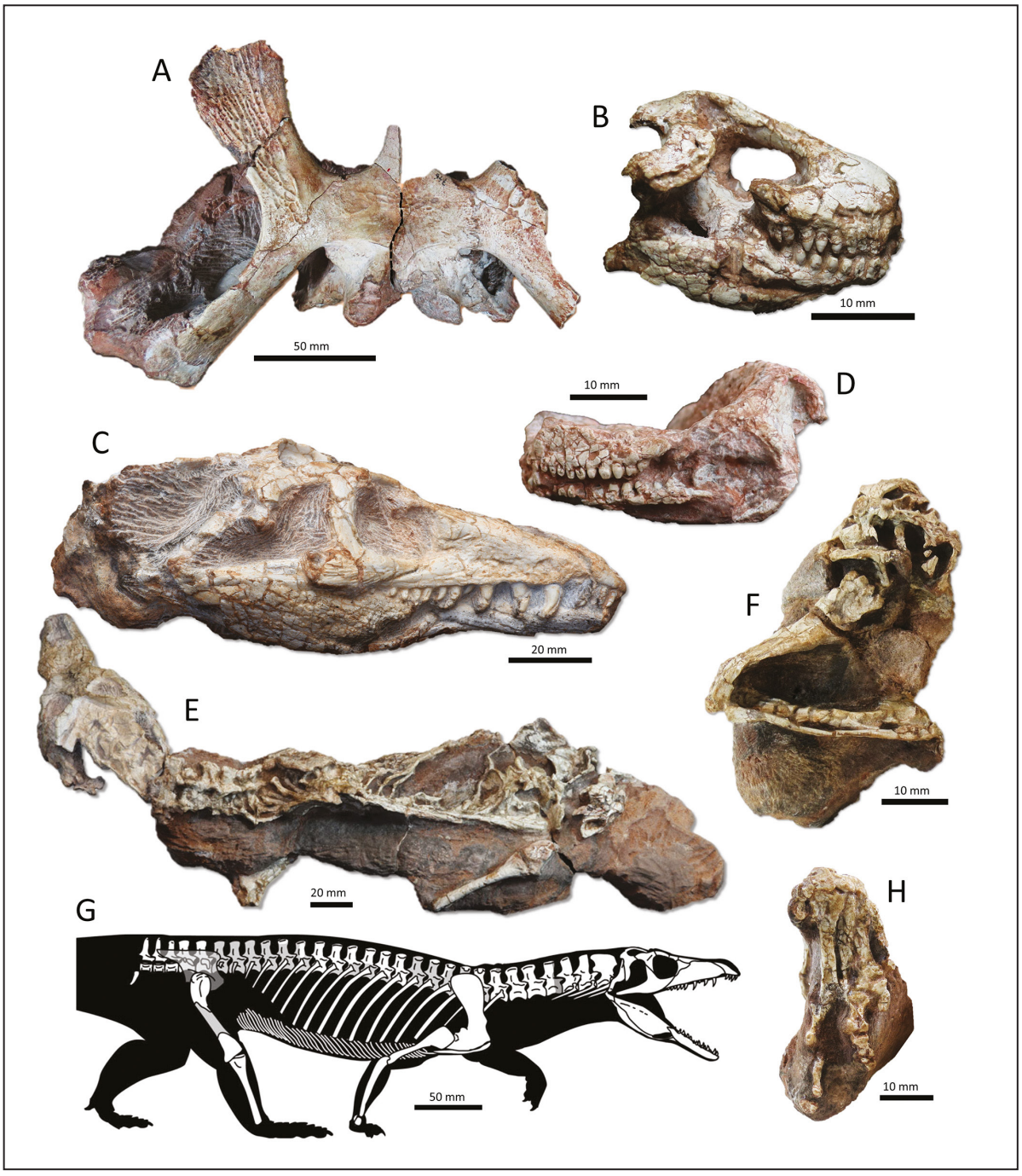

Figure 3. Representative fossil specimens from the Bica São Tomé fossil site. A, *Tomeia witecki* (Temnospondyli), holotype (UFSM 11408), posterior skull in ventral view; B, *Procolophon trigoniceps* (Procolophonoidea) (CAPPA/UFSM 0189) skull in right lateral view; C, *Teyujagua paradoxa* (Archosauromorpha), holotype skull (UNIPAMPA 653) in right lateral view; D, *Oryporan insolitus* (Procolophonoidea), holotype skull (UFSM 11443) in left lateral view; E, *T. paradoxa*, holotype (UNIPAMPA 653) skull and postcranium; F, *Elessaurus gondwanoccidens* (Archosauromorpha), holotype (UFSM 11471) left hindlimb and axial bones; G, *T. paradoxa*, skeletal reconstruction (mirrored from De-Oliveira et al. 2024); H, *Elessaurus gondwanoccidens*, holotype (UFSM 11471) left foot. Art in G by Voltaire D. P. Neto.

UFSM 11448, UFSM 11449, and UFSM 11454), citing the diagnostic presence of "bicuspid, labio-lingually expanded and highly meso-distally compressed molariforms'' as justification for the assignment. Among these materials, a comparatively enormous skull stands out, possibly constituting the largest known specimen for the species (UFSM 11409a). This material would later be described in greater detail by Dias-da-Silva et al. (2017). It is worth noting that specimen UFSM 11443 would later be recognized as representing another genus and species of procolophonid by Pinheiro et al. (2021). Other materials attributed to Procolophonoidea by Da-Rosa et al. (2009) include a fragmentary vertebra (UFSM 11469), a long bone fragment identified as a femur (UFSM 11453), and a mandibular fragment (UFSM 11474). The latter exhibits a peculiar morphology, and its assignment to Procolophonoidea lacks a more in-depth evaluation.

As reported earlier, the work by Dias-da-Silva et al. (2017) describes in greater detail the specimen UFSM 11409a. This

specimen is of great significance, as it appears to be the largest specimen ever reported for *Procolophon trigoniceps*, surpassing even the largest African specimens (see Dias-da-Silva et al. 2017 for further details). The assignment of UFSM 11409a to the species was based on the recognition of bicuspid molariform teeth and a large subtemporal emargination, being also supported by phylogenetic analysis (Dias-da-Silva et al. 2017). Two other specimens attributable to Procolophonoidea were presented for the Bica São Tomé site by Dias-da-Silva et al. (2017). The first of these is a well-preserved, large dorsal vertebra (UNIPAMPA 0655). Its morphology is similar to what has been previously described for procolophonids from the Sanga do Cabral Formation. (as in Dias-da-Silva et al. 2006b). A second specimen (UNIPAMPA 0680) is a fragment of a right mandibular ramus bearing bicuspid molariform teeth, a typical characteristic of *Procolophon trigoniceps*.

The specimen, which is likely the best-preserved *Procolophon trigoniceps* for the Sanga do Cabral Formation, also found at the Bica São Tomé site, was described in detail by Silva-Neves et al. (2018). It concerns CAPPA/UFSM 0189, a virtually complete skull with the mandible still in occlusion (Fig 3, B). Its morphology is characteristic of the taxon, not differing significantly from similar-sized South African specimens.

One of the most intriguing specimens of Procolophonoidea recovered from the Bica São Tomé site was described in detail by Pinheiro et al. (2021). This is specimen UFSM 11443, which had previously been identified as *P. trigoniceps* by Da-Rosa et al. (2009) (Fig. 3, D). A more detailed study, aided by images from computed microtomography, allowed recognition that the specimen belongs to a unique taxon of early-diverging procolophonid, only distantly related to *P. trigoniceps*. The new taxon was named *Oryporan insolitus*, and differs from *P. trigoniceps* in a series of cranial and dental characteristics. According to Pinheiro et al. (2021), *O. insolitus* is phylogenetically one of the earliest procolophonids to show clear adaptations to herbivory, contributing substantially to the understanding of the group's evolution.

One last contribution presenting new materials of Procolophonoidea for the Bica São Tomé Site is the recognition, by Pohlmann et al. (2024), of the presence of temporal fenestration in a large specimen of *P. trigoniceps*. Although confirmed in some rare South African materials, such structure had never been recorded in Brazilian specimens of the species. Temporal fenestration is considered an anomalous feature for *P. trigoniceps* by the authors.

We emphasize that Procolophonoidea is the most represented taxon in the Bica São Tomé Site and in the Sanga do Cabral Formation as a whole. Thus, beyond the already published works, literally hundreds of specimens collected at the Bica São Tomé site await screening, preparation, and cataloging, especially in the collection of the Laboratório de Paleobiologia at Unipampa. The majority of these materials consist of fragmented cranial and post-cranial remains, providing limited anatomical/taxonomic information. Nevertheless, a detailed evaluation of the recovered fragmentary specimens is underway.

5.3 Archosauromorpha

Archosauromorpha are defined as all those Diapsida more closely related to crocodilians and birds than to lizards and snakes (see De-Oliveira et al. 2020 for a review). Although they may appear restricted in terms of diversity of body plans today, archosauromorphs formed the dominant group in Mesozoic terrestrial ecosystems, with immense diversity of early groups, as well as significant adaptive radiations of clades more closely related to both crocodilians and birds.

The relevance of archosauromorphs in both current and Mesozoic ecosystems, exemplified by the dominance of dinosaurs during that era, makes the origins and early diversification of the group a highly significant topic. Although the origin of Archosauromorpha is traced back to the Permian, their first major diversification event, including an increase in relative abundance in ecosystems and the emergence of new groups, occurred after the end-Permian extinction (e.g. Pinheiro et al. 2016). Therefore, rocks from the Early Triassic are exceptionally relevant for understanding the onset of the clade's dominance (De-Oliveira et al. 2020).

The first records of Archosauromorpha for the Bica São Tomé site were already presented by Da-Rosa et al. (2009). They consisted of a well-preserved dorsal vertebra (UFSM 11394) attributed to cf. Archosauromorpha, along with less well-preserved vertebrae, found either isolated or in association (UFSM 11467, UFSM 11475, UFSM 11458, UFSM 11460), and an ilium (UFSM 11444) attributed to cf. Archosauriformes. All the reported materials indeed allow their assignment to Archosauromorpha; however, they require a more detailed anatomical assessment to recover their classification at less inclusive taxonomic levels.

By far, the most relevant archosauromorph specimen ever recovered at the Bica São Tomé site (as well as at the whole Sanga do Cabral Formation) is *Teyujagua paradoxa*. Its skull, associated with some cervical vertebrae (UNIPAMPA 653) (Fig. 3, C), was discovered during an expedition to the site in 2015. The specimen was preserved as the core of a "rolled" carbonate concretion, making it impossible to identify the exact stratigraphic level from which the specimen originated. The taxon was described the following year by Pinheiro et al. (2016), with a detailed osteology published by Pinheiro et al. (2020). Throughout 2016, several similarly rolled concretions were also recovered by the Unipampa team near the location where the skull was found. Laboratory preparation revealed that one of these concretions enclosed a significant portion of the postcranial skeleton of *T. paradoxa*, which was described by De-Oliveira et al. (2024) (Fig. 3, E, G).

In addition to being the most complete and well-preserved specimen ever recovered in the Sanga do Cabral Formation, *T. paradoxa* holds special evolutionary significance. Its anatomy exhibits a mosaic of features typical of early archosauromorphs combined with traits typically found in archosauriforms (Pinheiro et al. 2016, 2020). In the evolutionary tree of archosauromorphs, *T. paradoxa* is recovered as one of the closest relatives of the archosauriforms, illuminating the early morphological evolution of this important clade.

An additional archosauromorph species was described based on material collected at the Bica São Tomé site by De-Oliveira et al. (2020). This specimen (UFSM 11471) is well-preserved and includes an almost complete hind limb, as well as the pelvic girdle and sacral and caudal vertebrae (Fig. 3, F, H). The animal was recovered as the sister taxon to the enigmatic Tanystropheidae and was named *Elessaurus gondwanoccidens* (De-Oliveira et al. 2020). If the relationships of *E. gondwanoccidens* with the tanystropheids is confirmed,

as it appears to be the case (Spiekman et al. 2021), the specimen also proves to be of deep macroevolutionary interest, as it would correspond to one of the oldest records of the group, being also the only one ever recovered in South America.

De-Oliveira et al. (2022) delved deeper into the investigation of the diversity of archosauromorphs from the Sanga do Cabral Formation, presenting four interesting specimens collected at the Bica São Tomé site. Some of them proved to be diagnostically significant, allowing their inclusion in a phylogenetic matrix. One of the specimens, UNIPAMPA 750, is a peculiar anterior cervical vertebra identified by the authors as cf. *Chasmatosuchus*. A second vertebra, this time belonging to the dorsal series (UNIPAMPA 684), was recovered as cf. *Proterosuchus*. Additionally, De-Oliveira et al. (2022) presented fragmentary elements (a parietal portion of a cranial roof and a neural spine), identifying them as Archosauriformes indet. The work of De-Oliveira et al. (2022) is relevant for presenting the first unequivocal records of Archosauriformes for the Sanga do Cabral Formation, substantially expanding the diversity of Archosauromorpha for the Brazilian Lower Triassic. Some of the specimens presented by De-Oliveira et al. (2022) were reassessed by Ezcurra et al. (2023). The latter allocates the specimens UNIPAMPA 750 and UNIPAMPA 684 to the new clade Chasmatosuchinae (Archosauriformes: Proterosuchidae).

5.4 General comments on the fossil diversity of the site

The Bica São Tomé site showcases an unequivocal diversity of at least three taxa of archosauromorphs, representing the majority of the clade's diversity within the Sanga do Cabral Formation. It is noteworthy that all described species of archosauromorphs from the Sanga do Cabral Formation have their holotypes recovered from this site, and numerous new specimens (potentially including new species) are currently under evaluation.

It is important to note that the majority of specimens collected at the Bica São Tomé fossil site are still undergoing sorting and preparation, without precise taxonomic identification. Nonetheless, the site presents a considerably high number of collected specimens (256), deposited in the scientific collections of the Universidade Federal do Pampa and the Universidade Federal de Santa Maria. Among the identified specimens, Procolophonidae are the most represented, followed by Archosauromorpha and Temnospondyli. Fragments of fish (not described in detail) have also been reported, and these are currently undergoing study. The taxa thus far reported for the site are representative of a typical Early Triassic disaster fauna (Fig. 4, 5). The absence of synapsids, which are common in localities of the same age in Russia, India, and South Africa, remains enigmatic and unexplained.

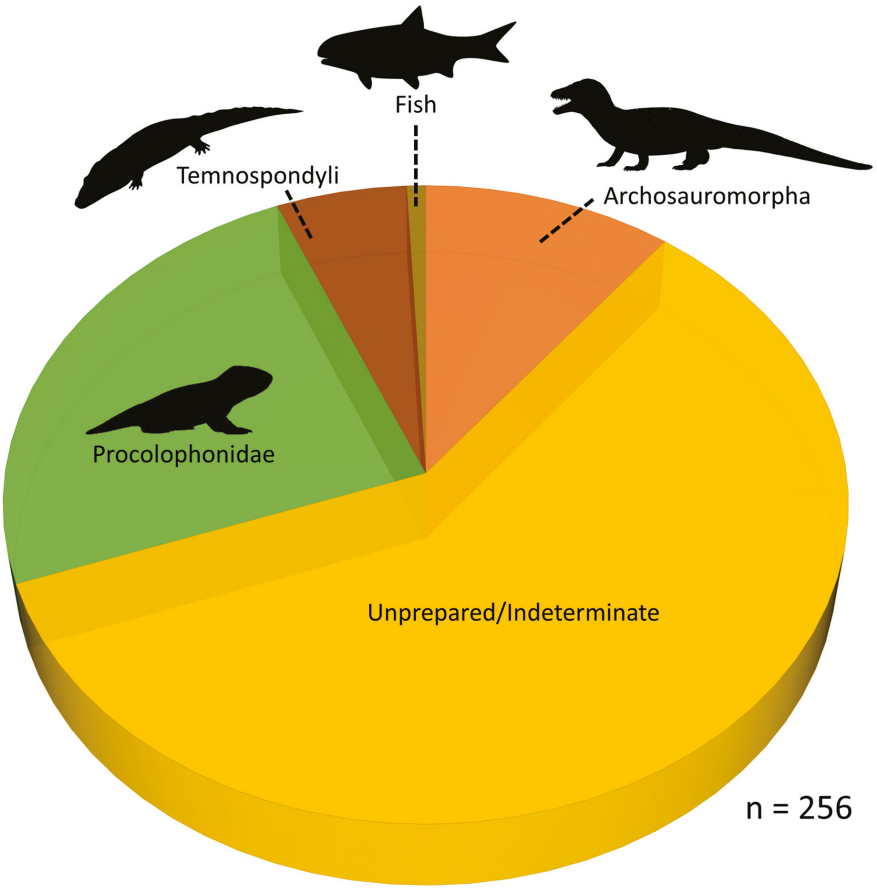

Figure 4. Taxonomic representation of fossil groups found at the Bica São Tomé fossil site. Silhouette credits: Procolophonidae, Felipe A. Elias; Temnospondyli, Dmitry Bogdanov; fish, Tree of Life App; Archosauromorpha, Márcio Castro. Images used under permission or licensed via Wikimedia Commons.

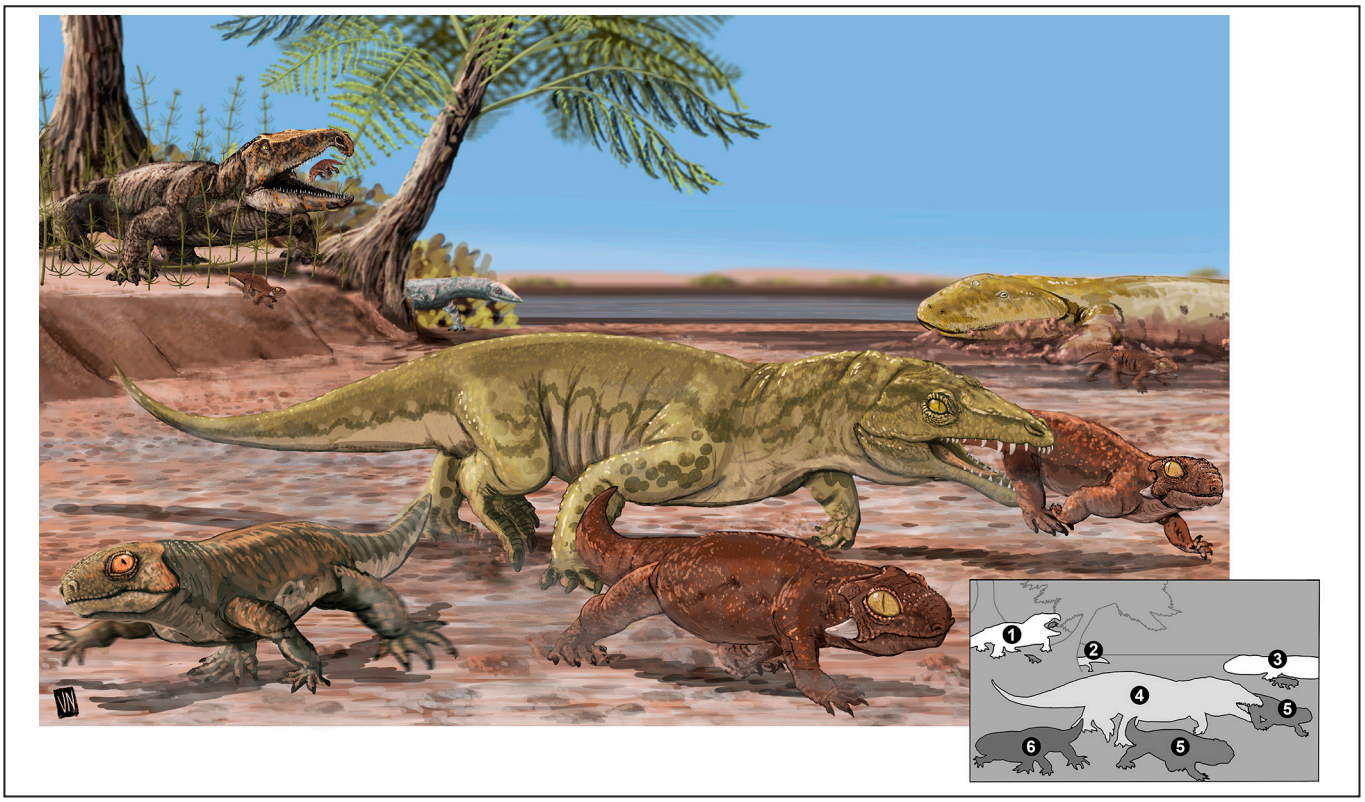

Figure 5. Artistic reconstruction of the Bica São Tomé fossil assemblage. 1. Proterosuchidae indet; 2. *Elessaurus gondwanoccidens*; 3. *Tomeia witecki*; 4. *Teyujagua paradoxa*; 5. *Procolophon trigoniceps*; 6. *Oryporan insolitus*. Artwork by Voltaire Neto.

6. Geoconservation

Considering the importance of this site for scientific purposes, including its participation in the Geopark Raízes de Pedra Project, several geoconservation measures are proposed here.

Outcrops Bica 1 and 5 are situated in private areas, with the latter being the most significant in terms of fossil representation. Therefore, we suggest that these outcrops be reserved exclusively for scientific purposes, with tourism activities discouraged. The remaining outcrops can be utilized for tourism and educational purposes, with special emphasis on the water fountain area due to its existing infrastructure.

The water fountain area currently includes a parking and camping area (see Fig. 2, B), but better visual organization is necessary. This could involve the installation of educational signs, for both paleontological information and urban usage guidance. Outdoor signs and totems represent feasible solutions that could be implemented by the municipal government or private entrepreneurs. One challenge to address is providing access for buses and large vehicles, which may require the involvement of the state government responsible for roads and tourism management. Expansion of the entrance and parking area, along with improved organization of visitor activities, is essential.

In addition to the measures mentioned above, it is crucial to implement specific strategies for the effective protection of fossil outcrops. This may include installing physical barriers around the most sensitive areas to prevent damage caused by unaware visitors. Furthermore, regular surveillance by trained personnel can help prevent illegal fossil collection and other harmful impacts on the environment. Environmental education and public awareness also play a crucial role, highlighting the importance of fossil outcrops for science and the need to preserve them for future generations. Collaboration between local authorities, landowners, and communities may be essential for the development and effective implementation of these protection measures. It is also important to emphasize that none of the conservation measures suggested here will influence land productivity or its use for agricultural purposes.

7. Final remarks

The Bica São Tomé fossil site within the Sanga do Cabral Formation has played a crucial role in enhancing our understanding of the Early Triassic period in South America. As we continue to uncover new insights into post-extinction biotic recovery, it is essential to prioritize measures for the preservation and controlled scientific exploration of such fossil sites.

Implementing strategies to safeguard these valuable resources will ensure their long-term conservation and sustainable utilization for scientific research. By adopting responsible practices in exploration and preservation, we can uphold the integrity of these sites and continue to advance our knowledge of Earth's evolutionary history.

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Authorship credits

Author	A	B	C	D	E	F
FLP						
AASDR						

A - Study design/ Conceptualization **B** - Investigation/ Data acquisition
C - Data Interpretation/ Validation **D** - Writing
E - Review/Editing **F** - Supervision/Project administration

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Linha São Luiz Geosite, Rio Grande do Sul State: 25 years of discoveries, and a unique window to the Brazilian Mesozoic

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Abstract

The Linha São Luiz Geosite is one of the most remarkable outcrops from the central region of Rio Grande do Sul state, southern Brazil. With more than 20 meters of vertical exposure, the locality preserves records of distinct sedimentary episodes, and one of the richest fossil assemblages known in southern Brazil. After a quarter of a century from the first expeditions to the site, the Linha São Luiz still yields new discoveries, registering exquisitely preserved fossils from micro and macrovertebrates, invertebrates, and plants, as well as trace fossils generated by these groups. In this contribution, we assembled representatives from distinct fields of paleontological study to provide a summary of the fossil assemblage from this site. We also briefly discuss the history of research and report geoconservation strategies which are being implemented at the locality, in order to preserve this important window to the Brazilian Mesozoic.

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1. Introduction

Located mere three kilometers away from the center of the Faxinal do Soturno municipality, the Linha São Luiz outcrop is a prominent locality. Over more than two decades of research by various specialist teams, the site has yielded a vast paleontological record, with hundreds of specimens being uncovered. The São Luiz Geosite is noteworthy, for its strata preserve a wide variety of fossil types, from microfossils to plant remains, micro and macro-invertebrates, tiny vertebrates to large dinosaurs, ranging from both somatofossils and ichnological remains. This turns the locality into a unique window to the past, specifically to the end of the Triassic Period, and perhaps even the beginning of the Jurassic. Thus, the outcrop documents part of important faunal and floristic turnovers that would shape the Earth's ecosystems in the following geologic stages. Despite the already abundant fossil record, the site still yields new fossils and species yet unknown to science, even a quarter of century after its discovery. In this contribution, we provide an overview of the known fossil record at the Linha São Luiz Geosite, trace the historical background of the prospections performed at the locality, and report efforts for the conservation of the area and promotion of its cultural importance as a heritage site.

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2. Geological Settings

The Paraná Basin, situated on continental crust, is filled with sedimentary and volcanic rocks ranging in age from the Ordovician to the Cretaceous periods (Figure 1A). Covering an area of 1,500,000 km², the basin extends across Brazil (1,100,000 km²), Uruguay, Argentina, and Paraguay, with a maximum sediment thickness of 8000 meters. This thickness results from polycyclic deposition events related to successive sedimentation episodes driven by tectonic activities affecting Southwestern Gondwana (Milani 1997; Milani et al. 1998). During the Paleozoic Era, the Paraná Basin functioned as an intracratonic basin, recording significant transgressive-regressive cycles linked to the stabilization of West Gondwana, the Andean active margin, climatic changes, Panthalassa paleo-ocean activity, and the formation of Pangea (Milani et al. 2007; Limarino et al. 2014). The Mesozoic breakup of Gondwana, and consequently Pangea, led to the formation of multiple rift and proto-oceanic basins, profoundly affecting the depocenters of adjacent intracratonic basins (Milani et al. 1998; Lovecchio et al. 2020). In the Paraná Basin, this context resulted in unconformities related to active margin tectonics of southwestern Gondwana and the South Atlantic rifting process, with repeated reactivation of NW-SE, NE-SW, and E-W fault systems driving sedimentation and preservation of stratigraphic units (Milani 1997; Zerfass et al. 2003, 2004).

Seven main continental Mesozoic successions have been identified in the Brazilian portion of the basin (Milani 1997; Scherer 2000; Scherer et al. 2023): (1) Sanga do Cabral Formation (Induan/Olenekian), consisting of fluvial, lacustrine and aeolian deposits; (2) Santa Maria and Caturrita formations (Ladinian to Norian) composed of fluvial-lacustrine deposits; (3) Mata Sandstone (which was originally recognized as part of the Caturrita Formation by Andreis (1980) and separated from it by later authors) deposits of braided fluvial system; (4) Pirambóia Formation, a wet aeolian system with cyclic fluvial incursions; (5) Guará Formation (Upper Jurassic), constituted by fluvial and fluvial-aeolian systems; (6) Botucatu Formation (Lower Cretaceous), recording dunes of dry aeolian system fossilized under the Serra Geral Formation volcanic lavas; and (7) Bauru Group (Upper Cretaceous) composed of fluvial and aeolian deposits.

This study focuses on the second succession (2), comprising the Santa Maria and Caturrita Formations, a continental deposit occurring only in the central block of Rio Grande do Sul State, South Brazil (Figure 1B; Zerfass et al. 2003; Scherer et al. 2023). In terms of sequence stratigraphy, the Santa Maria and Caturrita Formations comprise the Santa Maria Supersequence, a second-order continental sequence which is subdivided into third-order sequences, from base to top: Pinheiros-Chiniquá, Santa Cruz, Candelária and Mata (Figure 1C; Zerfass et al. 2003; Horn et al. 2014; Schultz et al. 2020). Each sequence begins with fluvial deposits (low-

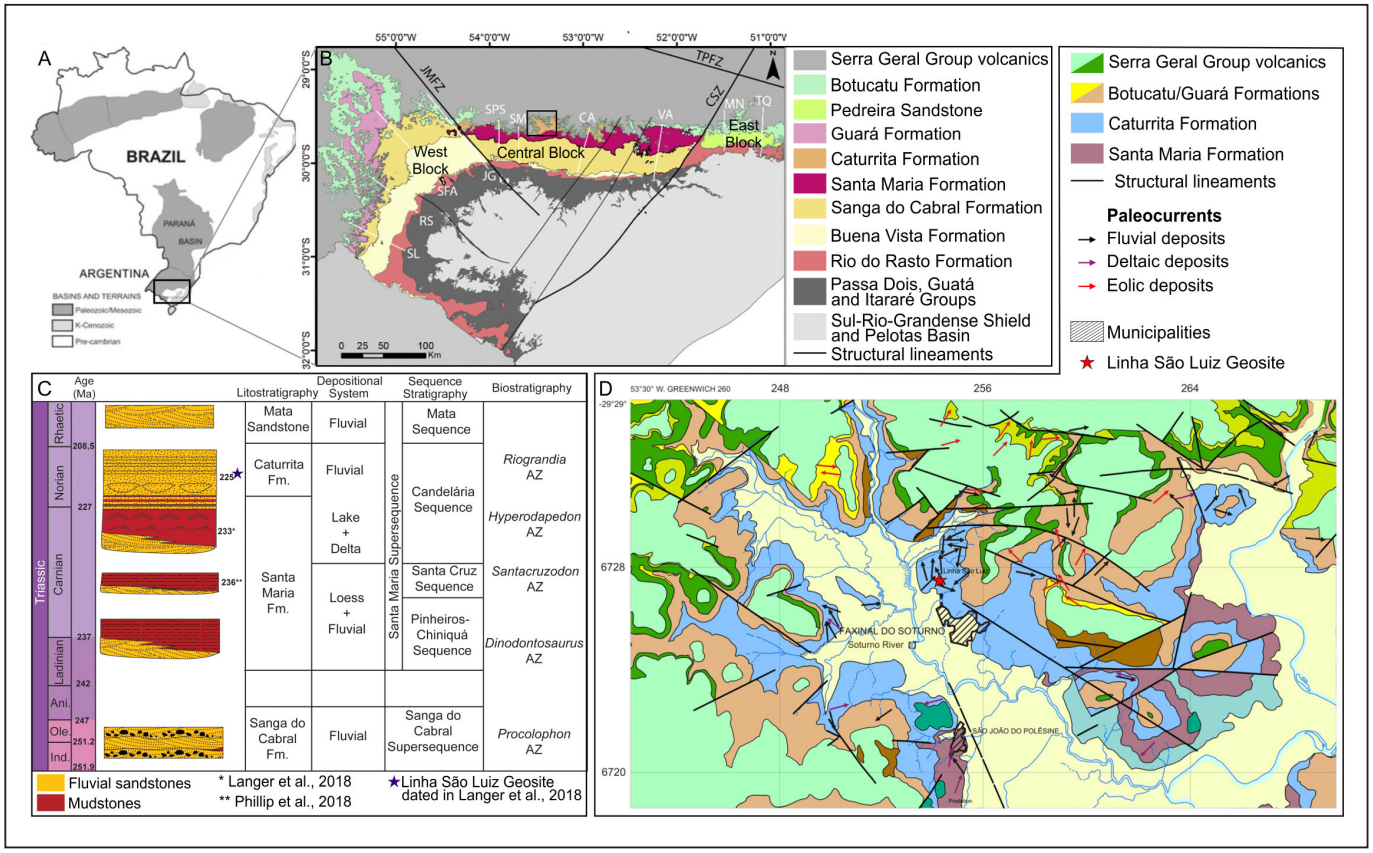

Figure 1. Location and geological context of the Linha São Luiz Geosite. A, Brazilian phanerozoic basins locating the study area at the southern portion of the Brazilian Paraná Basin in the Rio Grande do Sul State (rectangle). B, Geological context of the central portion of the Rio Grande do Sul State with the East, Central, and West Blocks of the Paraná Basin, locating the Faxinal do Soturno municipality and surroundings (rectangle). C, Stratigraphical chart of the Triassic layers from the Paraná Basin, including (Sanga do Cabral and Santa Maria Supersequences), with lithostratigraphic, depositional environments, and biostratigraphic information. D, Geology of Faxinal do Soturno and surroundings, locating the Linha São Luiz Geosite (star). Modified from modified from Crisafulli et al. (2016), Scherer et al. (2023) and Schultz et al. (2020). Abbreviations: Ani, Anisian; Ind, Induan; Ole, Olenekian.

sinuosity rivers) overlain by aeolian and shallow lacustrine deposits. This stratigraphic stacking is interpreted as cyclic basin subsidence induced by tectonic uplift of the source areas (Zerfass et al. 2004). The three first sequences contain a globally recognized and richly fossiliferous record of tetrapods divided into four successive faunal associations, or Assemblage Zones (AZ) that define a precisely dated biostratigraphy, aiding correlation, especially, with other South American and African faunas (Schultz et al. 2020).

The Candelária Sequence comprises the upper part of the Santa Maria Formation and the Caturrita Formation, including the *Hyperodapedon* and *Riograndia* Assemblage Zones, respectively (Figure 1C; Schultz et al. 2020). This sequence begins with white to reddish sandstones featuring planar and trough cross-stratification, occasional mudstone intraclasts, and plant fossils, interpreted as ephemeral braided river deposits (Zerfass et al. 2003). These are overlain by laminated reddish mudstones and very fine-grained massive or stratified sandstones with climbing and wave ripples, suggesting deposition in sheet deltas and ephemeral lakes under increased humidity (Horn et al., 2018b). The sequence transitions from dominant mudstones to interlayered fine-grained, massive sandstones and laminated mudstones, indicative of mass flows from seasonal downpours. Subordinate stratified sandstones show planar bedding, thick lamination, low-angle cross-stratification, and climbing ripples, interpreted as deposits from hyperconcentrated flows in ephemeral fluvial systems with lateral avulsions and frontal deconfinement, forming sheet-like channel deposits with lateral accretion macroforms (Faccini 2000; Faccini et al. 2003; Horn et al., 2018a).

The Linha São Luiz Geosite integrates the final part of the Candelária Sequence (Figure 1C, D), traditionally related to the Caturrita Formation (excluding the Mata Sequence), and integrating the *Riograndia* AZ (Bonaparte et al., 2010a; Soares et al. 2011; Schultz et al. 2020; Martinelli et al. 2021). The 25 years of research at the Linha São Luiz Geosite allowed excellent detailing of the facies, sedimentary structures, and fossil content. The outcrop, with *circa* 23 meters of vertical exposure (Figure 2), can initially be divided into at least two main parts: one predominantly fluvial and one predominantly lacustrine, overlain by a deltaic system.

The lower portion of the package (Figure 2A), approximately 11 meters in thickness, comprises facies Sh, Sr, and Sm at its base, characterized by paleocurrents predominantly directed eastward. These facies exhibit amalgamated layers indicative of deposition within a meandering fluvial system, with evidence of rhizobioturbation at certain levels and one level containing *Taenidium barreti* bioturbation (Jenisch et al. 2017). Overlying these facies and exhibiting greater thickness is facies Sm, which can be interpreted either as deposits from high-concentration sediment-gravity flows or as layers that have undergone post-depositional fluidization, leading to the loss of primary sedimentary structures (Jenisch et al. 2017). The coarser segment of this unit is a medium-grained sandstone, approximately 1 meter thick, containing vertebrate remains characteristic of the *Riograndia* AZ. This level has been dated using U-Pb radiometric techniques by Langer et al. (2018), yielding a maximum deposition age of ~225.42 ± 0.37 Ma (Early Norian), corroborated by relative dating within the AZ (Soares et al. 2011; Schultz et al. 2020). The top of these strata, capping the lower succession, is marked by extensive rhizobioturbation, including a piece of wood with roots in life position and additional *Taenidium barreti* bioturbation. These features suggest the establishment of larger vegetation within a stable, subaerially exposed substrate, indicative of a paleoenvironment conducive to biological activity (Crisafulli and Dutra 2009; Jenisch et al. 2017).

The upper portion of the Geosite (Figure 2B) is characterized by a coarsening-upward sequence, beginning with a mudstone package (facies Fl) measuring 2.20 meters in thickness. This unit contains the greatest diversity of fossil biota, including branchiopods, insects, wood fragments, leaves, shoots, and fish scales. Within these levels, occasional inputs of silt and very fine sand create two intervals of ferriferous symmetrical ripples, suggesting deposition in shallow yet perennial water bodies located on floodplains (Jenisch et al. 2017). This mudstone package is progressively replaced by a heterolithic succession, comprising tabular, lenticular, and occasionally sigmoidal beds of facies Sm, Sh, and St. It is common to observe facies Fl overlaying these sandy facies, primarily deposited through decantation processes. The association of these facies indicates the development of river mouth bars formed by the discharge of fluvial currents into water bodies and crevasse splay deposits within a fluvial floodplain. The presence of roots and desiccation cracks at the tops of individual layers signifies episodic subaerial exposure interrupted by occasional depositional events. The uppermost part of the sequence is capped by a fine-grained heterolithic package, ~1 meter in thickness, exhibiting abundant drying cracks and rhizoturbation, along with clusters of Branchiopoda. At one level, carapaces are associated with two theropod footprints (Silva et al. 2012; Jenisch et al. 2017). Overall, this upper package of the Linha São Luiz Geosite can be subdivided into an intermediate portion representing lacustrine deposits and an upper portion indicative of a fluvial system characterized by river mouth bars and crevasse splay deposition.

The two primary packages of the outcrop exhibit discordant ages, with accumulating evidence reinforcing this difference over the years. The lower portion has been radiometric dated and shows strong biostratigraphic correlation with other outcrops of the *Riograndia* AZ, characterized as Early Norian (Late Triassic) (Bonaparte et al. 2010a; Soares et al. 2011; Langer et al. 2018; Schultz et al. 2020; Martinelli et al. 2021). This also befits the observed vertebrate assemblage, including typically Triassic fossils, such as procolophonids, rhynchocephalians, and non-mammaliaform cynodonts, as well as lagerpetids and an early sauropodomorph. In contrast, the fossil content of the upper package suggests a younger age. For instance, the branchiopods are more closely related to Jurassic taxa (Cabral 2011; Rohn et al. 2014; Jenisch et al. 2017), and the plants are evolutionarily more complex, corresponding to the Upper Triassic to Lower Jurassic transition (Barboni and Dutra 2013). Footprints attributed to large theropods might also indicate affinity to Jurassic forms (Silva et al. 2012), though large-bodied saurischians are already present in Upper Triassic communities. Further evidence of the age discrepancy between the two levels includes the presence of prominent rhizoturbation, a trunk in life position, and *T. barretti* ichnofossils, indicating subaerial exposure and a period of non-deposition at the boundary of the two packages (Crisafulli and Dutra 2009; Jenisch et al. 2017). This evidence implies that the upper package might not belong to the Caturrita Formation (*sensu* Andreis et al. 1980), although it does not clearly align with other known Jurassic units of the Paraná Basin, requiring further investigations.

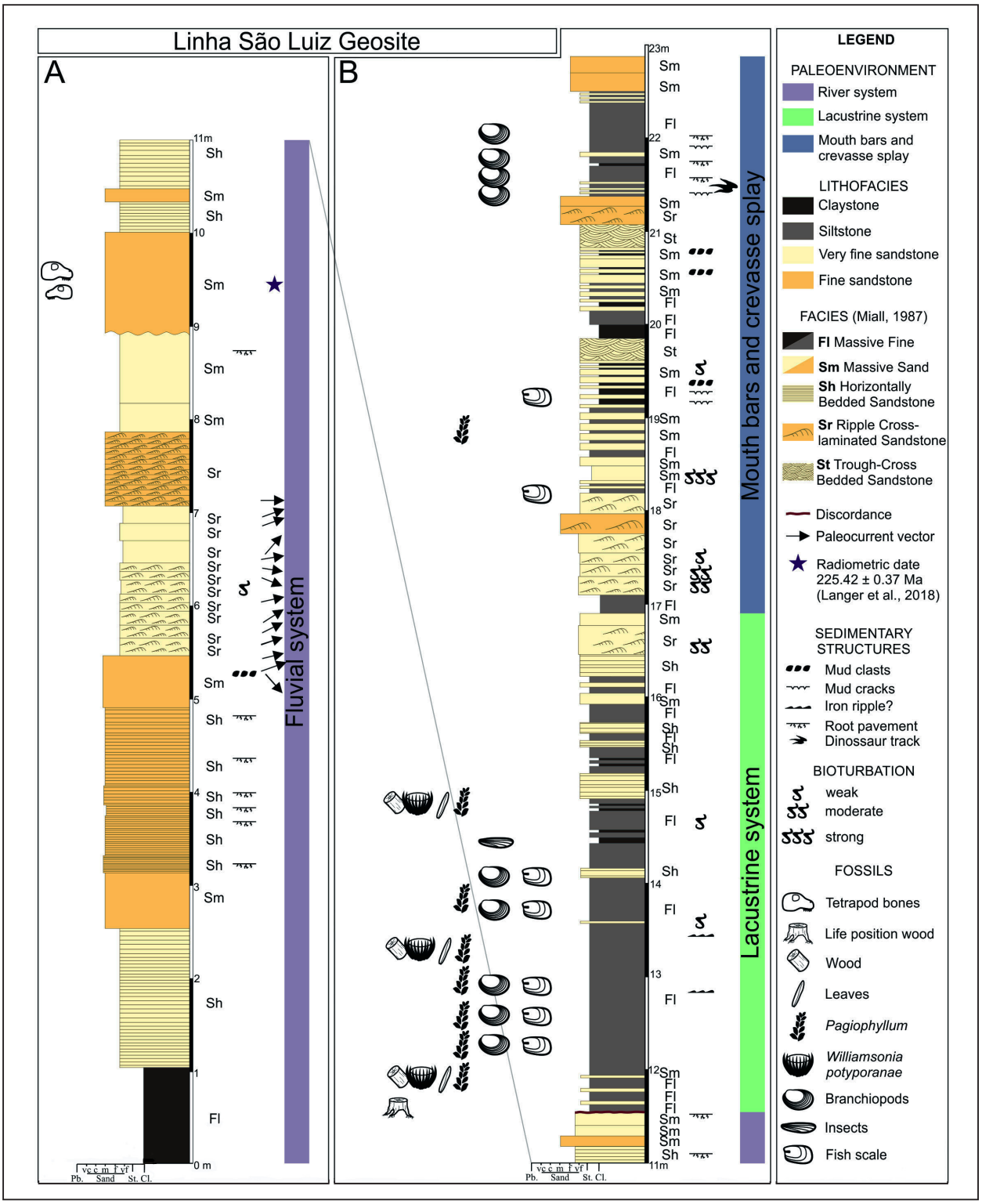

Figure 2. Stratigraphic section and fossil distribution at the outcropping areas of the Linha São Luiz Geosite. A, basal part of the outcrop. B, central and top of the outcrop. Modified from Barboni and Dutra (2013) and Jenisch et al (2017).

3. History of Research

Many of the fossil localities which characterize the *Riograndia* Assemblage Zone (Bonaparte et al. 2001, 2003, 2005, 2010a; Langer et al. 2007; Soares et al. 2011; Schultz et al. 2020), especially those containing a rich microvertebrate content, were discovered in the years of 1998 – 2000 in expeditions led by the former Fundação Zoobotânica do Rio Grande do Sul (FZB-RS) and Instituto de Geociências of the Universidade Federal do Rio Grande do Sul (IG-UFRGS), in collaboration with other institutions (Figure 3). A brief narrative detailing some of these discoveries was provided by Bonaparte and Migale (2010, 2015), from the point of view of the Argentine paleontologist José Fernando Bonaparte (1928-2020), who was employed by the former FZB-RS and then as a CNPq research fellow

at the IG-UFRGS and actively participated during these first expeditions in the search for vertebrate fossils. He also got financial support from the National Geographic Society (USA) to develop long-term fieldwork at the Faxinal do Soturno and Candelária regions during those years. Based on these accounts, the paleontologists were drawn to the locality of Linha São Luiz by Daniel Cargnin, a priest who resided in the region and who held a profound interest in fossil prospection and collection and who ultimately came to discover this fossil locality in Faxinal do Soturno (Figure 3). Though not an academic, Cargnin had a fundamental role in the development of paleontological studies, especially regarding vertebrate paleontology and paleobotany, for he and his brother Abraão were based in several municipalities of the Central Depression of Rio Grande do Sul, often collecting a vast number of Triassic fossils, and acting to raise the awareness of the locals to their importance.

Most vertebrate taxa discussed in the following section were collected in the interstice between 1998 and 2005, and less frequently since then, during several expeditions led by the aforementioned institutions (Figure 3). These fossils would be prepared and studied in the following years, and indeed, many still await proper assessment.

In turn, the study of fossil plants gained momentum following the discovery of vertebrates at the outcrop, leading to greater attention and systematic collections after 2004. A collaborative research team led by Pires and Guerra-Sommer (UFRGS, UNIVATES, and FZRS) named the first trunk morphotaxon *Sommerxylon* (Pires and Guerra-Sommer 2004). Jorge Ferigolo (FZRS) and Robson Tadeu Bolson (UFPR) also contributed to this work. New floral elements, including conifer stems, were described in 2009 (Crisafulli and Dutra 2009). This work attracted the interest of researchers such as Alexandra Crisafulli (Universidad Nacional del Nordeste, Argentina) and Tania Lindner Dutra (UNISINOS University, São Leopoldo), who would continue research at the São Luiz site over the next decade. Fieldwork and projects by the Geology undergraduate program at Unisinos University, led by Tânia Lindner Dutra, in the later part of that decade, resulted in the preliminary description of new conifer leaves and stems. Notably, the publication of the “flower-like” cycad cone *Williamsonia potyporanae* Barboni and Dutra (2013) provided evidence that the upper strata of the São Luiz outcrop, along with the tetrapod footprints, date to the Jurassic period (Barboni and Dutra 2013; Silva et al. 2012).

In the 2010s, records of invertebrates started to be reported in the upper strata, comprising a diverse and well-preserved assemblage of insects and abundant spinicaudatans (reports not published yet). From 2014 onwards, Spinicaudata received special attention for paleoenvironmental and taphonomic studies (Rohn et al. 2014; Jenisch et al. 2017). Following the retirement of paleobotanist Tânia Lindner Dutra from the MHGEO in 2017, curator Rodrigo Scalise Horodyski continued fieldwork at the São Luiz site. These ongoing efforts have resulted in the collection of over 730 fossil specimens, including undescribed vertebrates, invertebrates, and plants. Currently, research is being conducted to describe and interpret the

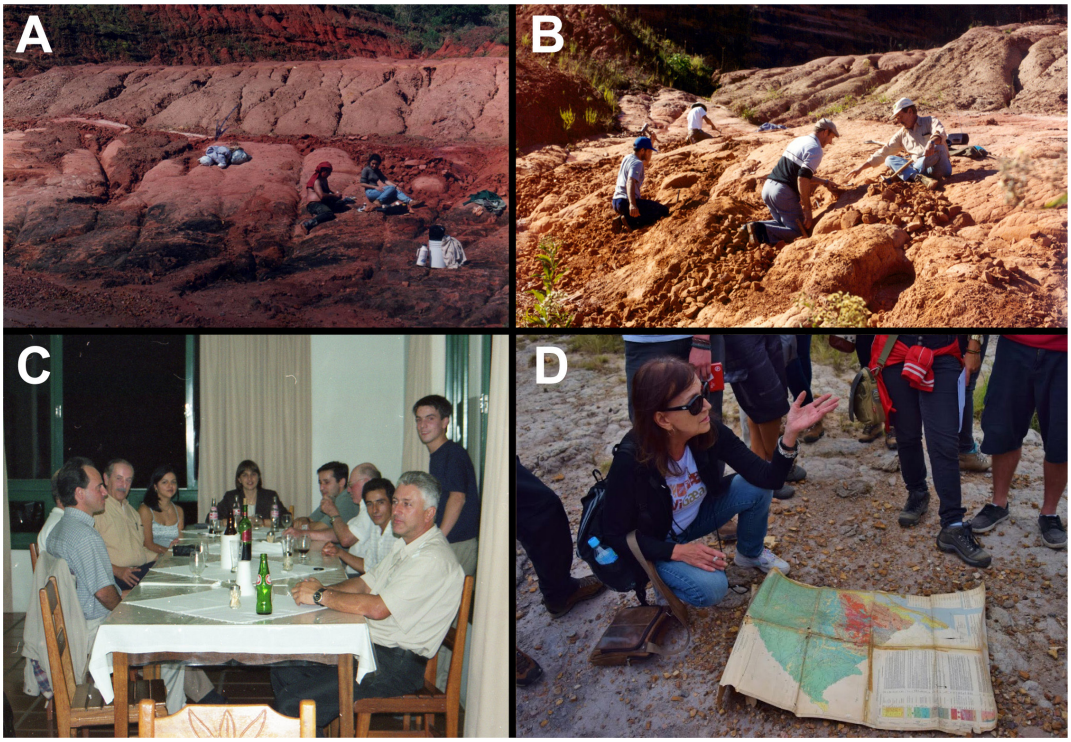

Figure 3. Early expeditions to the Linha São Luiz Geosite. A, fieldwork conducted by the former Fundação Zoobotânica do Rio Grande do Sul, with Jorge Ferigolo and Ana Maria Ribeiro excavating the outcrop in 1998. B, fieldwork by the Universidade Federal do Rio Grande do Sul, in 1999, with Rogerio Rubert, Daniel Hernández, Claudio Bortolas, and Mario Barberena. C, Dinner meeting at the Paleon Hotel in Mata where the UFRGS team joined Daniel Cargnin and municipal authorities before fieldwork at Linha São Luiz in 1999. In the picture can be seen Mario Barberena (left) and Daniel Cargnin, Daniel Hernández, Rogerio Rubert, Agustín Martinelli, and Adauto, driver of the UFRGS (right). Photograph taken by José Bonaparte. D, Tânia Lindner Dutra, during fieldwork conducted in 2015 by the UNISINOS team.

insect fossils and to integrate data from the assemblages of plants and carapaces.

Starting at the decade of 2010, other institutions intensified efforts of prospection at the site, and with the establishment of the Centro de Apoio à Pesquisa Paleontológica from the Universidade Federal de Santa Maria (CAPPA/UFSM), located 5.5 km from the outcrop, an intensified monitoring of the site became possible. The constant prospections and attention given to the site greatly reduced the loss of material due to erosion. Additionally, efforts conducted by the team at CAPPA/UFSM, in partnership with the public administration of Faxinal do Soturno and the administration of UNESCO Geopark Quarta Colônia led to the mitigation of important sources of vulnerability to the site, namely the accumulation of debris and the expansion of vegetational cover by exotic trees (see Geoconservation, below).

4. Fossil Record

4.1. Vertebrates

Fossil vertebrates are predominant at the top of the fluvial stage in the fine sandstones of facies Sm (Figure 2), which is dominated by small-sized tetrapods (Figure 4), microvertebrate of estimated skull lengths of 15 to 40 millimeters (Bonaparte et al. 2010a; Schultz et al. 2020). These fossils occur as isolated elements, semi-articulated skeletons and occasional clumps of disarticulated bones. This peculiar preservation

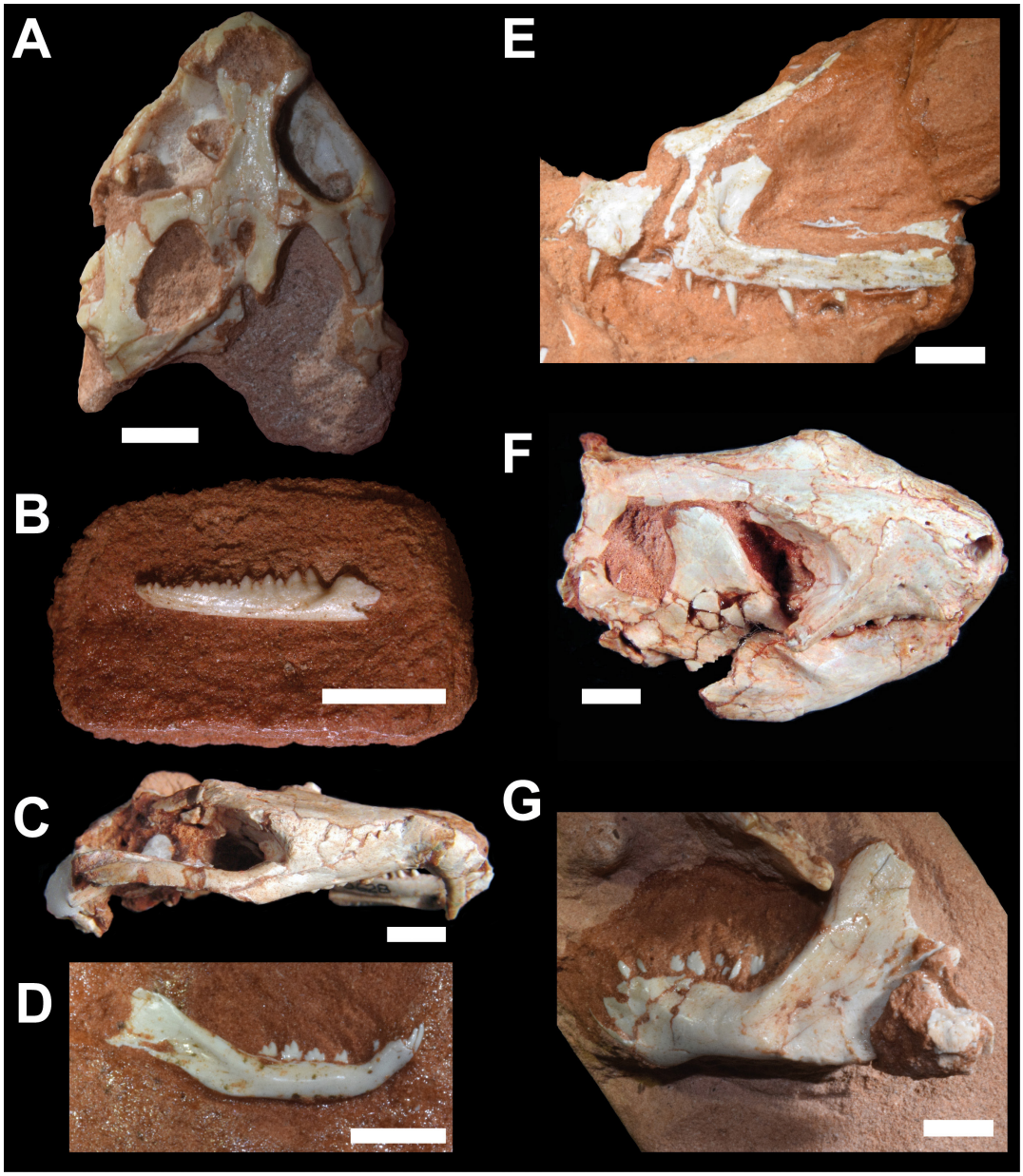

Figure 4. Microvertebrates of the Linha São Luiz Geosite. A, *Clevosaurus brasiliensis* skull (CAPPA/UFSM 0131) in dorsal view. B, *Lanceirosphenodon ferigoloi* left dentary (CAPPA/UFSM 0226, holotype). C, *Brasilodon quadrangularis* skull (UFRGS-PV-0628-T), skull in right lateral view. D, *B. quadrangularis* right mandibular ramus (CAPPA/UFSM 0424) in lateral view. E, *Maehary bonapartei* (CAPPA/UFSM 0300, holotype), partial skull in left lateral view. F, *Riograndia guaibensis* (UFRGS-PV-0596-T), skull in right lateral view. G, *R. guaibensis* (CAPPA/UFSM 0425) left mandibular ramus in lateral view.

of tiny microvertebrates has long intrigued paleontologists. Though suspicions were raised that some accumulations might represent regurgitalites (Arantes et al. 2008), the genesis of this taphocoenosis was never deeply investigated. Among the sample, the most abundant records are of sphenodontids, followed by cynodonts, archosauromorphs and procolophonids. Romo de Vivar et al. (2020a) provided an account on the relative abundance of tetrapod fossils at the Linha São Luiz Geosite.

The only macrovertebrates (Figure 5) in this assemblage are represented by an articulated skeleton of the saurischian dinosaur *Guaibasaurus candelariensis* (Bonaparte et al. 2007; Langer et al. 2011), and an isolated archosauromorph tooth (De-Oliveira et al. 2023). Apart from these, the lacustrine and yields occasional fish scales which still await detailed studies. Finally, a large set of footprints was recorded on the upper layers of the mouth bar system, those being referred to a theropod of moderately large size (Silva et al. 2012), though no tetrapod bones were yet recorded on these layers. A list of occurrences is provided below, followed by a brief description of the taxa.

4.1.1 Systematic Paleontology

CYNODONTIA Owen (1861)
PROBAINOGNATHIA Hopson (1990)
PROZOSTRODONTIA Liu and Olsen (2010)
ICTIDOSAURIA Broom, 1929 (sensu Martinelli and Rougier 2007)
Riograndia Bonaparte et al. (2001)
Riograndia guaibensis Bonaparte et al. (2001)

Riograndia guaibensis (Figure 4F, G; Electronic Supplementary File 1) is a small cynodont with faunivorous-omnivorous habits that is the guide taxon of the *Riograndia* AZ (Soares et al. 2011, see also Schultz et al. 2020; Martinelli et al. 2021). Although its holotype (MCN-PV2264, Bonaparte et al. 2001) comes from the Sesmaria do Pinhal site, at Candelária municipality, the Linha São Luiz Geosite has provided numerous and well-preserved specimens, being the most abundant cynodont at this locality. Several important specimens for understanding the taxon have been collected from this outcrop (Bonaparte et al. 2010a; Soares

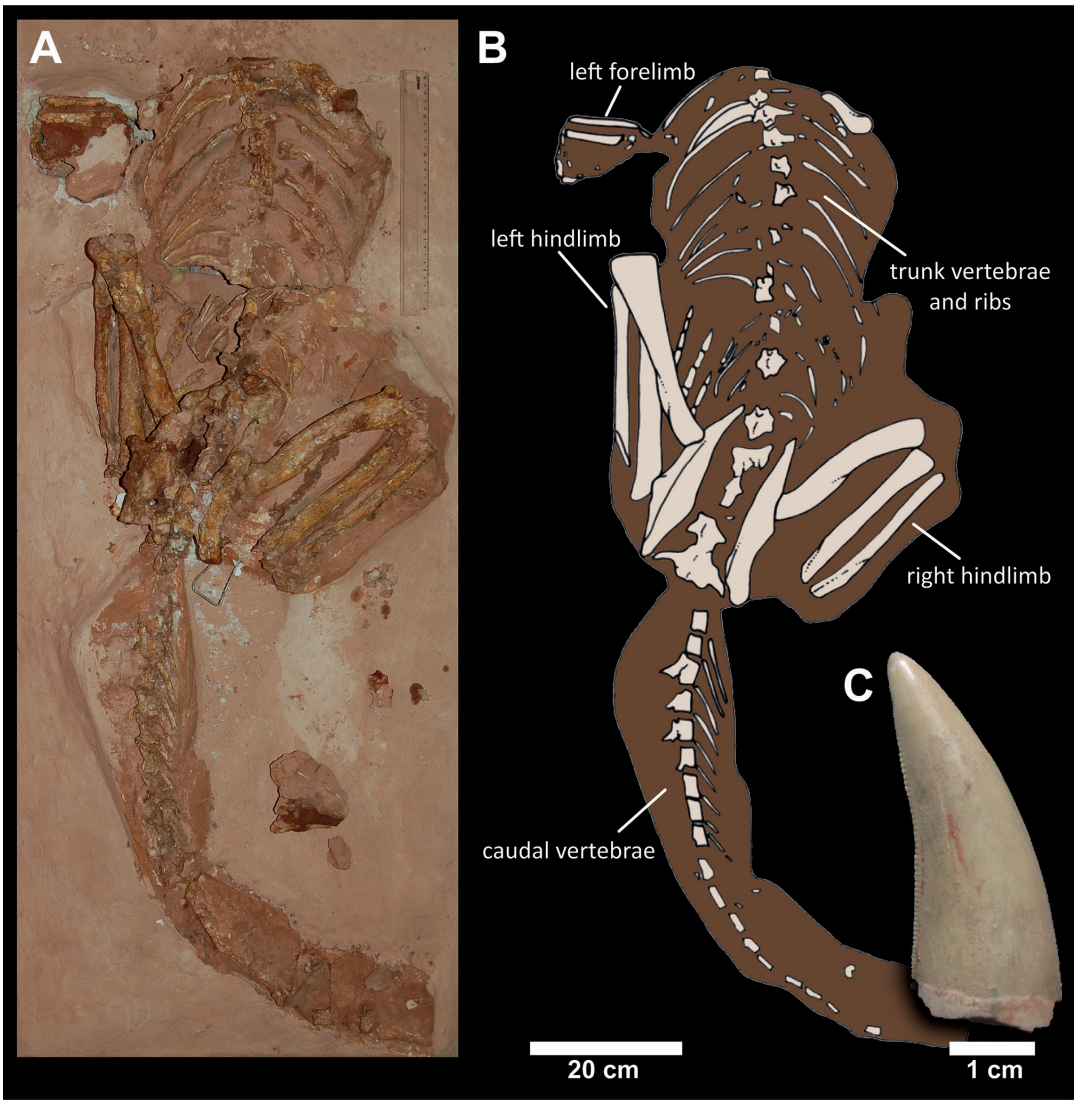

Figure 5. Macrovertebrate remains from the Linha São Luiz Geosite. A, B, articulate incomplete skeleton of *Guaibasaurus candelariensis* (UFRGS-PV-0725-T). C, isolated tooth of a carnivore archosauromorph (CAPPA/UFSM 0050). Line reconstruction in B modified from Bonaparte et al. (2007).

et al. 2011; Guignard et al. 2019a; Fonseca et al. 2024), as the specimen UFRGS-PV-0596-T (Fig. 4 F), mistakenly pointed out by Soares et al. (2011) as recovered from Sesmaria do Pinhal 1 site, Candelária. *Riograndia guaibensis* has a set of anatomical features that are important for understanding the evolution of prozostrodonts including a set of derived features in the dentition, braincase, cranial endocast, nasal cavity and postcranium (Bonaparte et al. 2001; Bonaparte et al. 2010a; Soares et al. 2011; Guignard et al. 2019a; Rodrigues et al. 2019; Kerber et al. 2021; Fonseca et al. 2024). Due to its abundance and wide distribution, it has allowed the correlation to other fossiliferous outcrops that can be associated with other Triassic faunas, establishing the *Riograndia* Assemblage Zone (Soares et al. 2011, see also Schultz et al. 2020; Martinelli et al. 2021).

TRITHELEDONTIDAE Broom, 1912 (sensu Martinelli and Rougier 2007)
Irajatherium Martinelli et al. (2005)
Irajatherium hernandezi Martinelli et al. 2005

Irajatherium hernandezi (Figure 6, and Electronic Supplementary File 2) is the largest prozostrodont cynodont from the Faxinal do Soturno Fauna, slightly larger than *Riograndia* and *Brasilodon*. It exhibits upper postcanines with a main bulbous cusp, flanked by small mesial and distal cusps, whereas the lower postcanine teeth are sectorial, with a main cusp followed by distal cusps that decrease in size. It is considered the oldest member of the cynodont clade Tritheledontidae (Martinelli and Rougier 2007), although some phylogenies did not recover tritheledontids as monophyletic (e.g., Kerber et al. 2022). Similar to *Riograndia guaibensis*, the holotype of *I. hernandezi* comes from Sesmaria do Pinhal (holotype UFRGS-PV-0599-T). However, fossils of this cynodont have also been found in Linha São Luiz Geosite, represented by cranial, dental, and postcranial materials (Oliveira et al. 2011; Kerber et al. 2022), contributing to the knowledge of its anatomy. This taxon is one of the least known cynodonts from this site.

MAMMALIAMORPHA Rowe, 1988 (sensu Abdala 2021)
BRASILODONTIDAE Bonaparte et al. (2005)
Brasilodon Bonaparte et al. (2003)
Brasilodon quadrangularis Bonaparte et al. (2003)

Brasilodon quadrangularis (Figure 4 C, D) is an abundant cynodont at Linha São Luiz Geosite. It is represented by crania, mandibles, and postcranial remains (Bonaparte et al. 2003, 2005, 2010a, 2012; Martinelli and Bonaparte 2011; Guignard et al. 2019b). The upper postcanine teeth have a main central cusp and two mesial and two distal cusps forming a quadrangular shape in occlusal view, which served to name the species (Bonaparte et al. 2003). The lower postcanine has a “triconodont” pattern with discrete lingual accessory cusps. *Brasilitherium riograndensis* (holotype UFRGS-PV-0594-T), described together with *B. quadrangularis* in 2003, was differentiated from the latter mainly by its smaller size and different skull proportions, as well as the presence of a cusp d in lower postcanines (Bonaparte et al. 2003, 2005). However, subsequent works have considered this taxon as a junior synonym of *B. quadrangularis* (Liu and Olsen 2010; Guignard et al. 2019b; Martinelli 2017; Martinelli et al. 2019; Kerber et al. 2022). Another taxon described on the basis of a skull with jaws is *Minicynodon maieri* (Bonaparte et al. 2010a), which also has undistinguished features of those of present in the wide sample of *Brasilodon*, and thus is considered a junior synonym too (Martinelli 2017; Guignard et al. 2019b; Martinelli et al. 2019).

Brasilodon quadrangularis is an important cynodont in understanding the evolution of mammalian traits, being considered the sister group to Mammaliaformes (Liu and Olsen 2010; Martinelli et al. 2017a, b; Stefanello et al. 2023; Kerber et al. 2024). Besides having its anatomy well-documented through various specimens, within the evolutionary context of non-mammaliaform cynodonts, it exhibits a wide range of cranial, dental, postcranial, and neurological anatomical innovations, such as the presence of a promontorium, a trait shared with mammaliaforms (Martinelli and Bonaparte 2011; Rodrigues et al. 2013, 2014; Martinelli 2017; Martinelli et al. 2017a, b; Botha-Brink et al. 2018; Guignard et al. 2019b;

Figure 6. Artistic impression of the small cynodont *Irajatherium hernandezi*. Artwork by Márcio L. Castro.

Abdala et al. 2020; Stefanello et al. 2023; Kaiuca et al. 2024; Kerber et al. 2024).

PARAREPTILIA Olson, 1947
PROCOLOPHONIDAE Seeley, 1888
LEPTOPLEURONINAE Ivakhnenko, 1979
Soturnia Cisneros and Schultz (2003)
Soturnia caliodon Cisneros and Schultz (2003)

Soturnia caliodon is the only Late Triassic procolophonid known in South America (Cisneros and Schultz 2003) and is regarded as one of the latest known surviving members of Parareptilia, together with Norian and Rhaetian representatives of the Northern Hemisphere (Butler et al. 2024). It possesses the typical bicuspid distal teeth on the maxilla, which characterizes advanced procolophonids, whereas its incisiviforms present a single cusp (Dalle-Laste et al. 2024), such as the dentary teeth. The bulbous teeth possessed a thick enamel layer and were firmly set in the dentigerous bones. This set of traits are suggested to have given the teeth stable occlusion and long useful life, adaptive features for its proposed diet of tough fibrous vegetation (Cabreira and Cisneros 2009). The taxon is known from several specimens, including a fairly complete skull (UFRGS-PV-1111-T) which shows two robust quadratojugal spines which were probably recovered by keratinous tissue in life (Melo et al. 2012). Nonetheless, only the holotype (MCN PV2738) has reported postcranial remains, including a segment of the axial skeleton and a right humerus (Cisneros and Schultz 2003).

LEPIDOSAUROMORPHA Gauthier, 1984 (sensu Gauthier et al. 1988)
Cargninia Bonaparte et al. (2010a)
Cargninia enigmatica Bonaparte et al. (2010a)

The holotype of *Cargninia enigmatica* (UFRGS-PV-1027-T) is known from a single left dentary, missing its rostral extremity. It was presented as having only 6-7 preserved teeth (Bonaparte et al. 2010a), though later authors recognized it originally preserved at least 14 teeth of an estimated total of more than 20 tooth loci (Romo de Vivar et al. 2020b). These authors also tentatively referred to a second specimen of the species in the same work while presenting lepidosauromorph maxillary remains (UFRGS-PV-0819-T) that could not be confidently referred to as *C. enigmatica* by the lack of overlapping elements. The teeth of *C. enigmatica* are homodont, with closely-spaced crowns that are finger-shaped. The presence of replacement pits in the lingual side of some teeth and partial ankylosis in some elements indicates that the taxon had a pleuroacrodont tooth attachment, differing from most rhynchocephalians, which are also markedly heterodont. The low tooth crowns also differ *Cargninia* from kuehneosaurids. Nonetheless, the fragmentary condition of the known materials allows only to refer the material as either a non-rhynchocephalian lepidosauromorph, or a basal lepidosaurian (Romo de Vivar et al. 2020b).

LEPIDOSAURIA Haeckel, 1866
RHYNCHOCEPHALIA Günter, 1867
SPHENODONTIA Williston, 1925
Clevosaurus Bonaparte and Sues (2006)
Clevosaurus brasiliensis Bonaparte and Sues (2006)

The first fossils of *Clevosaurus brasiliensis* were described by Bonaparte and Sues in 2006, based in two specimens, comprising a complete skull and an articulated mandible of an adult specimen (UFRGS-PV-0748-T, the holotype), and an incomplete skull and mandible of a juvenile specimen (UFRGS-PV-0613-T), which was later referred to another genus (see below). In the years following the description, dozens of specimens were added to the sample, making *C. brasiliensis* one of the most abundant taxa at the Linha São Luiz Geosite (Romo de Vivar et al. 2020a). Postcranial remains were described by Arantes et al. (2009), including the axial skeleton and limb elements such as tibia, fibula, and phalangeal elements. The extensive sample allowed several authors to conduct quantitative analyses. While Hsiou et al. (2015) regarded that the phylogenetic relationships of Clevosauridae were uncertain, even with the description of new specimens, other workers provided glimpses on the paleoautoecology of the animal. An assessment of the mandibular morphological variation (Romo de Vivar Martínez and Soares, 2015) indicated a dietary shift among the sample, with adult specimens probably adopting an omnivorous diet, with more plant material than other species of *Clevosaurus*. Furthermore, pathological mandibles suggested that *Clevosaurus* might exhibit agonistic behavior similar to that seen in *Sphenodon punctatus*, where individuals bite each other in intraspecific combats (Romo-de-Vivar-Martínez et al. 2017). A recent effort including micro-CT imaging (Chambi-Trowell et al. 2021) presented a detailed description of the craniomandibular anatomy of the taxon, reinforcing its diagnosis. *C. brasiliensis* is recognized by several cranial features, such as its short rostrum (Figure 4A; Electronic Supplementary File 3), characteristic palatal dentition with three rows of teeth, and a unique type of tooth implantation. Furthermore, the authors provided an extensive phylogenetic revision for Clevosauridae, and recovered *C. brasiliensis* closely related to the North American *C. bairdi*, from the Lower Jurassic of Canada. Finally, some of the specimens previously assigned to *C. brasiliensis* were recognized as an independent genus and species, *Microsphenodon bonapartei* (see below).

Microsphenodon Chambi-Trowell et al. (2021)
Microsphenodon bonapartei Chambi-Trowell (2021)

Originally recognized as a juvenile of *Clevosaurus brasiliensis* (Bonaparte and Sues 2006; Hsiou et al. 2015; Romo de Vivar Martínez and Soares 2015), the materials referred to *Microsphenodon bonapartei* allow the reconstruction of most of the skull and mandible (missing only the premaxillae, vomer and stapes). In addition to the skull, the first two cervical vertebrae are known from the holotype (Chambi-Trowell et al. 2021). *M. bonapartei* is generally smaller than adult specimens of *C. brasiliensis*, and among other features, has a dentition which is notoriously distinct from the latter. *M. bonapartei* has a pronounced tooth differentiation, with a marked caniniform both in the maxilla and the dentary. The parietal table is relatively wider than in *C. brasiliensis*, though the skull is generally narrower than in that taxon. It is remarkable that the combination of plesiomorphic and apomorphic traits shown by *Microsphenodon bonapartei* not only renders it easily distinguishable, but also affects its phylogenetic relationships. Indeed, Chambi-Trowell et al.

(2021) recovered the taxon as one of the earliest members of Eusphenodontia, and positioned outside of Clevosauridae.

Lanceirosphenodon Romo de Vivar et al. 2020a
Lanceirosphenodon ferigoloi Romo de Vivar et al. 2020a

Lanceirosphenodon ferigoloi (Figure 4B) is a small sphenodontian known only from its holotype (CAPPA/UFSM 0226), which consists of an almost complete left dentary, missing only its posteriormost portion. *L. ferigoloi* presents features shared with non-eusphenodontian rhynchocephalians and was regarded by the original authors as an early juvenile. Despite the early ontogenetic state, Romo de Vivar et al. (2020a) erected a combination of several diagnostic features to support the taxon. It possesses a remarkable dentition composed of two series of alternating teeth, and two modes of tooth attachment – whereas the posteriormost teeth show a degree of acrodonty, the successional teeth are markedly acrodont. The last two teeth are spearhead-shaped (hence the etymology of the genus), and located close to the low coronoid process, a feature distinct from *C. brasiliensis* and *M. bonapartei*, the other sphenodont taxa from the Linha São Luiz Geosite (Chambi-Trowell et al. 2021). Its piercing dentition was compatible with an insectivore diet similar to that inferred for *Microsphenodon*. While some of its anatomical differences to other Triassic sphenodontians may be related to ontogeny, several of the aforementioned features are age-independent. Therefore, the diversity and morphological disparity of Triassic Rhynchocephalia, such as attested by the taxa at the Linha São Luiz Geosite, among other triassic localities, might support the idea of a pre-Triassic origin for the group, as advanced by some authors (Simões et al. 2018; Hsiou et al. 2019).

ARCHOSAUROMORPHA von Huene, 1946
ARCHOSAURIFORMES Gauthier, 1986
ARCHOSAURIA Cope, 1869
Archosauria indet. De-Oliveira et al. 2023

Although the Linha São Luiz Geosite is remarkable for its microvertebrate fossil biodiversity, the record of larger animals is very scarce. Apart from footprints (Silva et al. 2012), the single record of an unequivocal large predator resides in an isolated tooth (Figure 5C). The assessment of the material, realized by De-Oliveira et al. (2023), recognized it as the tooth of a carnivorous archosaur, with distinct serrations and a robust shape. Its subcircular cross-section allows its shape as a pachydont morphotype, common in the mesial teeth of several Triassic carnivores, including (but not restricted to) dinosaurs. The tooth shows a large abrasion facet at its apex, extending in both medial and distal carinae, suggesting it may have been a shed tooth, replaced after being worn by predation. Though fragmentary, this fossil fills an ecological gap in the fossil record of the Linha São Luiz Geosite, with the recognition of archosaurs as the apex predators in the locality, such as in most Brazilian Triassic faunas (Schultz et al. 2020).

PTEROSAUROMORPHA Padian, 1997
LAGERPETIDAE Arcucci, 1986 (sensu Nesbitt et al. 2009a; Nesbitt et al. 2009b)
Faxinalipterus Bonaparte et al. (2010b)
Faxinalipterus minimus Bonaparte et al. (2010b) (emended by Kellner et al. 2022)

Among the microvertebrate fossils that abound in the Linha São Luiz Geosite, paleontologists found in 2002 a set of small, elongated, and hollowed bones of a small archosauromorph (UFRGS-PV-0927-T). Three years later, in 2005, the team found remains of a maxilla of peculiar morphology (UFRGS-PV-0769-T). Suggesting that all elements represented a single taxon, Bonaparte et al. (2010b) presented the specimen as an early pterosaur, *Faxinalipterus minima*. In a later study, Kellner et al. (2022) reevaluated the material and found it unlikely that the two specimens, collected in two distinct opportunities and lacking overlapping materials, could be referred to a single animal. Furthermore, the phylogenetic study of the holotype (UFRGS-PV-0927-T) allowed the authors to recognize it not as a pterosaur, but as a representative of Lagerpetidae, an earlier lineage of Pterosauromorpha. The preserved elements were reevaluated as pertaining to fragments of both humeri, as well as the proximal portion of a femur, tibia, fibula and two incomplete metatarsals. Finally, an amendment to the specific name was advanced, from *F. minima* to *F. minimus*.

GRACILISUCHIDAE Butler Sullivan, Ezcurra, Liu, Lecuona & Sookias, 2014
Maehary Kellner et al. 2022
Maehary bonapartei Kellner et al. 2022

In the same work that reassessed the phylogenetic positioning and the anatomy of *Faxinalipterus minimus*, Kellner et al. (2022) presented a second small purported ornithodiran from the Linha São Luiz Geosite. Specimen CAPPA/UFSM 0300 (Figure 4E; Electronic Supplementary File 4) comprises a partial skull, associated to a few vertebral centra and a partial scapula. Interestingly, the maxilla of the new material was anatomically compatible to the maxilla (UFRGS-PV-0769-T) originally proposed by Bonaparte et al. (2010b) to be part of *Faxinalipterus*. Contrary to those authors, Kellner et al. (2022) referred the specimens CAPPA/UFSM 0300 and UFRGS-PV-0769-T as representative of a new taxon, *Maehary bonapartei*. Among the features that allow the recognition of the taxon, are the maxilla with a tall dorsal process creating a wide antorbital fenestra, and the maxillary teeth, which were devoid of serrations, but ornated by two apicobasally oriented grooves, unique for the taxon. The slender jaw suggested *M. bonapartei* fed on small delicate insects, which it probably captured with its piercing teeth (Figure 7). In its original description, the taxon was recovered as the earliest-diverging member of Pterosauromorpha, but this positioning was defied recently by Müller et al. (2023), who recovered the taxon as a gracilisuchid.

DINOSAURIA Owen, 1842
SAURISCHIA Seeley, 1888
GUAIBASAURIDAE Bonaparte et al. (1999)
Guaibasaurus Bonaparte et al. (1999)
Guaibasaurus candelariensis Bonaparte et al. (1999)

The type locality of *Guaibasaurus candelariensis* is an outcrop ca. 100 km far from the Linha São Luiz Geosite, in the municipality of Candelária. The species was originally known from a few vertebrae and some incomplete bones of the girdles and hindlimbs described by Bonaparte et al. (1999) as a saurischian of uncertain affinities. Even though no skull or dental remains of this dinosaur were ever found,

Figure 7. Artistic impression of the life habits of the small archosaur *Maehary bonapartei*, hunting an indeterminate Odonata over the branches of an Araucariaceae. Artwork by Márcio L. Castro.

the authors were inclined to postulate it was a carnivorous saurischian. Nonetheless, the remains, though well preserved, were too scarce to propose a phylogenetic position for the taxon confidently. Part of this scenario would change when a second, more complete skeleton was unearthed in the Linha São Luiz Geosite. Collected in 2002 and described five years later (Bonaparte et al. 2007), the specimen UFRGS-PV-0715-T (Figure 5A, B) preserved most of the postcranial elements in remarkable articulation but lacked cervical and skull elements. Therefore, though more completely known, the taxon remained entangled in phylogenetic uncertainty. Bonaparte et al. (2007) suggested that *Guaibasaurus* was a taxon closely related to the origin of Sauropodomorpha, but yet retained several features shared with Theropoda which could indicate its position as an early eusaurischian. Langer et al. (2011), on the other hand, advanced the phylogenetic hypothesis that *Guaibasaurus* was a theropod, this time supported by a numeric phylogenetic study, yet the authors emphasize that the support within Theropoda was weak and obscured by the several plesiomorphic traits retained by the taxon. Indeed, the taxon has a rogue distribution among independent phylogenetic approaches, floating from a basal position within Eusaurischia, or as an early theropod or sauropodomorph (Cabreira et al. 2016; Ezcurra 2010; Langer et al. 2011; Müller et al. 2018; Novas et al. 2021; Pol et al. 2021; Pretto et al. 2019). Much of this conundrum rests in the matter that, though an almost complete postcranium is known for *Guaibasaurus*, it lacks skull and neck elements, which differentiated early in the split between Theropoda and Sauropodomorpha (Leal et al. 2004; Müller et al. 2018; Pretto et al. 2019). It is, nonetheless, an unmistakable member of Saurischia, and the only dinosaur known from somatofossils in the entire Linha São Luiz Geosite.

4.2. Invertebrates

In the middle and upper sections of the Linha São Luiz stratigraphy (Figure 2), invertebrates represent the most prevalent body fossils (Figure 8). These invertebrates are often found in association with plant remains and fish scales within lacustrine facies, and with ichnofossils in the heterolithic upper strata.

Branchiopods (commonly referred to as 'conchostracans') constitute the most abundant fossils, typically preserved as remains and/or molds of entire carapaces, which may be either articulated or disarticulated (Rohn et al. 2014; Jenisch et al. 2017). Notably, these skeletons, which are poorly mineralized, lack evidence of bioerosion, encrustation, abrasion, or corrosion (Jenisch et al. 2017). The distribution of these fossils is facies dependent and ranges from dispersed to densely packed, consistently aligned parallel to the bedding plane. They occur in three distinct modes: at the interface of siltstones/heteroliths with mudstones (Ht), within the middle of mudstone strata (Fl), and within plane-parallel sandstones (Sm). Jenisch et al. (2017) identified two distinct taphofacies for branchiopods. The first taphofacies is characterized by a muddy matrix with a polymodal distribution of carapaces, which are dispersed to loosely packed. This distribution suggests episodes of flooding within the lake, leading to the decantation of fine sediments and the non-selective mortality of the autochthonous assemblage, with a short residence time in the taphonomically active zone. The second taphofacies is found within a heterolithic muddy matrix at specific lake body levels and within upper crevasse splay facies. This facies features a juxtaposition of dispersed articulated carapaces and densely packed lenticular groupings, with relative size selection and a mix of closed, open, and disarticulated valves. The internal structure of these layers indicates deposition through traction and traction-suspension processes, likely resulting from sporadic river overflow events. These events concentrate autochthonous (closed) valves alongside allochthonous or parautochthonous (open and isolated) valves (read more in Jenisch et al. 2017).

Insects are less abundant within these strata and are exclusively associated with lacustrine facies (Figure 2). They are typically found as isolated wing molds and occasionally as larvae, with the head, thorax, and abdomen preserved in mold form (Correa et al. 2019). Despite multiple insect reports from the Linha São Luiz Geosite, no publications have been released to date. However, new studies are underway, and preliminary details are presented below.

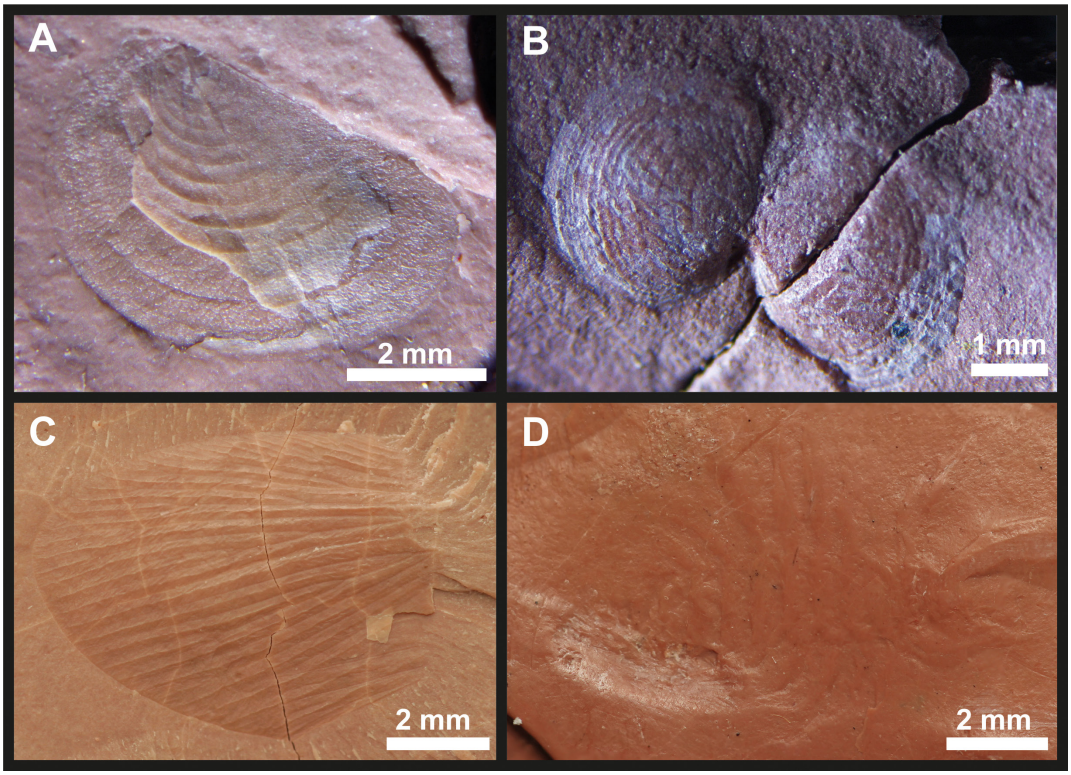

Figure 8. Invertebrate fossils of the Linha São Luiz Geosite. A, *Nothocarapacestheria soturnensis*, right isolated valve partially preserved (iridescent material) and external mold with growth lines and ornamentation. B, *Australestheria sp.*, articulated valves resting the bedding plane, rest preserved as whitish material. C, Blattodea indet. (ULVG13632) partial insect hindwing preserved as mold. D, mold of holometabolan larva (ULVG11209), showing anterior (thorax) and upper posterior (abdomen) regions.

4.2.1 Systematic Paleontology

ARTHROPODA Latreille, 1829
BRANCHIOPODA Latreille, 1817
DIPLOSTRACA Gerstecker, 1866
SPINICAUDATA Linder, 1945
EOSESTHERIOIDEA Zhang et al. 1976
EOSESTHERIIDAE Zhang et al. 1976
Nothocarapacestheria Rohn et al. 2014
Nothocarapacestheria soturnensis Rohn et al. 2014

Nothocarapacestheria soturnensis is a large Spinicaudata (Figure 8A) characterized by an oval carapace and a small larval valve with a submedial, marginal, and small umbo, featuring 18-27 growth bands (Rohn et al. 2014). The carapace ornamentation is complex, transitioning distally from isodiametric irregular reticles to elongated polygons, and finally to radial lirae in the most distal regions (Rohn et al. 2014). The microornamentation, distinguished by irregular mamelons, sets *N. soturnensis* apart from the genus *Carapacestheria* Shen (1994), found in the Lower Jurassic of Antarctica. The name *Nothocarapacestheria* reflects this distinction, as “Notho” implies “false” *Carapacestheria*. According to Rohn et al. (2014), the similarities between *N. soturnensis* and *Carapacestheria*, along with significant differences from other members of the Eosestheriidae family from the Upper Triassic of Argentina and Chile (Gallego et al. 2005; Gallego 2010), suggest that the Spinicaudata of the Linha São Luiz Geosite could indicate a Lower Jurassic age, at least for the lacustrine system of the outcrop. Recently, *N. soturnensis* was also described from the Sinemurian (Lower Jurassic) of China (Teng and Li 2024), reinforcing the hypothesis regarding the age of this geological package in southern Brazil.

FUSHUNOGRAPTIDAE Wang, 1974
Australestheria Chen in Zhang et al. 1976
Australestheria sp. Rohn et al. 2014

The specimens of *Australestheria* sp. from the Linha São Luiz Geosite are medium-sized and rounded, with a straight and short dorsal margin, and a small supramarginal submedial umbo (Figure 8B). They exhibit 12 to 19 growth lines, which are characterized by regular bands weakly ornamented with thin homogeneous punctuations that show slight orthogonal alignment (Rohn et al. 2014). The growth lines can be either continuous (straight) or slightly serrated (beaded structures) with discrete punctuations forming small arrow shapes (Rohn et al., 2014). This feature of very weak and smaller arrows distinguishes these specimens from the type species of the genus *Australestheria corneti* from the (Middle?) Jurassic of the Democratic Republic of the Congo (Zhang et al. 1976; see discussion in Rohn et al. 2014). Another species of *Australestheria*, *A. barbosai*, associated with *Pseudograpta mendesi* (Cabral 2011; Christofoletti et al. 2021), occurs in the Pirambóia Formation, an overlying unit in the Paraná Basin. A Middle Jurassic age has been suggested for this formation, again reinforcing the possible Jurassic age of the strata containing conchostracans at the Linha São Luiz Geosite (Cabral 2011; Rohn et al. 2014).

FUSHUNOGRAPTIDAE Wang, 1974
Fushunograptidae indeterminated Jenisch et al. 2017

This morphotype, identified by Jenisch et al. (2017), features medium to large carapaces with an oval to round shape, an inframarginal submedial umbo, and 15 to 25 growth lines. The ornamentation on the dorsal margin is irregularly reticulate, transitioning from the central part to a well-developed striate to radial lirae pattern with occasional transverse bars on the ventral margin (Jenisch et al. 2017). These characteristics distinguish it from *Australestheria sp.*, the other Funshunograptidae present at the outcrop (Rohn et al. 2014; Jenisch et al. 2017). Currently under investigation, this morphotype occurs exclusively in the second taphofacies. It is more common than *Australestheria sp.*, which is found only in the first taphofacies, but less frequent than *Nothocarapacestheria soturnensis*, which occurs in both taphofacies (Jenisch et al. 2017).

INSECTA Linnaeus, 1758
PTERYGOTA Brauer, 1885
BLATTODEA Latreille, 1810
Blattodea indeterminate unpublished

Although rare, these remains are important to highlight the diversity of invertebrate fossils at the Linha São Luiz Geosite. The site yielded isolated wings, a hindwing, and a forewing, tentatively related to cockroaches. The good preservation of these specimens in mold allows for detailed observation of the wing veins (Figure 8C). However, further studies are required to fully characterize the anatomy of the specimens and elucidate their taxonomic categorization.

HOLOMETABOLA Burmeister, 1835
Holometabola indeterminate unpublished

Correa et al. (2019) reported the occurrence of an adpressed three-dimensional mold of a holometabola larva slightly compressed, which exhibits the head, thorax, and abdomen (Figure 8D). Some anatomical details suggest a possible relationship with the subfamily Chauliodinae (Corydalidae) or to a larva of aquatic beetles (Coleoptera). The systematic affinity and paleoenvironmental significance of this specimen are still under further investigation. The larva, along with other insect wings, is found in association with plant remains and Branchiopoda carapaces within the lacustrine strata of the outcrop.

PTERYGOTA Brauer, 1885
Pterygota indeterminate unpublished

Three samples from the Linha São Luiz Geosite contain wings attributed to Pterygota. Two of these samples are fragments that are difficult to classify systematically. However, the third sample includes a forewing and hindwing that may be associated with either Odonata or Neuroptera, pending further examination. All these samples are still under study.

4.3 Paleobotany

The Linha São Luiz Geosite boasts a substantial record of plants, characterized by diverse forms of preservation, detail, and abundance (Figure 9). Paleosols and root pavements are present at specific levels within both the lower sandstone and upper crevasse splay deposits. Rhizoturbations manifest as large, fibrous impressions of homogeneous size, associated with shrub vegetation in unconfined river channels, or as thin, intensely branched undergrowth (Barboni and Dutra 2013; Dutra and Crisafulli 2022). Both types exhibit diagenetic halos that facilitate easy identification. In contrast, the lacustrine package contains the greatest abundance of fossil plants, both autochthonous and parautochthonous (Crisafulli and Dutra 2009). Trunks, shoots, and leaves are evenly distributed within the fine sediment strata, with approximately 90% of the paleobotanical assemblage consisting of conifer remains (Dutra and Faccini 2002; Pires and Guerra Sommer 2004; Wilberger 2009; Crisafulli and Dutra 2009).

The fossilized wood logs found at the Linha São Luiz Geosite are notably small compared to the large trunks of the Mata Sequence, which is renowned for its sizable trunks. These smaller trunks have a pith that allows for identification (Crisafulli and Dutra 2009). Among the trunks under study, two species have been reported: *Sommerxylon spiralosus* Pires and Guerra-Sommer 2004 and *Kaokoxylon zalesskyi* (Sahni) Maheshwari 1967 (in Crisafulli and Dutra 2009). The trunks are completely silicified, with some densely impregnated with iron oxides (Pires and Guerra-Sommer 2004; Pires et al. 2005; Crisafulli and Dutra 2009), ensuring excellent preservation of their features, including reproductive structures of ovules and seeds located near the trunk (Crisafulli et al. 2018; Dutra and Crisafulli 2022).

A diverse array of leaves, shoots, and reproductive structures is also preserved at the site (Figure 9), either as impressions or covered by coatings of oxides. Among the notable finds are Bennettitales such as *Pterophyllum* leaves (*sensu* Brongniart 1825 *apud* Barboni and Dutra 2013) and reproductive cones, with such excellent preservation that allows for the three-dimensional reconstruction of the structure of *Williamsonia potyporanae* Barboni and Dutra (2013). Additionally, leaves of *Pelourdea* and leaves and conifer branches of *Pagiophyllum* Heer 1881 (in Wilberger 2009) have been reported, which require further investigation.

Martins et al. (2022) detailed the presence of iron films on leaves and branches, identifying them as amorphous and acicular goethite, with spheroidal ferrihydrite associated with microfeatures of twisted and stalks. These features were possibly produced by microaerophilic and neutrophilic iron-synthesizing bacteria during eodiagenesis, ensuring the exceptional preservation of the micro-anatomical structures of plants from the Linha São Luiz Geosite (Martins et al. 2022).

The paleoassemblage, containing autochthonous to parautochthonous primitive conifers and paleosols preserved in a restricted lacustrine/deltaic context within a broader river system, supports a depositional environment characterized by a warm and seasonal climate with periods of intense rainfall, attested by wood dendrochronological data (Pires et al. 2005; Crisafulli and Dutra 2009). The periodic high-water supply ensured the preservation and seasonal renewal of woody and herbaceous vegetation, which was physiognomically similar to the vegetation currently covering modern rain shadow and continental areas at the boundary between tropical and subtropical climate belts (Barboni and Dutra 2013).

4.3.1 Systematic Paleontology

GYMNOSPERMAE Lindley, 1830
PINALES Gorozhankin, 1904
TAXACEA Gray, 1822
Sommerxylon Pires and Guerra-Sommer 2004
Sommerxylon spiralosus Pires and Guerra-Sommer 2004

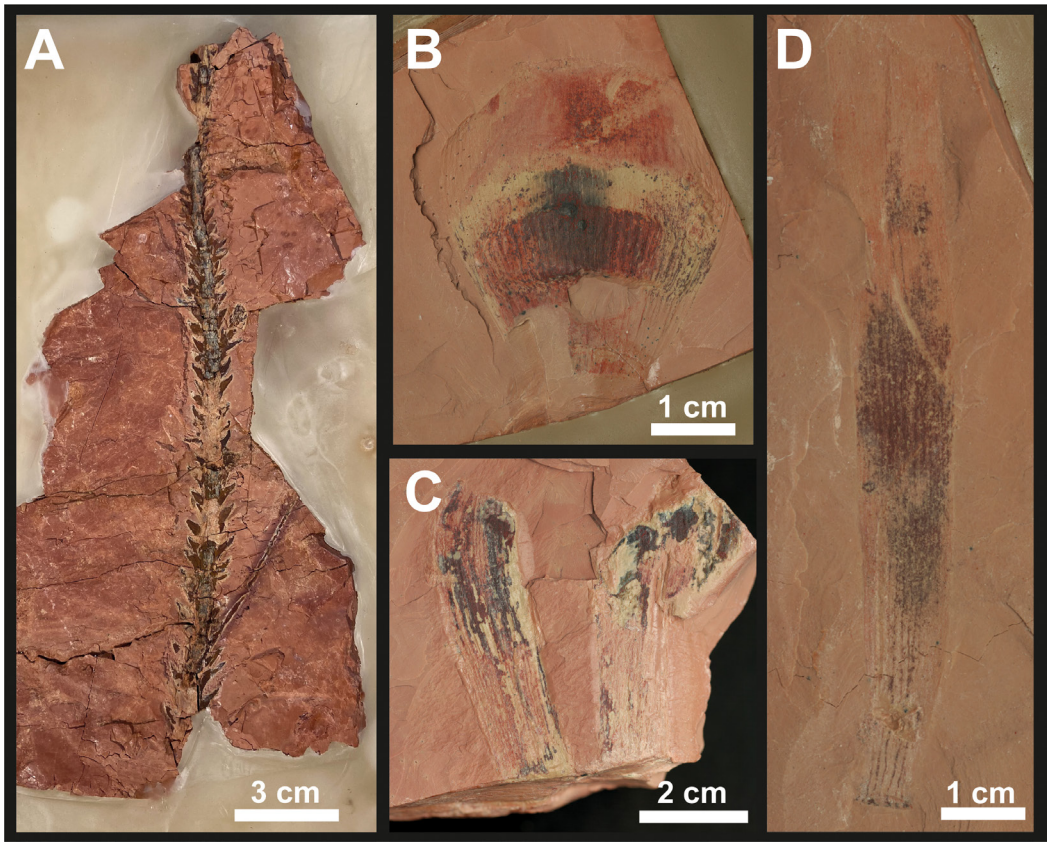

Figure 9. Examples of fossil plants of the Linha São Luiz Geosite. A, *Pagiophyllum sp.* (ULVG8266), stem with helicoidally arranged needle leaves preserved in 3D and partially covered by goethite. B, *Williamsonia potyporanae* (ULVG7186), complete cone with the receptacle and fertile and sterile rings of interseminal scales. C, cf. *Pelourdea* (ULVG13575a) leaf segments. D, *Pterophyllum?* (ULVG7326), impressions of coriaceous leaf segments.

This taxon is characterized by a heterocellular medulla with parenchymatic and sclerenchyma cells, endarch primary xylem and secondary xylem with dominance of uniseriate areolate pits, spiral thickenings on the radial walls of the tracheids, medullary ray homocellular, uniseriate and absence of resinous canals and axial parenchyma. The medullary parenchyma has thin-walled cells grouped in nests (Pires and Guerra-Sommer 2004). The growth rings of *Sommerxylon spiralosus* are distinct with a gradual transition from early to latewood suggesting that growth phase in each cycle developed at a slow rate, and the growing environment was relatively uniform with not very extensive periodic phases of growth restriction The different cycles of growth were affected by external factors as cyclic reduction of water supply (Pires et al. 2005).

CONIFERALES Engler, 1897

Kaokoxylon Kräusel 1956

Kaokoxylon zalesskyi (Sahni) Maheshwari, 1967

Kaokoxylon zalesskyi in Linha São luiz Geosite was described in Crisafulli and Dutra (2009) as a pycnoxylic homogeneous wood with wedge-shaped, endarch, and cuneiform primary xylem, and the secondary xylem with marked growth rings typically auraucarioid. In a subsequent work by Crisafulli et al. (2018), a seed was also identified, immersed in the lignified xylem tissue. This integument seems to be thick in texture, with well-developed nucellus, micropylar part and megagametophitic. Two nucellar cavities enclosed by a common integument which probably contain a sarcotesta and endotesta. Part of the peduncle of this seed is also preserved (Crisafulli et al. 2018). Crisafulli and Dutra (2009) highlight the presence of a *K. zalesskyi* trunk with roots in life position at the limit between the lower sandstone package and the intermediate lacustrine mudstones.

ARAUCARIACEAE Henckel and Hochstetter, 1865

Pagiophyllum Heer, 1881

Conifer leaves, branches, and shoots were preliminarily related to Pagiophyllum by Wilberger (2009) based on epidermal anatomy. Preserved mainly as three-dimensionally preserved (Figure 9A) shoots and twigs covered by goethite (Dutra and Crisafulli 2022; Martins et al. 2022), this material is abundant in the lacustrine layers of the Linha São Luiz Geosite. Alternatively, part of the materials assigned to the taxon may be referrable to *Agathoxylon* or *Brachyphyllum* (Crisafulli and Dutra 2009; Dutra and Crisafulli 2022).

BENNETTITALES Engler, 1892

WILLIAMSONIACEAE (Carruthers) Nathorst, 1913

Williamsonia (Carruthers) Harris, 1969

Williamsonia potyporanae Barboni and Dutra (2013)

Williamsonia potyporanae is a detailed isolated and pedunculate ovulate structure (Figure 9B), probably in the stage of seed maturity (seed cone) covered by two layers of elongated, parallel orientated, striate, hairy membranaceous bracts (Barboni and Dutra 2013). The advanced morphology

of ovulate structure suggest warm and wet conditions, but seasonally or irregularly distributed humidity, with short and intense rain episodes. These characteristics of *W. potyporanae* display affinities to taxa found in Jurassic and Cretaceous, as discussed by Barboni and Dutra (2013).

Pterophyllum? Brongniart, 1825

Described in Barboni and Dutra (2013), these impressions of coriaceous leaf segments have an elongate and ensiform shape, slightly curved with five to six veins that rarely bifurcate in the admedial part, with parallel and equidistant courses (Figure 9D). These give place to nearly ten veins in the mid portion of the segment, which contains two to three veins per millimeter. The affinity with *Pterophyllum* is supported by total length, smooth margins, parallel veins with few ramifications, as well as the constricted and decurrent base on both sides of the segment (Barboni and Dutra 2013). It is interesting to note that this genus is mostly composed of species from the Triassic/Jurassic boundary (Barboni 2010).

DIVISION UNKNOWN

Pelourdea Seward 1917 emend. Ash 1987

Pelourdea indeterminate unpublished

This vegetative structure is still under investigation and is represented by fragmented leaves with parallel venation (Figure 9C). If the taxonomic placement of the materials comes to be confirmed, the occurrence of yet another plant taxon may demonstrate the potential for continued research at the Linha São Luiz Geosite.

5. Geoconservation

The Linha São Luiz Geosite is located in a rural area, though the surroundings of the main outcropping are not employed in agriculture. Despite this, over the last fifteen years, the outcrop has been severely endangered by the proliferation of exotic pine trees, *Pinus* sp. (Ziemann and Figueiró 2017). Apart from covering fossil-bearing areas, the trees established especially over the fine and brittle

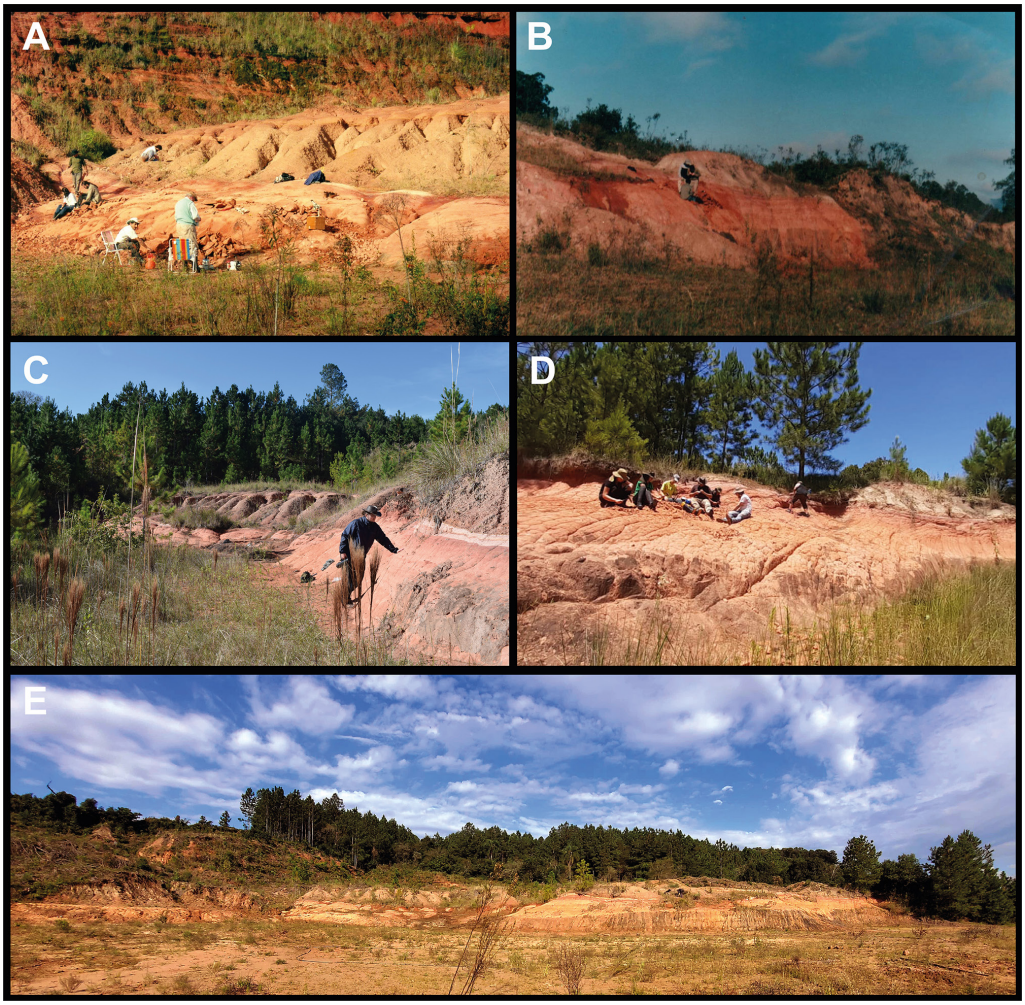

Figure 10. The Linha São Luiz Geosite over the years. A, B, fieldwork conducted during the early years of exploration, at the beginning of the decade of 2000. A, view of the ravine facing roughly S-SE, the most fossiliferous site with microremains of tetrapod at the time, taken in 2005, with Dr. José F. Bonaparte and technician Daniel Hernández near the middle of the photograph; B, view of the ravine facing roughly S-SW, where a partial skeleton of *Guaibasaurus candelariensis* was found. C, D, fieldwork conducted by the team of CAPPA/UFSM at the beginning of the decade of 2020. Shots taken in roughly the same views of A and B. Note the advance of pine trees over the outcrop, and the accumulation of sediment at the base of the outcrop, obscuring fossiliferous levels. E, current state of the outcrop (at 2024), after the removal of the accumulated sediment and of the pine trees that threatened the site.

mudstones of the lacustrine system deposition (Figure 10), degrading much of the area through root development. An evaluation of the vulnerability of fossiliferous sites (Figueiró et al. 2022) was developed during the establishment of the UNESCO Quarta Colonia Geopark with the Linha São Luiz Geosite figuring among the most relevant sites in terms of heritage value, and the most vulnerable locality with fossils in the territory.

Over the year of 2023, driven by the qualification of the territory in the UNESCO Global Geopark network, the municipality of Faxinal do Soturno undertook an important step in the maintenance of the locality, removing the main cover of exotic trees. In the same endeavor, accompanied by paleontologists, the municipal public administration removed the sediment accumulated by erosion at the base of the main vertebrate-bearing strata, re-exposing almost 2 meters of outcrop and restoring the exposure to conditions similar to those of the time of the first discoveries at this fossiliferous locality. This activity will not only allow the update of the status of this site as a locality under low risk of degradation in future vulnerability evaluations but also facilitate the access of the locality by researchers, bolstering the very activities of fossil prospection and collection, which originally gave the site its scientific and heritage relevance.

5.1. Digitalization

Geological formations are constantly changing through the eons, and their fossils are usually fragile and one of a kind. Since fossilized remains are the main study object of paleontology, one cannot afford to lose any data, especially considering the efforts and resources involved in collecting them. Digitalization is a great way of making perishable items eternal in the virtual realm, where they can be more easily shared, stored, and open to new types of analysis, made possible by computer algorithms (Falkingham 2012).

Based on our previous research (Almeida et al. 2023) in 3D reconstruction and virtualization of paleontological materials, we recreated several specimens found at this outcrop. Some fossils from the paleontological collection of CAPPA/UFSM are provided as 3D models for download in the Supplementary Files of this paper. Other specimens will be, in time, made available as QR codes and other sources of digital storage. This way, anyone interested in the locality can get to really know its flora and fauna. This effort not only gives the wider public direct access to science, but also protects this valuable cultural heritage.

Finally, joint efforts are being made to scan and recreate the complete Linha São Luiz Geosite in 3D. This site is being integrated into Virtual Reality and will be made available for digital exploration in a forthcoming endeavor.

6. Final Remarks – Perspectives

Along the 25 years passed since Daniel Cargnin first reported to paleontologists his discovery of a new fossil-bearing area, in the outskirts of Faxinal do Soturno, a rich history of research has unfolded. Several institutions, as well as renowned scientists from Brazil and abroad, focused their research on the ravines and beautifully preserved fossils from the Linha São Luiz Geosite, providing a rich account of several taxonomic groups and working together to elucidate the story told by its fossils and sedimentary layers. From the dawn of dinosaurs and stem-mammals in the Triassic, to the establishment of ancient Jurassic conifer forests, the Linha São Luiz Geosite is now not only a fossil-bearing area restricted to scientists, but a source of cultural heritage, protected by the people of the local communities. And after a quarter century of work and discoveries, there are still questions to be settled and new taxa to be uncovered from this which is one of the richest fossiliferous outcrops in Brazil.

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Authorship credits

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LK						
AGM						
JPS						
RC						
RSH						
GCA						
HSB						
DSO						
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CLS						

A - Study design/ Conceptualization **B** - Investigation/ Data acquisition
C - Data Interpretation/ Validation **D** - Writing
E - Review/Editing **F** - Supervision/Project administration

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Journal of the Geological Survey of Brazil

Pripiri Geosite, Coração de Jesus, Minas Gerais, Brazil: paleontological relevance, quantitative assessment, and initiatives for its promotion

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Abstract

The Quiricó Formation is the richest fossiliferous unit of Sanfranciscana Basin. Its paleoasis context (a paleolake record inserted in a desert setting) includes vertebrates, diverse microfossils, and paleobotanical content. This study presents new findings regarding the fossil content of the formation, focusing on discoveries made at the Pripiri Geosite, located in Coração de Jesus municipality, northern part of the state of Minas Gerais, Brazil. Among the discoveries are poorly informative fragments of putative archosaurs and novel microfossiliferous taxa. The microfossil assemblage includes dinocysts and Euglenophyceae, both associated with microbial mat-forming cyanobacteria. These, in turn, comprise the filamentous *Pseudoanabaena* sp. and the coccoidal cells of *Aphanocapsa* sp. or *Chroococus* sp. These microbial mats are recurrent throughout the analyzed stratigraphic succession, primarily observed in sandstone bars featuring distinct evaporitic features. This assemblage provides ecological insights concerning the biota resistance to extreme climatic conditions, and their occurrence in oxygen-rich waters. The preservation of these cells in evaporite-rich rocks is also of great interest for astrobiological studies and the search for past life on Mars. Therefore, due to the importance of Pripiri locality, a quantitative analysis of its geodiversity and geoheritage value were performed, revealing that Pripiri comprises a geosite of national relevance in terms of its scientific, touristic and educational values. In this sense, some initiatives have been carried out to geoconservation and to promote the local geodiversity, aiming to contribute to the paleontological knowledge of the Early Cretaceous, as well as to the social and economic development of Coração de Jesus.

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1. Introduction

The Sanfranciscana Basin, located on the São Francisco Craton, constitutes the Phanerozoic sedimentary cover. It encompasses diverse sedimentary formations deposited over the São Francisco Supergroup, including the glacial sediments of the Santa Fé Group deposited during the Carboniferous–Permian interval, the arid to fluvial-paleoasis deposits of the Lower Cretaceous Areado Group, and the desertic and volcanic rocks of the Upper Cretaceous Urucuia and Mata da Corda groups (Zalán and Silva 2007). These formations, spanning a wide temporal range, document significant climatic changes and biotic evolution, rendering the Sanfranciscana Basin a pivotal window into the continental interior during the Pangea's breakup and the emergence of South America.

The fossil assemblage within the Sanfranciscana Basin comprises specimens ranging from invertebrate to vertebrate fossils, as well some palynomorphs (Arai et al. 1995; Bittencourt et al. 2022). The stratigraphic sequence reveals an evolutionary narrative, with initial fossil occurrences confined to lacustrine deposits of the Santa Fé Group (Permian–Carboniferous sequence) and include ichnofossils whose precise origins remain debated (Bittencourt et al. 2022).

Subsequently, the Areado Group (Lower Cretaceous), particularly the Quiricó Formation, emerges as a significant paleontological repository within the basin (Carmo et al. 2004; Leite et al. 2018, 2024; Leite and Carmo 2021; Coimbra 2020; Cabral et al. 2021; Bittencourt et al. 2022). Notable findings from this formation include the terrestrial squamata *Neokotus sanfranciscanus* (Carvalho and Santucci 2018; Bittencourt

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et al. 2020) and diverse bony fish fragments such as Semionotiformes, Amiiformes, fin spines, teeth, and denticles from at least three different species of Hybodontiformes sharks, and remains of coelacanthiform fish from the genus *Mawsonia* were also found (Fragoso et al. 2019). Comprising invertebrates, there are described species of conchostraceans and a great number of ostracods taxa (Leite and Carmo 2021; Bittencourt et al. 2022). Additionally, palynomorphs, larvae of insects of the species *Saucrolus silvai*, thousands of specimens of the ray-finned fish *Dastilbe moraesi*, and some species of plants were recorded in the Presidente Olegário (State of Minas Gerais) region: conifers *Brachyphyllum obesum* and *Podozamites lanceolatus*, the nymphaceous *Nymphaeites choffatti* and the grass *Paraleptaspis varjensis* (Arai et al. 1995; Duarte 1997), among others, further enrich the paleontological record.

The Areado Group also preserves a distinct marine fossil record. This includes radiolarians, dinoflagellates, acritarchs, sponge spicules, and foraminifera recovered in western portion of the state of Minas Gerais (Kattah and Koutsokos 1992; Pessagno and Dias-Brito 1996; Arai 1999; Dias-Brito et al. 1999; Azevedo et al. 2024). This fossil record supports the occurrence of an intracratonic wide sea, namely Arai Sea, during the Aptian. Although still under debate, this idea is reinforced by the occurrences of evaporites deposits and a series of marine fossil assemblage in other Brazilian intracratonic basins, such as Parnaíba and Araripe basins (see deeper discussion in Azevedo et al. 2024).

In Coração de Jesus (State of Minas Gerais) region, the first complete skull of a titanosaurid in South America, *Tapuiasaurus macedoi,* was founded in the deposits of Areado Group (Zaher et al. 2011). In addition, noasaurid theropod bones and a complete skull from an abelisaurid specimen (*Spectrovenator ragei*) were described (Silva 2013; Zaher et al. 2020). The region also features ichnofossils, lizard remains, lepisosteiformes, lungfish, and a large variety of ostracods (Cabral et al. 2021; Carvalho and Santucci 2021). The Três Barras Formation hosts dinosaur footprints attributed to theropods, ornithischians, and sauropods (Mescolotti et al. 2019).

Conversely, the Mata da Corda Group primarily preserves macrovegetation represented by dicotyledonous leaves and palynomorphs in the Coromandel (State of Minas Gerais) region (Leonardos et al. 1995). This includes several gymnosperms spores and angiosperms pollens, as well as fewer specific spores. Also, fungi and undetermined spores were also recovered. Authors attributed a tropical climate during the deposition of the above assemblage, which took place between 80 to 85 Ma, based on the occurrence of these same taxa in the Brazilian marginal basins.

All this geodiversity points to the high potential of the Sanfranciscana Basin sedimentary succession record for geoheritage and geoconservation purposes, considering the geological, paleontological, and speleological richness (e.g. Campos and Dardenne 2002) observed among the most notable localities, with not only scientific value, but also for touristic and social usefulness and value. This geological context may be of great importance for economic development purposes as well. This is because the area where the deposits recorded of the Sanfranciscana Basin occur is among the poorest regions in Brazil, presenting a Human Development Index (HDI) of 0.642, considered a low index for social development (PNUD 2024). In this sense, geosites and abundant occurrence of geodiversity sites (*sensu* Brilha 2016), can serve as tools for territorial management, economic, and social improvement through cultural and tourism activities, enhancement of services provisions, and of the development of other associated economic activities (Nascimento et al. 2015).

Here, we describe the Pripiri locality as a geosite. It is located in the vicinity of the municipality of Coração de Jesus, in the northern part of the Minas Gerais state. We propose its classification as a geoheritage based on its scientific relevance, due to the recent discovery of new fossils here presented, in addition to its fossil content previously published. The area of Coração de Jesus comprises Precambrian carbonate rocks of the Lagoa do Jacaré Formation and an abundant lacustrine to the desertic record of the Cretaceous Areado Group, within which the geosite is situated. In addition, considerations concerning the conservation of this geosite and its potential educational and touristic uses are also presented. Thus, in the near future, the initiatives listed here may serve as a guideline for the establishment of social and economic politics in Coração de Jesus, aiming for its social development.

2. Geological context

The subject of this study is situated within the São Francisco Basin, which, as described by Alkmin and Martins Neto (2001), constitutes the western segment of the São Francisco Craton. It has received sedimentary deposits from at least four distinct geological events since 1.8 billion years ago, filling successive basins with varying ages, tectonic histories, and paleogeographic scenarios. These basins include Precambrian formations (Espinhaço and São Francisco supergroups) as well as Phanerozoic successions (Santa Fé, Areado, Mata da Corda, and Urucuia groups). The Phanerozoic strata, covering sequences from the Permocarboniferous to the Cretaceous interval, represent the final depositional cycle of the São Francisco Basin and form part of the Sanfranciscana Basin (Campos and Dardenne 1997a; Sgarbi et al. 2001).

The Sanfranciscana Basin spans approximately 150000 km^2, oriented in a north-south direction, with dimensions of roughly 1100 km in length and 200 km in width, and it is exposed in the states of Minas Gerais, Bahia, Tocantins, Maranhão, and Piauí (Sgarbi et al. 2001). According to Campos and Dardenne (1997b), it can be characterized as an intracontinental sag basin type with low subsidence, occasionally influenced by taphrogenic processes. Tectono-stratigraphically, it can be subdivided into two sub-basins: Urucuia (north) and Abaeté (south), separated by the Alto do Paracatú, which outcrops west of the city of Coração de Jesus (Campos and Dardenne 1997b). The basin is delineated by five units, separated by significant regional disconformities. From bottom to top, its stratigraphy comprises the Santa Fé (Permo-Carboniferous), Areado (Lower Cretaceous, Albian interval), Mata da Corda (Upper Cretaceous), and Urucuia (Upper Cretaceous) groups, as well as the Chapadão Formation (Quaternary - recent sedimentary deposits) (Campos and Dardenne 1997a, 1997b).

The Areado Group, the focus of this study, is exposed in both the southern and northern portions of the basin. Deposition of the Areado Group is associated with crustal stretching during the opening of the South Atlantic Ocean, followed by a phase of mechanical subsidence (Campos and Dardenne 1997a, 1997b; Fragoso et al. 2011). From base to top, it comprises

the following formations: 1- Abaeté Formation, characterized by conglomerates and sandstones interpreted as alluvial fans and fluvial deposits (Campos and Dardenne 1997a, 1997b, Mescolotti et al. 2019); 2- Quiricó Formation, the primary focus of this work, of Barremian–Albian age (Figure 1), primarily composed of sandstones, mudstones, and siltstones, with subordinate occurrences of cherts, pseudomorphic salt layers, and limestones, indicative of a lacustrine and playa-lake environments (Campos and Dardenne 1997; Sgarbi et al. 2001; Fragoso et al. 2011; Mescolotti 2019; Simplício et al. 2017, Cardoso et al. 2022, 2024); and 3- Três Barras Formation, consisting of sandstones, mudstones, occasional conglomerates, and chert lenses, interpreted as fluvio-deltaic and aeolian paleoenvironments (Sgarbi 2000; Simplício et al. 2017). The uppermost part of the Três Barras Formation is interbedded and overlain by effusive and pyroclastic volcanic alkaline rocks, plutonic alkaline rocks, and epiclastic sedimentary rocks of the Mata da Corda Group (Sgarbi et al. 2004).

In the Coração de Jesus region, units of the Sanfranciscana Basin outcrop as small plateaus in angular unconformity with the Bambuí Group rocks, a succession of carbonate-siliciclastic rocks ranging up to 1000 m in thickness and of Ediacaran to Cambrian age (Warren et al. 2014). The studied sedimentary succession is represented exclusively by deposits from the Quiricó Formation, the middle portion of the Areado Group.

Age		Lithostratigraphic units			Age and/or data source
Holocene Pleistocene Pliocene		Chapadão Formation			Correlation with eluvial and alluvial covers of other chronocorrelative basins in Brazil
Late Cretaceous	Campanian	Mata da Corda Group	Capacete Formation		88.5 ± 1.9 to 71.5 ± 1.8 Ma based on K-Ar radiometric dating of illites Stratigraphic correlation Biostratigraphic correlation
	Coniacian		Patos Formation		87 to 83 Ma based on kimberlite clusters 81 to 68 Ma based on U-Pb radiometric dating ca. 90 Ma based on Ar-Ar radiometric dating 87 to 80 Ma based on K-Ar radiometric dating
		Urucuia Group	Serra das Araras Formation		Field relationship with the Mata da Corda Group
			Posse Formation		Field relationship with the Mata da Corda Group
Early Cretaceous	Albian	Areado Group	Três Barras Formation	Olegário Member	No chronostratigraphic studies
				Quintinos Member	106.1 ±2.2 88.8 ± 1.8 Ma, based on K-Ar radiometric dating of authigenic K-feldspar microcrystals Stratigraphic correlation
			Quiricó Formation		Biostratigraphic correlation based on non-marine ostracod fauna and fish-bone fragments
			Abaeté Formation		No chronostratigraphic studies
Permian Carboniferous		Santa Fé Group			Paleomagnetism Ichnofossils Stratigraphic correlation

Figure 1. Geochronologic chart of the Sanfranciscana Basin. Ages: Albian between 113 and 100.5 Ma; Coniacian between 89.8 ± 0.3 and 86.3 ± 0.5 Ma; and Campanian between 83.6 ± 0.2 and 72.1 ± 0.2 Ma. Modified from Maraschin et al. (2016), and references therein.

3. Materials and methods

The Pripiri Geosite (16°40'9.30"S, 44°37'8.46"W) encompasses an area of 170000 m², situated near the São Geraldo village, within the municipality of Coração de Jesus, in the northern region of the state of Minas Gerais, Brazil (Figure 2). This site contains micro- and vertebrate fossils, a diverse array of sedimentary structures, and intriguing chemical features within a paleoasis context, deposited immediately following the breakup of Pangea, at the end of the Early Cretaceous.

For data acquisition, four field trips were conducted between 2022 and 2023 for rocks and structural reconnaissance, drone surveys, and sample collection. Concerning geoconservation, a qualitative assessment of several sites in the area was conducted during fieldwork, following the four parameters outlined by Brilha (2016), such as representativeness, integrity, rarity, and scientific knowledge. Subsequently, a quantitative assessment of its scientific value, potential for educational and touristic purposes, as well as the risk of degradation, was conducted for the Pripiri site using the GEOSSIT simulator provided by the Brazilian Geological Survey website https://sgb.gov.br/geossit. This simulator adheres to criteria outlined by Garcia-Cortés and Urquí (2009), Brilha (2005), and Brilha (2016), with certain parameters adapted to better evaluate Brazilian specificity.

The scientific value is estimated based on seven criteria: representativeness, key locality, scientific knowledge, integrity, geological diversity, rarity, and use limitations. Considering the evaluation of potential educational and touristic uses, ten criteria are shared, which are vulnerability, accessibility, use limitations, safety, logistics, density of population, association with other values, scenery, uniqueness, and observation conditions. Also, didactic potential and geological diversity are criteria specific for quantifying the educational potential, and interpretative potential, economic level, and proximity of recreational areas are relevant only for the evaluation of potential touristic use. The degradation risk, which is related to human activities, is based on five criteria: deterioration of geological elements, proximity to areas/activities with the potential to cause degradation, legal protection, accessibility, and density of population.

The microfossiliferous and mineral assemblage were observed in 25 thin sections produced at Lamination Laboratory of the Centro de Estudos em Geociências, Universidade Federal dos Vales do Jequitinhonha e Mucuri (CeGeo/UFVJM) and now included in the repository of the Laboratory of Paleontology of CeGeo/UFVJM in serial number from C.LAM-19 through C.LAM-23. Thin sections were analyzed under a petrographic microscope Zeiss, model AxionVision 2.0, coupled to acquiring and analyzing image system at the Microscopy Laboratory, also at UFVJM.

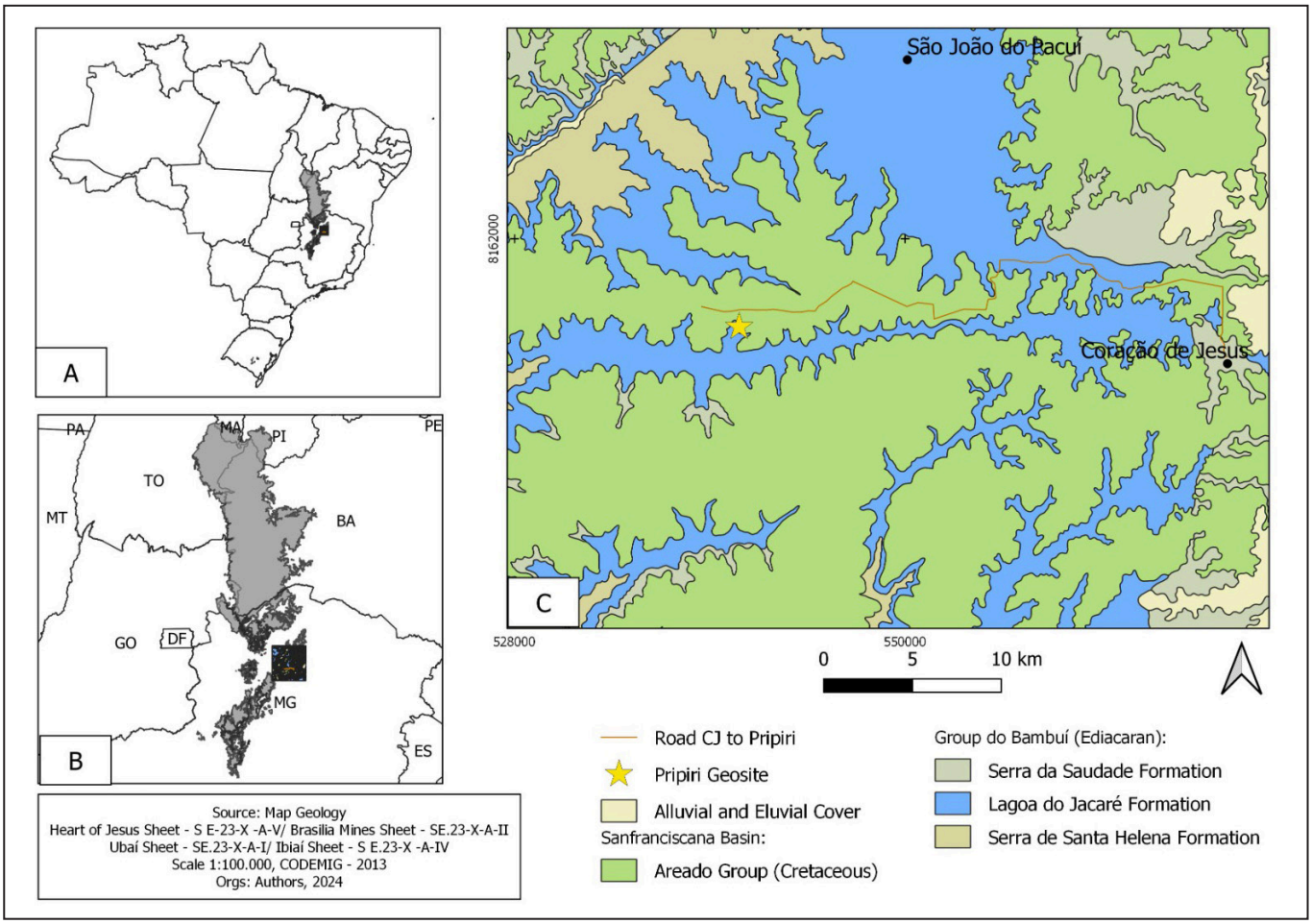

Figure 2. Geological map of Sanfranciscana Basin and the localization of Coração de Jesus municipality and the Pripiri Geosite. A: The Sanfranciscana Basin in the context of Brazilian territory. B: Detail of Sanfranciscana Basin in central Brazil. The color square corresponds to the image in C. C: The geological context of Pripiri Geosite and the access route from Coração de Jesus (CJ) to the site.

4. Results

4.1. New paleontological data and its paleoenvironmental context at Pripiri Geosite

The data collected at the Pripiri Geosite showed that it records approximately 30 meters of pelite-fine sandstone strata alternating to decimetric medium to coarse tabular sandstone bars, resulting in decametric sedimentary cycles (Figure 4a). Pelite strata are light beige to dark brown, with centimetric layers containing a considerable amount of highly friable fine to medium sand. Sandstone bars are reddish to brown, well-cemented, and represent the levels responsible for the stability of the entire outcrop (Figures 4a). Distinct evaporitic features occur from the middle portion of the succession upwards. Sandstone bars contain abundant millimetric white globular structures, randomly distributed among the grains, identified as popcorn and cauliflower-like evaporitic structures (Figures 4c and 4d). They may also appear in the pelite strata at the top of the succession. Decimetric anhydrite crystals also comprise the evaporitic features of this succession and were identified at the uppermost pelite level (Figure 4e). According to petrographic analysis, these structures comprise pseudomorphs of salt and Ca-sulfate replaced by calcite.

The newly discovered paleontological record of Pripiri Geosite includes vertebrate macrofossils and an abundant microfossiliferous assemblage, including dinoflagellate cysts (dinocysts), Euglenaceae green algae, and cyanobacteria. The former ones were recovered in two pelite levels in the middle portion of stratigraphic succession, while the organic-walled microfossils were recovered in the sandstone bars.

The new macrovertebrate record comprises hundreds of long-bone fragments and one rib (Figures 5a-b). Based on the paleontological context of other sites at Coração de Jesus, and due the size of the rib bone and fragments, they are tentatively attributed to archosaurs. However, since they are highly fragmented and poorly preserved, they are not very informative and cannot be classified taxonomically, similar to previously described occurrences in the Sanfranciscana Basin, as noted by Bittencourt et al. (2015).

The organic-walled microfossils were observed in thin sections and occur as microbial mats associated with popcorn structures and centimetric to decimetric anhydrite crystals (Figures 5c-d). The microbial mats presented eukaryotic

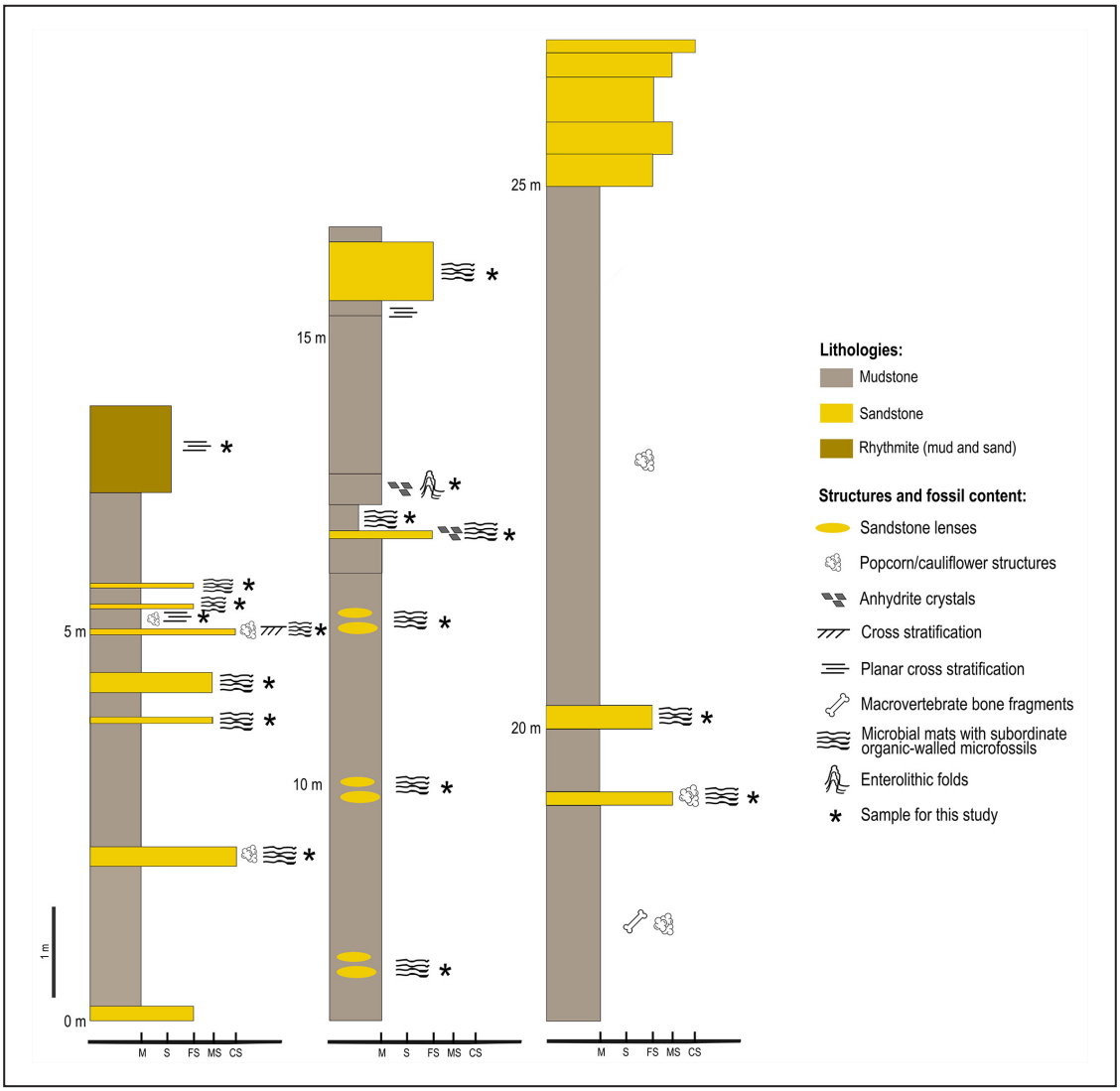

Figure 3. Simplified stratigraphic column of Pripiri Geosite showing the its evaporitic feature and the fossiliferous levels. The granulometric scale stands M for mud, S for silt, FS for sine sandstone, MS for medium sand, and CS for coarse sand.

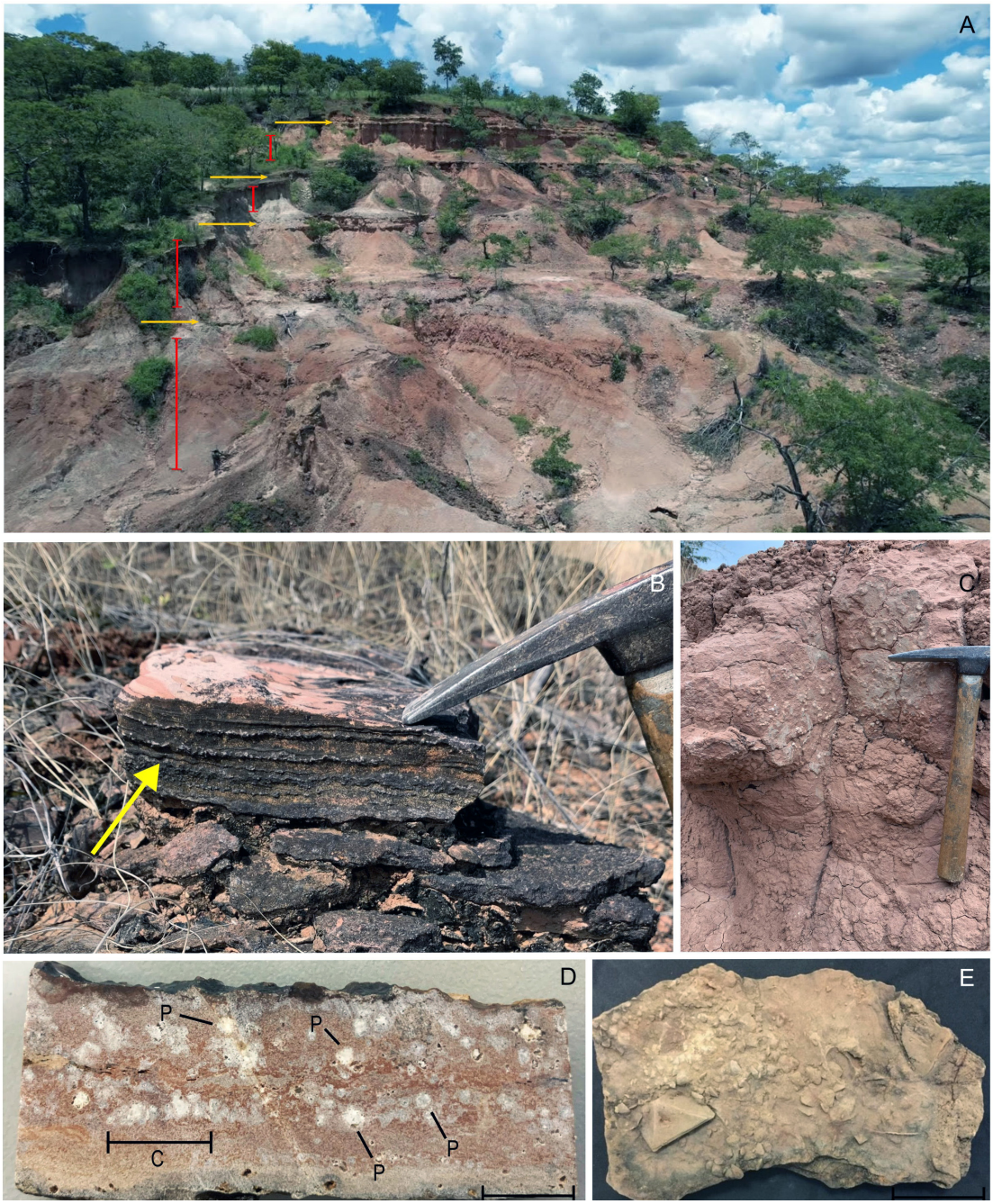

Figure 4. GImportant sedimentary aspects of Pripiri Geosite. A: The general view of the outcrop showing the sandstone bars (yellow arrows) intercalated with pelite levels (red bars) and the resulting sedimentary cycles. B-D: Evaporitic features in sandstones of Pripiri Geosite. B: Popcorn and cauliflower-like structures *in situ* (yellow arrow) preserved in a well-cemented sandstone bar. C: Popcorns in the topmost mudstone level in the outcrop. D: Hand sample containing both cauliflower-like (C) and popcorn structures (P). E: decimetric anhydrite crystals collected in the middle portion of the analyzed succession. Scales: 1 cm in D and 2 cm in E.

fossils of dinocysts (Figures 5e-f) and green algae of the family Euglenaceae (Figure 5f), as well as prokaryote cells represented by two cyanobacteria taxa (Figure 5g). In Pripiri Geosite material, they occur as abundant and dispersed cells among the former extracellular polymeric substance, now preserved as organic matter within the crystalline net. Detailed studies on their taxonomy and paleoecological potential will be carried out in the next steps of this research.

The mat-forming cyanobacteria taxa include two morphotypes, one filamentous and one coccoid taxon. They were identified based on their morphology, size, and mode of occurrence. The filamentous taxon (Figure 5g) was identified as *Pseudoanabaena* sp., a typical filamentous cyanobacteria found in lacustrine microbial mats and already identified in the fossil record. This taxon comprises simple, short, solitary, straight to slightly waved, unbranched trichomes that may present narrow envelopes. The Pripiri materiallacks tricome cells, meaning that the observed specimens correspond to empty sheaths, fitting all other *Pseudoanabaena* diagnosis features.

The cocoidal taxon comprises empty, single-layered, round to oval sparse cells (Figure 5g), occurring associated with the filaments. Due to their poor preservation and, thus, lack of

informative features, they are attributed either to *Aphanocapsa* sp. or *Chroococus* sp. Both taxa fit the morphology, ecology, and mode of occurrence as mat-forming groups and have been identified in the Phanerozoic fossil record.

4.2. Quantitative assessment of Geosite Pripiri

Considering the research undertaken so far, the Pripiri may be classified as a geosite of national importance and relevance (Table 1). Considering the seven criteria to evaluate the scientific value (i.e., representativeness, key locality, scientific knowledge, integrity, geological diversity, rarity, and use limitations), the high score is mainly related to the fact the site is the best-known exposure/outcrop in the area to represent the elements of interest. Also, the fact that there are previous publications regarding its stratigraphy and fossil record in international magazines and chapter books (i.e., Bittencourt et al. 2017, 2022; Cabral et al., 2021). There are at least four types of geological scientific interest, such as paleontologic, stratigraphic, astrobiologic, and evaporitic layers for paleoenvironmental analysis.

In contrast, the tourism and educational values of Pripiri Geosite presented low rates in almost all parameters, mainly due to a lack of appropriate infrastructure. Aspects such as security, accessibility, vulnerability, and exclusivity received a score of 1. On the other hand, logistical support, regional singularity, infrastructure for landscape and geological features observation, infrastructure for tourism activities, and the requirement for intense outreach activity received a score of 3. The educational potential and geological diversity, key aspects for a geoheritage and geoconservation role, received a score of 4. The sum of these scores classified the Pripiri Geosite as of national importance.

The evaluation of the degradation risk, represented in table 1 by the drawbacks, included several aspects related to the possible loss of this rock record. It assessed the likelihood of deterioration of all geological features due to erosion and the impact of cattle grazing. Despite its restricted nature, the geosite is not classified as an area susceptible to protection under any environmental law or statute. Another negative aspect identified during the evaluation in the GEOSSIT system is related to difficulties in accessing the site: even though the site is less than 1 kilometer from the main access road, it is not easily accessed by those who do not know the region or the farm where it is inserted, and there is currently no direct route. To access the geosite, one should follow the unpaved road

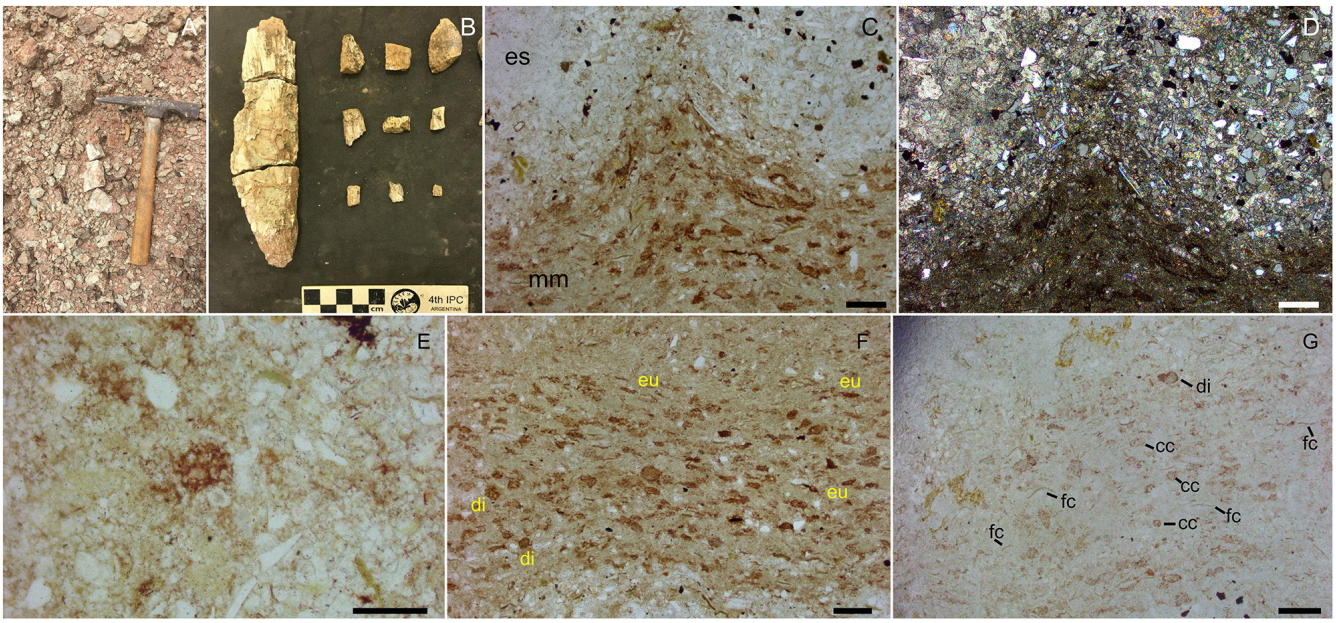

Figure 5. SiFigure 5. The newly discovered paleontological content of Pripiri Geosite. A: fragments of putative archosaur in the outcrop. B: fragments and one partially preserved rib. C-D: microbial mats associated with pseudomorphs of evaporitic minerals in parallel nicols (C) and crossed nicols (D); mm= microbial mat, es= evaporitic structure. Note in C the interaction between the microbial laminae and the evaporitic pseudomorph minerals, as well as abundant quartz grains in D. E: details of a dinocyst. F: dinocysts and Euglenaceae cells embedded in a former extracellular polymeric substance of a microbial mat; di= dinocysts, eu= euglenoid cells. Note their deposition as authigenic elements deposited over the mat. G: mat-forming cyanobacteria; fc= filamentous cyanobacteria (*Pseudoanabaena* sp.), cc= coccoidal cyanobacteria (*Aphanocapsa* sp. or *Chroococus* sp.), di= dinocyst.

Table 1. Quantitative Assessment of the Geosite Pripiri and some of its characteristics.

	Scientific value	**Potential educational use**	**Potential touristic use**
Classification and quantification	Geosite of national relevance (215 points)	National relevance (235 points)	Regional or local relevance (145 points)
Positive aspects	Types of interest: paleontology, stratigraphy, mineralogy, paleoenvironment and paleoclimate, Astrobiology	Geodiversity features relevant for all teaching levels	Paleontological and paleoenvironmental interest
Drawbacks	High degradation risk	Safety facilities must be built	Distance and infrastructure

to the São Geraldo village and then follow to the northwest. Figure 2 shows the route to reach the farm where the Pripiri Geosite is located.

Discussion

Numerous fossil-based investigations (e.g. Zaher et al. 2011; Bittencourt et al. 2017; Carvalho and Santucci 2018; Cardoso et al. 2022, 2024) have been conducted to elucidate the hypothesis of a lacustrine origin regarding sediment deposition within the Quiricó Formation. Conversely, some studies still pose some questions about this paleoenvironmental scenario (Bittencourt et al. 2019). According to these authors, based on the fossil assemblage identified in samples of rocks from the Coração de Jesus and Lagoa dos Patos region, it is suggested that some levels of the Sanfranciscana Basin, northern Minas Gerais, were deposited in a continental brackish water environment subject to vertical variation in salinity, but not lake, and thus, more paleontological and sedimentary data are needed for better interpretations.

The concept of salt pseudomorphs reported here (popcorns, cauliflower-like structures, and decimetric salt crystals) is extensively discussed by Cardoso et al. (2022) in other areas of the Sanfranciscana Basin. The authors presented evidence of halite residues within the central portions of calcite nodules. Through various analyses, they hypothesize a shallow saline lake scenario, wherein halite was replaced by calcite during early diagenesis. In this study, we also identified a sedimentary depositional regime represented by intercalation of siltstone and mudstone layers (composed of clay and micrite) with fine to coarse sandstones, evidencing deposition in alternating sedimentary flow regimes and associated with salt pseudomorphs. Microscopic studies showed that these pseudomorphs are replaced by calcite.

Although the environment was averse to life, some fossils were recovered at the Pripiri Geosite. Despite their low abundance, these fossils hold significant value. Macrofossils are very fragmented; however, their occurrence is valuable and paves the way for interpretations beyond paleobiological diversity, allowing future studies of taphonomical approaches applied to sedimentary dynamics of the paleolake. In this sense, the search for other complete macrofossil specimens must continue, similar to the paleontological site of Sesmarias locality also in Coração de Jesus, which is chronocorrelative to the Pripiri Geosite based on its lithostratigraphic succession and only 22 km away from each other.

The new microfossil content is the most promising source of data on the paleoecology and paleoclimate aspects of the Quiricó Formation. The dinocysts and euglenoids microfossils still devoid taxonomic classification, but their occurrences shed light on paleoenvironmental aspects of Quiricó Formation at Coração de Jesus, mainly regarding the understanding of life occurrence and preservation in extreme, arid, and hypersaline environments, as well contributes to the elucidation on climate cyclicity when coupled to the stratigraphic succession observed at the Pripiri Geosite (Köhher and Clausing 2000). Also, the association dinocysts-Euglenaceae-cyanobacteria may be applicable to interpretation concerning trophic stages in lake environments (e.g. Makri et al. 2019). Although the euglenoids and dinocysts comprise the phytoplankton components, they were observed among the cyanobacteria cells as mat dwellers, not mat-forming components. Finally, another important insight is that the occurrence of dinocysts points to well-oxygenated waters of the Coração de Jesus paleoasis, following the data of Köhler and Clausing (2000) for Lake Enspel, Upper Oligocene, Germany.

On the other hand, cyanobacteria microfossils were identified to genus level (however, a future reclassification cannot be ruled out), and their occurrence represents a yet-to-be-explored paleoecological window into a Cretaceous paleoasis system. Nevertheless, another outstanding potential may also be explored: as simple, prokaryotic cells preserved in association with salt minerals, these microfossils are of interest to Astrobiology, mainly for the search for past life in the rock record of Mars. If life once existed, it would have inhabited evaporitic oases, like those in Coração de Jesus, as a refuge during the drying period of Mars in the Hesperian Period, 3.6 Ga (Mancinelli et al. 2004). In addition, evaporitic rocks may preserve confident biosignatures (e.g. microfossils of halophilic bacteria) due to their short-term, aqueous deposition, and paleoenvironments like this have been pointed out as good targets for the search of past life on Mars for the next missions (Barbieri and Stivaletta 2011). Therefore, the occurrence of prokaryote records in an evaporitic-rich rock from Coração de Jesus fits the model for the life conditions on Mars during the Hesperian, and thus, this material would serve as a template for the search for past life on our neighboring planet.

Looking at the Pripiri Geosite through the prism of geodiversity and geoheritage, the criteria *representativy* enhances the importance of this geosite on the quantitative assessment (Brilha 2016). Its fossil assemblage, combined with the well-exposed stratigraphic content (it is certainly the best outcrop in the region to observe the relevant geological aspects) and the paleoenvironmental and paleoclimatic data preserved at Pripiri Geosite, support its national scientific value and relevance for Geoscience. Taken together, all these geological features also imply a high educational potential that may be applied at all levels of the Brazilian educational system.

Regarding its touristic use, factors such as its distance from the city (approximately 40 km from downtown), road conditions, access to the geosite, lack of other attractions, and poor scenic view are characteristics that decrease its potential. In addition, it must be taken into consideration that some knowledge of sedimentary processes, rock formation, and paleontology may be necessary to comprehend the geodiversity features of the site, which may complicate tourist activity. Special attention during the development of interpretation material is required to overcome this disadvantage. Also, infrastructure and facilities must be built for visitors, including those intended for students.

The brittle condition of rocks, coupled with geomorphology and land use, favors erosion processes. In addition, the lack of specific legislation to protect the area implies a high risk of degradation. Considering that the City Hall of Coração de Jesus intends to promote the geosite for education activities and tourism, careful planning and attention are necessary. Especially because, as discussed by Brilha (2016), a high degradation risk coupled with a high scientific value requires special attention to conciliate the preservation of the site and the educational and touristic uses.

Considering its scientific relevance and the social context in which the geosite is located, its use in educational activities and geotourism is desirable. Its potential would be amplified if actions were taken to associate and include other geosites and geodiversity sites in the vicinity. It should be noted that

a series of actions regarding the geoheritage of Coração de Jesus has been carried out by the Universidade Federal dos Vales do Jequitinhonha e Mucuri since 2022, in technical cooperation with City Hall of Coração de Jesus. Several lectures and classes with students of elementary and high school ages, as well as teachers, have been promoted, focusing not only on the geoheritage of Coração de Jesus but also on its potential for local economic development and social improvement through geotourism and geoconservation (following the ideas of Nascimento et al. 2015). These actions may stimulate a sense of belonging among residents while promoting the geoheritage. The development of geotourism in this context might occur in the future, only if educational activities are consolidated.

Conclusions

This study provides new insights into the fossil content of the Pripiri Geosite and the fossil record of the Sanfranciscana Basin and highlights its value for geotourism and geoconservation. The occurrence of newly reported eukaryotic and prokaryotic unicellular microfossils, which are significant for paleoenvironmental, paleoecological, and astrobiological analysis, was discussed. The abundance of microfossils in this succession shed light on paleoenvironmental aspects of Coração de Jesus paleoasis, and helps to understand the occurrence and maintenance of life in extreme environments, with important implications for the search for past life on Mars. Taken together, these findings and their contributions make the Pripiri Geosite an important Brazilian paleontological site.

In relation to geoconservation, the excellent exposure to the stratigraphic succession and the paleontological content coupled with the paleoenvironmental data reinforce the scientific, touristic, and educational relevance of the Pripiri Geosite at a national level. This scenario is going to be useful as a tool for social and economic development in Coração de Jesus municipality.

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Authorship credits

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C - Data Interpretation/ Validation **D** - Writing
E - Review/Editing **F** - Supervision/Project administration

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Oligocene – Miocene Angiosperm Fossil Site at the Boa Vista Basin, Paraíba State, Northeast Brazil

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Abstract

The Boa Vista Basin consists of a half-graben controlled by the extensional reactivation of the Serra do Monte Shear Zone, situated within the Transversal Zone, Alto Moxotó Domain of the Borborema Province. The basin was filled by a volcanic-sedimentary sequence characterized by basaltic flows, lacustrine bentonitic clays, and fluvial sandstones and conglomerates of the Campos Novos Formation. The age of the overlying basalts indicates the Oligocene-Miocene boundary. The palynomorph association observed in the Campos Novos Formation presents a preliminary age from the upper Eocene to the lower Oligocene. We identified the fossil material in the sandstones and bentonitic clays. The massive lithic arkosic sandstones present planar and trough cross-bedding and include pieces of silicified wood up to 2 m in length. The bentonitic clays present greenish, light brown, and dark brown colors, with fossil remains identified at the levels of greenish and light brown bentonitic clays in the Juá II and Bravo mines. About 200 specimens of leaves, fruits, and wood fragments were collected at these site, associated with ichnofossils in vertical and horizontal tubes. Among the numerous and varied leaf remains preserved as impressions, Fabaceae, Annonaceae, Lauraceae, Burseraceae, Anacardiaceae, Myrtaceae, and Malvales types dominate. The set attests to a tropical to subtropical flora, similar to elements that grow in the coastal areas of the state of Paraíba today. Some morphotypes are also characteristic of drier regions of Central Brazil. This set has preferential affinities with globally dry and locally humid environments. It seems to have a good relation with the more arid phases that accompanied the global temperature drop intervals at the Oligocene-Miocene boundary, supporting the geological age data.

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1. Introduction

This study presents an angiosperm fossil site identified from collection activities in open-pit bentonite mines of Juá II and Bravo, located on the eastern edge of the Boa Vista Basin. The dissemination of this paleontological site aims to stimulate the continuation of research in the area, which is highly vulnerable, and to highlight the importance and potential for telling the story of the Cenozoic in the region. The Boa Vista Basin (BVB) is located in the municipality of Boa Vista, in the state of Paraiba, covering an estimated area of 25 km², including volcanic rocks. The basin occurs over the Precambrian rocks of the Transversal Zone, Northeast of the Borborema Province, and its deposition is bounded to the south and southeast by the reactivated portion of the Serra do Monte shear zone (Figure 1). This site presents at least 24 taxa, including a new species, belonging to seven botanical families with taxonomy, phylogeny, and affinities with fossil floras known for the Cenozoic in tropical basins and with modern analogous floras.

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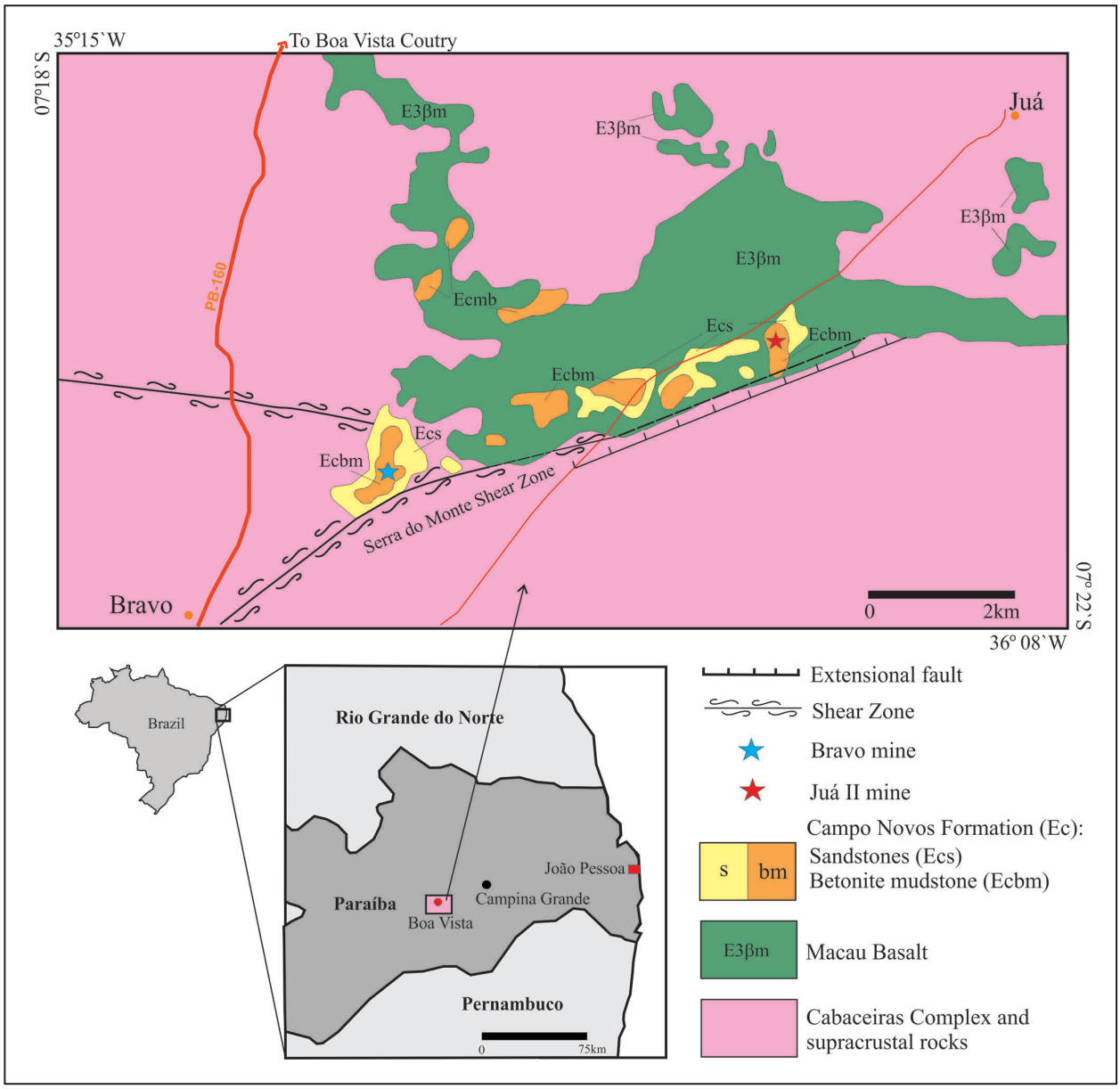

Figure 1. Location map of the Boa Vista Basin and the fossil sites of the Juá II and Bravo Mines.

2. Geological setting

The Boa Vista Basin consists of a half-graben (Figure 2), filled with a sequence of volcanic-sedimentary and sedimentary rocks. The structural control is driven by a system of interconnected extensional faults and dip-slip normal faults with NE-SW directions, related to the extensional reactivation of the Serra do Monte shear zone in the southern and southeastern parts (Souza et al. 2005; Lages 2017). This basin rests on rocks from the Alto Moxotó Domain (Zona Transversal, Borborema Province), represented in the area by migmatized orthogneisses from the Cabaceiras Complex and supracrustal rocks, as highlighted by Caldasso (1965), Barbosa and Souza (1999a), Souza et al. (2005), and Lages (2017).

The Boa Vista Basin is filled with a volcanic-sedimentary sequence, characterized by flows of olivine basalts, lapilli tuffs considered as part of the Macau Formation, from the Macau-Queimadas alignment, similar to the basalts occurring in the Macau-RN region (Souza et al. 2005), and sedimentary deposits of fluvio-lacustrine origin, formalized as the Campos Novos Formation (Holder Neto and Silva 1974). The volcanic rocks occur as irregular flows approximately 30 km in extent and E-W/WSW-ENE direction and are divided into lower and upper flows. The lower flows are massive and composed of vesicular to scoriaceous olivine basalts, invariably altered in sharp contact with the basement. The upper flow consists of olivine basalt, which caps the sediments of the Campos Novos Formation. They have textures of pillow lavas of various sizes and shapes, fragmented vitreous edges forming hyaloclastites, lapilli breccias between the pillows occurring as intrusions in aerial and sub-aquatic conditions, and whose rapid cooling is indicated by the fine grain of the flows. Effusive, glassy, aphanitic, commonly vesicular to pumiceous rocks, and pyroclastic varieties (lapillites) can be observed in the capping of the Juá II mine (Barbosa and Souza 1999a,b; Petta and Barbosa 2003; Lages 2017). The volcanic rocks are basalts

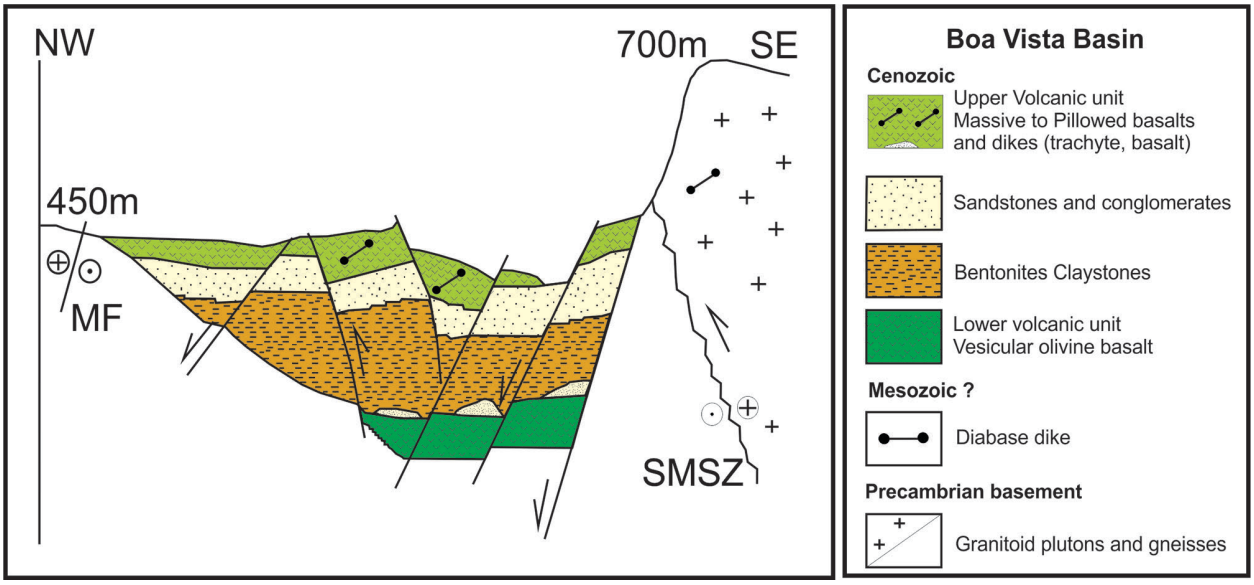

Figure 2. Schematic section of the Boa Vista Basin, NW-SE direction. Legend: The main faults are SMSZ, Serra do Monte Shear Zone, and MF, main fault (modified from Souza et al. 2005).

and basaltic andesites of ferro-tholeiitic affinity enriched in light rare earth elements and potassium poor (Souza et al. 2005; Lages 2017). The ages of these rocks were discussed by Souza et al. (2005), who synthesized the geochronology of the Macau-Queimadas alignment, indicating K-Ar ages ranging from 13 to 42 Ma, with ages in the BVB around 30 ± 6 Ma and 24-25 Ma, leading the authors to assume an Oligocene-Miocene age. Souza et al. (2013) dated the lower and upper basalts in the Boa Vista Basin at 27.3 ± 0.8 Ma and 25 ±1.3 Ma to 22.5 ± 0.2 Ma, respectively, using the 40Ar/39Ar technique.

The Campos Novos Formation comprises layers of bentonitic clays, friable or silicified sandstones, and clast-supported conglomerates. The bentonitic clays are fossiliferous, with color variations (brown, green, dark brown) according to the chemical composition of the clay minerals, and are interpreted as originating from the alteration of pyroclastic materials (ashes and tuffs) in a lacustrine environment (Barbosa and Souza 1999a). The friable or silicified sandstones of fluvial origin are predominantly composed of quartz, feldspars, and volcanic-clastic fragments, sometimes fossiliferous. These sandstones can be massive or with planar and through cross-bedding. The clast-supported conglomerates are polymictic, contain mainly quartz and volcanic rock grains, and occur in basal sections related to fluvial channels (Caldasso 1965; Caldasso and Andrade 1979; Barbosa and Souza 1999a; Dias et al. 2004; Lages 2017). In the palynological study by Roesner et al. (2004) of the bentonitic clays, the palynofacies were described, consisting essentially of amorphous organic matter, with an indication of restricted sedimentary input. The authors also suggest an age range from the upper Eocene to the lower Oligocene based on palynological association.

3. Materials and Methods

The fossil content discussed in this work was partly collected during field activities for the geological mapping project of the Boqueirão Sheet (Lages and Marinho 2012) by the Geological Survey of Brazil (SGB-CPRM) and partly during two expeditions (2011 and 2012) jointly conducted by the SGB-CPRM and the Life and Earth History Laboratory (LaViGaea) of the University of Vale do Rio dos Sinos (UNISINOS). There are 201 samples from the basal levels of the bentonitic clay layers of the Juá II Mine (UTM coordinates 812024/9187673) and the Bravo Mine (UTM coordinates 807649/9189873). Paniz (2015) and Dutra et al. (2023) described the identifications and diagnoses. The specimens are deposited in the Life and Earth History Laboratory (LaViGaea) collection at the University of Vale do Rio dos Sinos (UNISINOS).

4. History of paleontological studies

Paleontological research in the Boa Vista Basin is recent, with the earliest works mentioning the occurrence of fossil specimens without analysis or diagnosis. Caldasso (1965) published the first article describing the presence of fossilized trunks in a life position, with preserved roots in the basal layers of the Campos Novas Formation. Petta and Barbosa (2003) cited fossils such as leaf impressions, fish, and fragments of silicified wood. Barbosa and Souza (1999a) identified ichnofossils (tubes) and silicified woods. A palynological study highlighted a predominantly pollen association, with rare spores and absence of dinoflagellate cysts, where species such as *Margocolporites vanwijhei, Retitricolporites americana (?), Retitricolporites amapaensis, Retitricolporites quadrosi, Retitricolporites guianensis, Retitricolporites amazonensis, Verrucatosporites cf. V. usmensis, Perfotricolpites digitatus, Scabraperiporites nativensis, Monocolpites sp., Echiperiporites estelae, Echiperiporites akanthos, Monoporites annulatus, and Proxapertites spp.*, also occur *Cicatricosisporites spp.* and *Botryococcus spp* are notable (Roesner et al. 2004).

The geological mapping conducted by the Geological Survey of Brazil systematically collected the fossiliferous content found during field activities for identification, including fossil specimens of leaf impressions and fruits, characterizing the first occurrence of an angiosperm flora in the basin (Moura et al. 2008). The occurrence of a taphoflora composed of leaves, leaflets, fruits, and flower fragments

of a monocotyledon, with a predominance of families such as Fabaceae, followed by Lauraceae, Annonaceae, Burseaceae, Anacardiaceae, Myrtaceae, and Malvaceae was described by Paniz (2015). Dutra et al. (2023) described a new genus and a new species for the family Fabaceae (Detarioideae), with well-preserved tissues that allowed attribution to *Goniorrhachisinoxylon sergioarchangelskii*, also identifying a seasonal climate (possibly monsoons) for the late Oligocene, in the Northeast region of Brazil.

5. The Fossil Site of Juá II Mine and Bravo Mine

Researchers of the Geological Survey of Brazil collected the fossil occurrences described in this work at the Juá II Mine and the Bravo Mine (Figure 3). The geology of these fossil sites is represented by the siliciclastic sediments of the Campos Novos Formation, characterized by pelitic, arenaceous, and conglomeratic facies (Table 1) of a fluvial-lacustrine system, capped by basalt flows.

The pelitic facies are represented by bentonitic clays (Bm), which occur as massive and hardened, with colors varying from green, light brown to dark brown, where the color reveals the variation in the chemical composition of the clay minerals, such as illite, montmorillonite, smectite, and kaolinite. The most important specimens of plant fossils in the basin were collected in these facies. The green bentonitic clays, with an approximate thickness of 9m, contain few fossils preserved in molds and impressions. The lighter brown clays have an average thickness of 30m and present many plant fossils (leaves, fruits, flowers, and fragments of wood and roots in life position) and some ichnofossils. No fossil content was identified in the dark brown bentonitic clay, considered the main mineral deposit of bentonite (Figure 4). The pelitic layers (bentonitic clays) are interpreted as originating from the deposition in a lacustrine environment by volcaniclastic material in suspension.

The arenaceous facies are represented by arkosic to lithic arkose sandstones with planar cross-bedded (Sp), trough cross-bedded (St), and massive (Sm), according to the classification of fluvial lithofacies by Miall (1996). These facies locally occur in discordant, erosive contact with the Bm facies. In this facies, silicified wood up to 2m in length was identified, some in life position (Figure 5). Finally, the facies of clast-supported conglomerates (Gcm) occur as massive (Table 1) and are associated with the massive sandstones in fluvial channels (Figure 6).

In the Juá II Mine, basalts with pillow lava structures were described (Figure 7), massive and sometimes with vesicular to pumice aspects, isotropic in appearance and with a fine grain, dark gray showing rounded pockets sometimes filled with carbonates. Under the microscope, they display diabasic to ophitic textures with the mineral plagioclase (46%), augite (44%), and olivine (<1%), primary and secondary opaque minerals (7%) and secondary carbonates fill the vesicles (2%). Chemically, they belong to a subalkaline (low-potassium tholeiitic) suite with low concentrations of Zr, Sr, Ni, Nb, and MgO, containing normative olivine+hypersthene or quartz+hypersthene (Lages 2017).

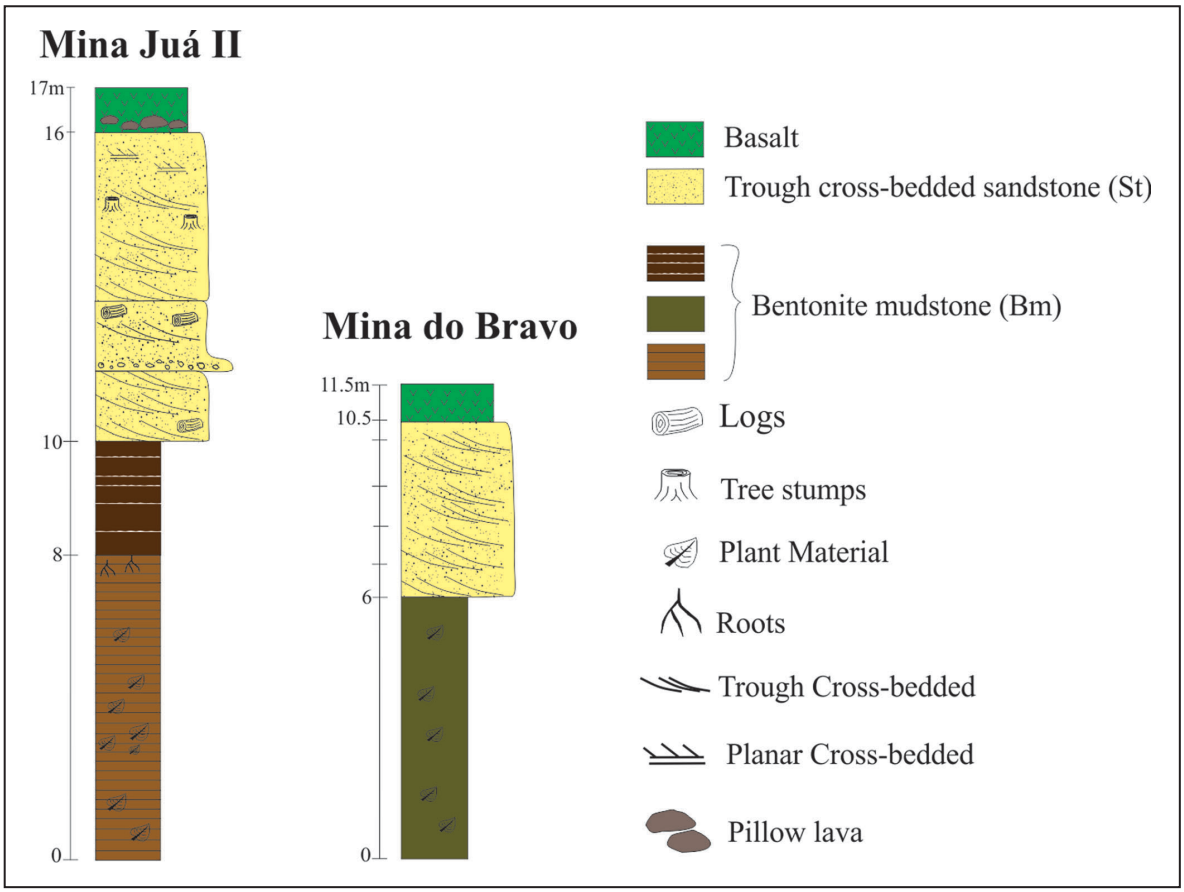

Figure 3. Composite profile of the Juá II Mine and Bravo Mine.

Table 1. Classification of lithofacies (adapted from Miall 1996).

Facies code	Facies	Description	Interpretation
Gcm	Clast-supported gravel	Well-selected, ranging in size from pebbles to cobbles, polymicts also occur, containing clasts of quartz and volcanic rocks. Locally in contact with volcanic rocks and sometimes with sandstones	Pseudoplastic debris flow (turbulent flow)
Sp	Planar cross-bedded sandstone	Medium to coarse grains, gray in color, arkose to lithic arkose	Dunes of sandstone with straight crest (2D) of linguoid type
St	Trough cross-bedded sandstone	Fine to pebbly grain, gray in color, with pebbly layers, composed essentially of quartz	Dunes of sandstone with sinuous crest (3D) of linguoid type
Sm	Massive sandstone	Fine-grained, coarse, gray, composed of quartz and strongly silicified	Sediment gravity flow deposits
Bm	Betonite mudstone	Compact and hardened, with colors varying from slime green, light brown to dark brown. Levels of siliceous concretions are observed, locally oriented. Root marks between the layers.	Precipitation of suspended sediment caused by alteration of pyroclastic materials in a lake environment

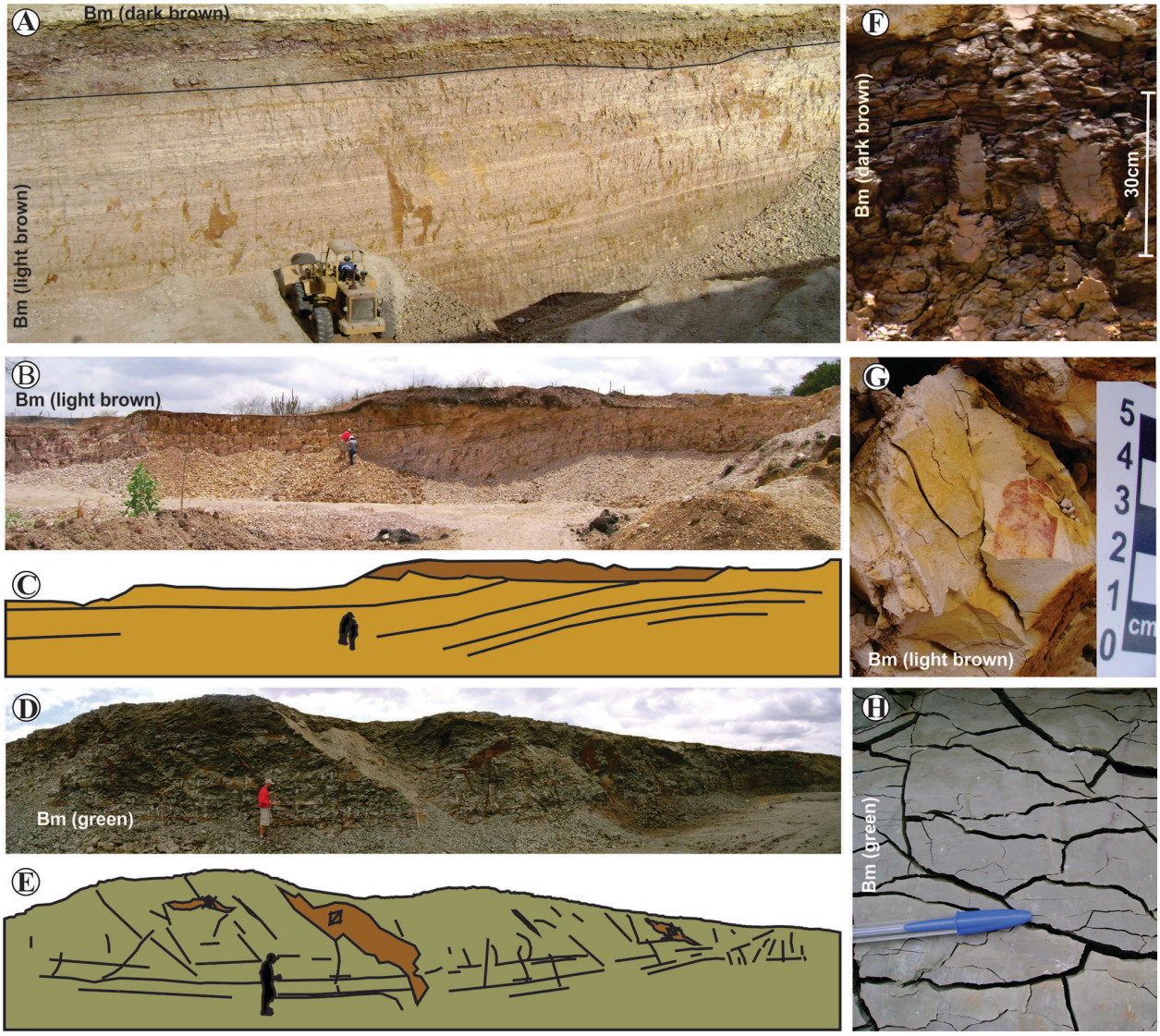

Figure 4. A) Relationship of the Bm facies, where the lighter brown presents extensive fossil material, and Bm dark brown lithofacies (top), these facies are absent of fossils. B) Light brown Bm facies, with a schematic drawing of the occurrence mode in C). D) Green Bm facies and E) its occurrence mode in the schematic drawing. F) Detail of the dark brown Bm facies. G) Detail of the light brown Bm facies. H) Detail of the green Bm facies.

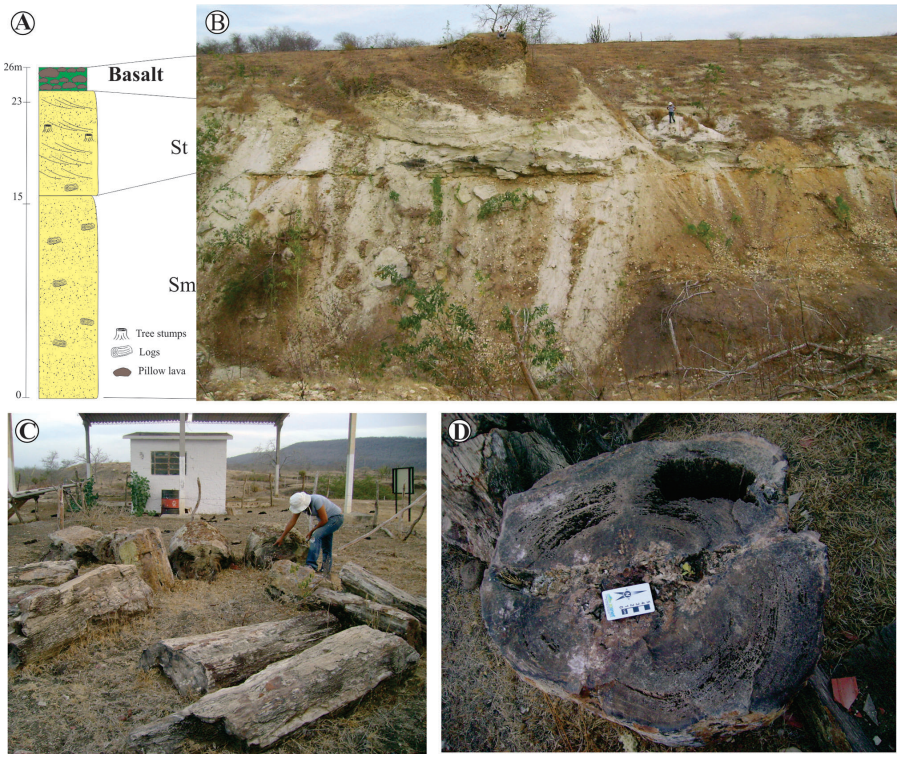

Figure 5. A) the Juá II mine pit's profile shows the presence of arenaceous facies containing fossil trunks. B) Outcrop with the relationship of the Sm and St lithofacies covered by the basalt flow. C) Fossil trunks collected and stored at the Juá II Mine. D) Detail of the fossil trunk.

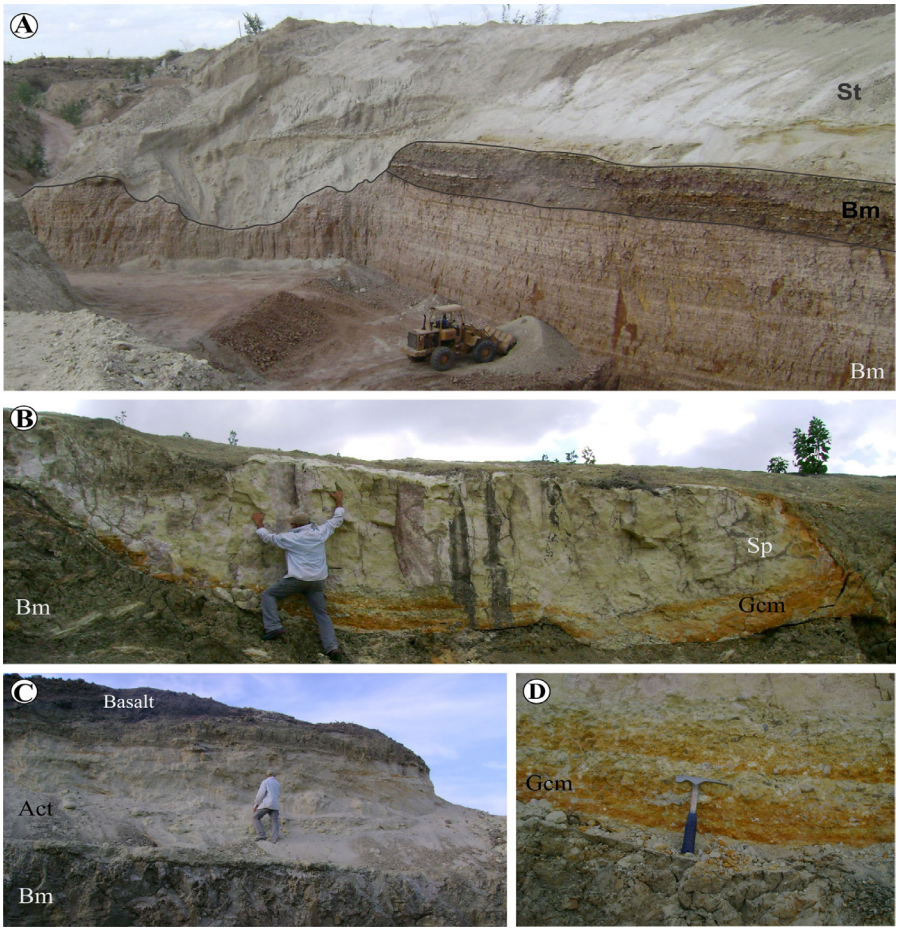

Figure 6. A) Discordant relationship of the Bm lithofacies with the St lithofacies associated with fluvial channels. B) The Fluvial channel with Sp and Gcm facies is in discordant contact with Bm facies. C) Basalt covering the Sp Facies. D) Detail of the Gcm facies.

6. Fossil content

In the light brown bentonitic clay facies, leaves, fruits, and wood fragments were identified, accompanied by ichnofossils in vertical and horizontal tubes (Figures 8 and 9). Autochthonous roots were also observed. The numerous and varied leaf impressions are dominated by laurophyllous, membranous, or coriaceous morphotypes characterized by smooth margins and brochidodromous venation. Some impressions show a reasonable preservation of third-order veins, which allows us to approximate their taxonomic affinities. The ensemble attests to a tropical to subtropical flora, with elements that still grow in the coastal areas of the same region today, with a dominance of leaves and leaflets related to the families Lauraceae, Fabaceae (aff. Caesalpinioideae), Anacardiaceae (aff. *Anacardium occidentale*), and Apocynaceae. These forms are also present in the drier inland areas of Central Brazil. The rarer forms are linked to the families Annonaceae, Tiliaceae (*Luehea* sp.), Chrysobalanaceae (aff. *Licania* sp.), and Burseraceae (aff. *Commiphora* sp.).

Paniz (2015) presented 24 taxa, including a new species, belonging to seven botanical families. These taxa have affinities with fossil floras known from tropical basins in the Cenozoic and with modern analogous floras (Appendix 1).

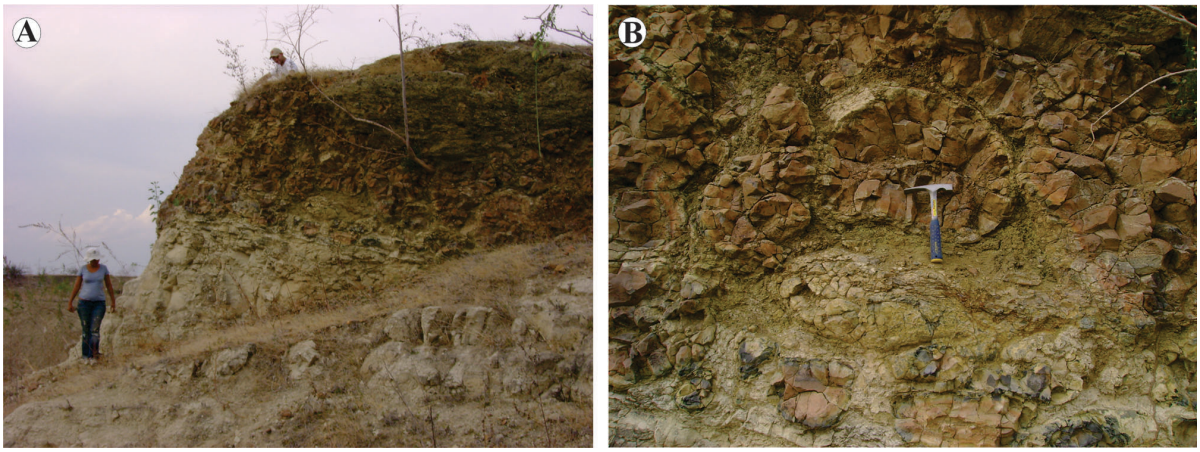

Figure 7. A) The main section shows the relationship of the St facies with the pillow lavas. B) Detail of the pillow lava texture.

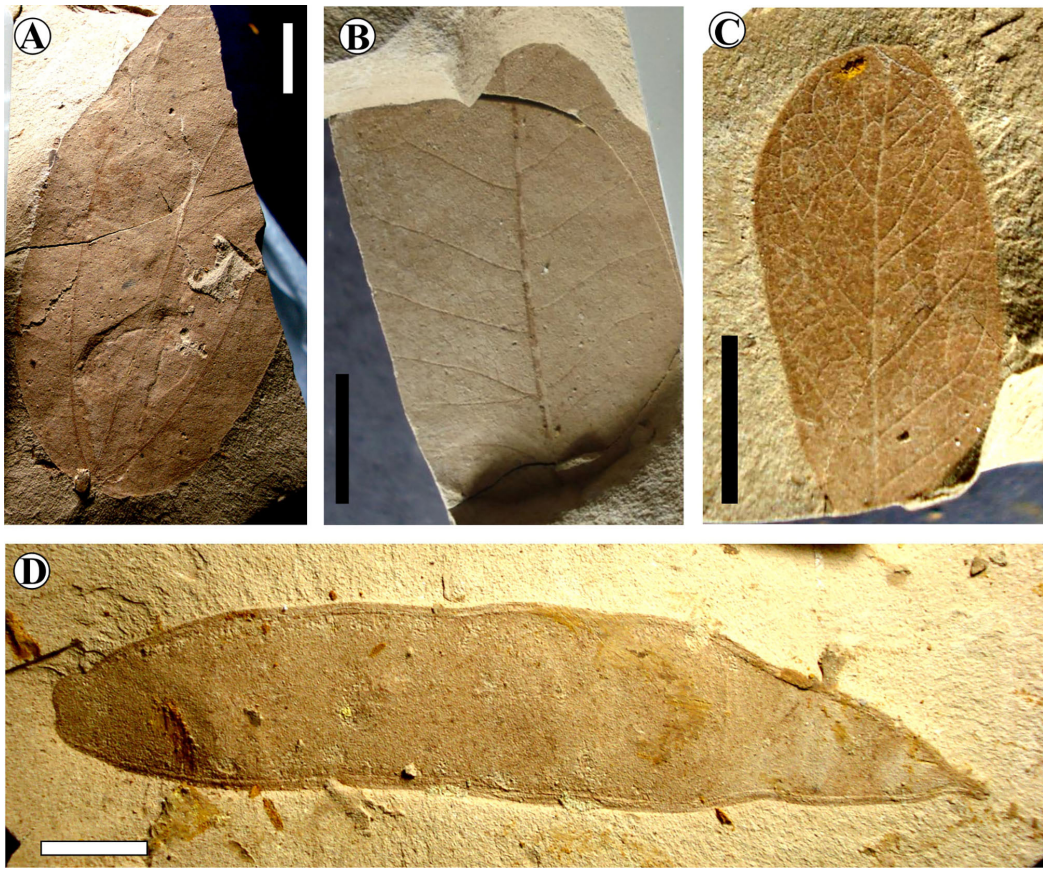

Figure 8. A) *Luheopsis* cf. L. *hoehmei* Burret (CPRM-CM 0232F). Family Malvaceae; B) *Anacarduim aff. Anacarduim occidentalis* (CPRM-CM0223F); C) *Dinizia aff. D. excelsa* Ducke (CPRM-CM0226); D) *Leguminocarpum paraibensis* Paniz (CPRM-CM0228F) (Paniz 2015). The scale bar is equal to 1 cm.

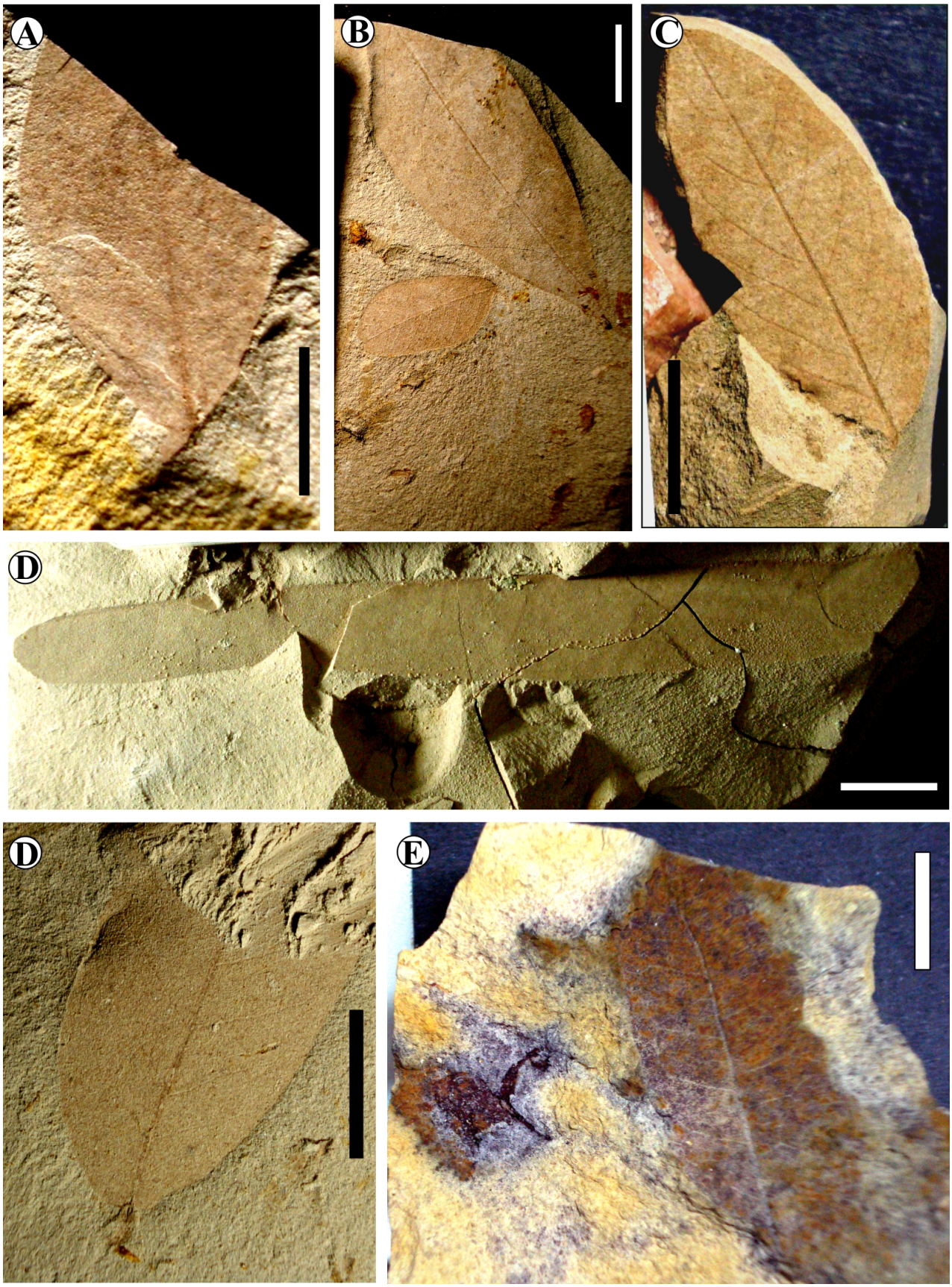

Figure 9. A) Laurophyllous morphotype related to the Apocynaceae family; B) Bottom left corner *Cassia* sp. (family Fabaceae) and *Nectandra* sp. family Lauraceae (1); C) *Dicotylophyllum* sp. 2. D) *Typha* sp., family Typhaceae, monocotyledon. D) Laurophyllous morphotype related to the Annonaceae family (1); E) probable element of the Sapindaceae family. The scale bar is equal to 1 cm.

7. Discussions and Conclusions

The bentonitic clays of the Campos Novos Formation constitute a significant deposit for the region's economy. The material studied was collected along the pits for clay extraction at the principal mines. Continuing the collection of fossil material, in partnership with mining companies, would be a path to broaden knowledge about the region's flora during the Cenozoic. From the analysis of this fossil ensemble described by Paniz (2015) and Dutra et al. (2023) in the Boa Vista Basin, it was possible to understand that there is a preferential affinity of this flora with regionally dry environments, but which are formed in humid areas. This affinity indicates that the environments, at the time of deposition, were characterized by dry climates, with rain seasons concentrated in a part of the year, similar to today's climate in the region but with more humidity. It suggests a relationship with the drier phases that accompanied the intervals of global temperature decline at the Oligocene-Miocene and Lower Miocene boundaries, supporting the geological age data. Some of the remains identified, especially those exhibiting morphologies found in the families Tiliaceae, Lauraceae, Annonaceae, and Fabaceae, had already been recorded in Brazil in older levels, in the Fonseca and Aiuruoca basins, in Minas Gerais, and for the Miocene, in the Pirabas Formation, in Pará. The physiognomic characteristics point to a tropical climate with seasonal or prolonged drought. Comparison with other assemblies shows proximity to the middle Eocene to lower Oligocene in central Brazil (Paniz 2015), corroborating the isotopic age data for the volcanic-sedimentary sequence of the Boa Vista Basin by Sousa et al. (2013). This paleoflora possibly reflects a dispersal (or contraction) of the region towards the tropics.

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Appendix 1

Paleobotany of the Fossil Site at Juá II Mine, Boa Vista Basin (Paniz 2015)

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Journal of the Geological Survey of Brazil

Fossiliferous sites of the southern coast of Rio Grande do Sul state, Brazil: geoheritage records of Quaternary sea-level, climate and environmental changes

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Abstract

The southern coastal plain of Rio Grande do Sul state hosts essential fossil records of both marine and terrestrial faunas that have provided invaluable information about the geological and environmental Quaternary history of southern Brazil. These fossils are found in surface and subsurface deposits on sites stretching from the continental shelf up to coastal lagoons inland. The sites on the shelf are time-averaged lag deposits formed of marine and terrestrial fossils exhumed and mixed together as a result of erosion of the original deposits by sea-level oscillations. Although lacking any precise stratigraphic context, the available numerical dates indicate Middle to late Pleistocene ages. Fossils removed from the shelf by waves today form large *Konzentratt-Lagerstätten* on the beach, called *concheiros*. The sites on continental areas occur in barrier-lagoon depositional systems, and include marine deposits formed under higher than present sea levels formed by Middle and late Pleistocene and Early-Middle Holocene marine transgressions. The fossiliferous sites with well-defined stratigraphic context encompass fluvial and aeolian (loess) deposits and paleosols associated with the Middle-late Pleistocene Santa Vitória Alloformation and Cordão Formation outcropping along Chuy Creek. Fossils of late Pleistocene terrestrial and Holocene marine organisms were collected from the bottom and marginal terraces of Mirim Lagoon. Although most sites are not directly under threat today, their wide distribution poses potential problems for protection. Current protection measures for the sites and associated fossils include requests by environmental agencies for preliminary surveys and fossil rescue programs prior to construction projects, and the proposal of a marine-coastal protected area is currently under consideration. Educational programs with schools and exhibits for the general public executed by the museums in the town of Santa Vitória do Palmar have contributed to public awareness about the importance of the regional paleontological heritage and have produced positive feedback and results that increased the number of known fossiliferous sites in the region thanks to communication by local people. These actions are essential to establish protection measures in case new developments emerge in the future that could threaten the sites and their fossils.

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1. Introduction

The coastal plain of Rio Grande do Sul state (CPRS) (Fig. 1), in southernmost Brazil, is a large geomorphological unit exhibiting a rich geodiversity of coastal features. The CPRS is the uppermost portion of the marginal Pelotas Basin, which encompasses sedimentary and fossil successions spanning from the Cretaceous to the Quaternary (Closs 1970; Barboza et al. 2021b). The sediments that form the Pelotas Basin were eroded from Precambrian rocks of the Sul-Rio-Grandense Shield and Paleozoic and Mesozoic sedimentary and volcanic rocks of the Paraná Basin (Villwock and Tomazelli 1995). Those sediments were accumulated on the continental margin after the opening of the Atlantic Ocean in the form of depositional systems, i.e., chronocorrelated facies associations that include an older Alluvial Fans System of Miocene-Pliocene? age, plus four Quaternary Barrier-Lagoon Systems and the adjacent continental shelf (Closs 1970; Villwock et al. 1986; Villwock and Tomazelli, 1995).

The Barrier-Lagoon Systems are the dominant geomorphological features of the CPRS, being the largest depositional systems of this type found along the Brazilian coast, and consist of long sandy barriers that isolate large coastal lagoons on the backbarrier lowlands (Villwock et al. 1986; Villwock and Tomazelli 1995). The older Barrier-Lagoon System II was established during the Middle Pleistocene,

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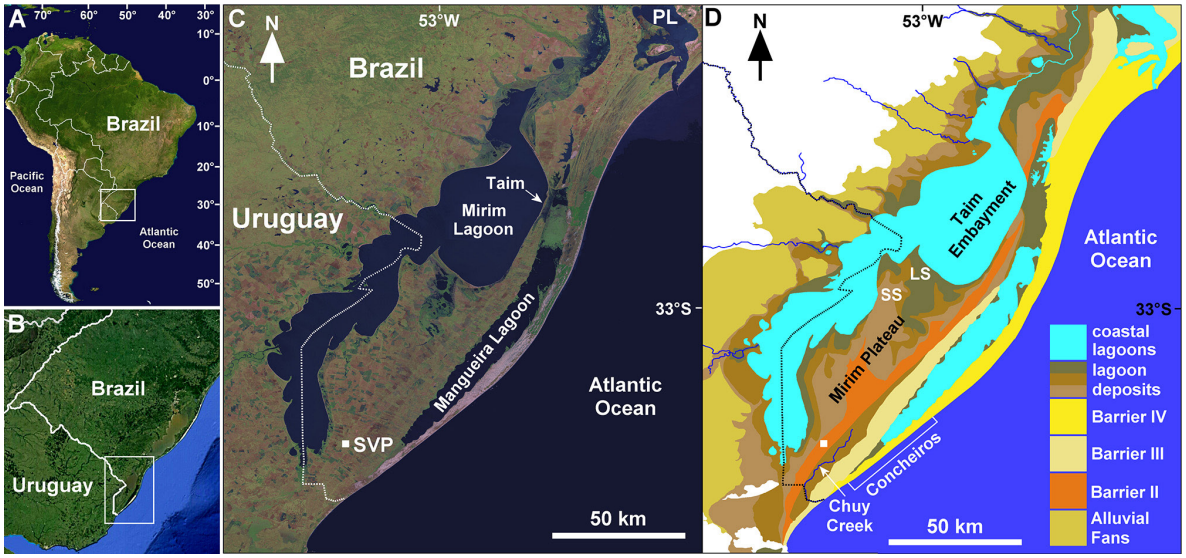

FIGURE 1 - A - Blue Marble image showing the location of Rio Grande do Sul. B - Location of the fossiliferous sites. LANDSAT image (C) and geological units (D) of the southern CPRS, with the fossiliferous sites indicated (not shown are the submerged deposits along the inner shelf and Mirim Lagoon) (PL: Patos Lagoon, LS: Latinos Spit, SS: Santiago Spit).

System III during the late Pleistocene, and System IV during the Holocene (Villwock and Tomazelli 1995; Lopes et al. 2014a). These systems are the result of glacioeustatic oscillations that produced high-frequency depositional sequences integrating a falling stage systems tract (Rosa et al. 2017). During glacial periods, sea level fell several tens of meters below the present, thus subaerially exposing most of the continental shelf. As a result of marine transgressions following the end of a glacial period, the advancing sea level reworked the upper 3-10 meters of the shelf sediments, thus building the coastal barriers that isolated large coastal lagoons on the back-barrier lowlands (Villwock and Tomazelli 1995; Dillenburg 1996).

The geological evolution of the CPRS favored the development of fossiliferous deposits that contribute to the rich geodiversity and geoheritage of the southern Brazilian coast. These deposits contain remains of different groups of organisms, including both marine and terrestrial species of invertebrates and vertebrates. Although such fossils are found along the entire CPRS, it is on the southern sector, between the estuary of Patos Lagoon and the mouth of Chuy Creek (Fig. 1), that such remains are more abundant. The fossils preserved along this area are important because they help to understand the geological evolution of the coastal plain, provide information on the marine and terrestrial faunas that inhabited the region in the past, and allow us to assess how climate changes throughout the Quaternary affected the environments and ecosystems in southern Brazil.

2. The fossiliferous sites of the southern CPRS

The oldest known published records of fossils from the southern CPRS date back to the late 19th century, when the naturalist Herrmann von Ihering described molluscan shells found near the town of Rio Grande and the locality of Santa Isabel on the eastern bank of São Gonçalo Channel that connects Mirim and Patos Lagoons (Fig. 1) (Ihering 1885, 1907). Later surveys and studies have shown that the fossils preserved in the southern CPRS occur essentially in two settings (Fig. 1D): 1) from the inner continental shelf to the beach, and 2) across terrestrial areas associated with the Barrier-Lagoon Systems II and III.

2.1. Submarine and coastal sites

The continental shelf stretching between southern Brazil and Uruguay is a low gradient (0.03º to 0.08º) prominent geomorphological feature measuring ~130 to 160 km in width, devoid of rocky features except for submerged linear rocky banks (Delaney 1965; Dillenburg and Barboza 2014; Caron 2014). Because the establishment of the barrier-lagoon systems since the Middle Pleistocene cut all fluvial discharges to the coastline, the shelf sediment cover is essentially relict terrigenous sand and contemporaneous hemipelagic mud (Martins et al. 1972; Kowsmann and Costa 1979; Kowsmann et al. 1977). Along the outer continental shelf off the northern-central CPRS, close to the shelf break, there is a strip of biogenic carbonate sediments formed mainly of broken and abraded shells (Kowsmann et al. 1977; Zembruscki 1979; Martins 1985). As the hydrodynamics of the outer shelf is not capable of producing such physical modifications, these are interpreted as relict material (*sensu* Emery 1968) originally accumulated and reworked in ancient shorelines under lower sea levels than the present.

In certain areas along the southern CPRS, large concentrations of biodetrital material, mainly fossil mollusk shells and other invertebrates, but also including fossils of terrestrial and marine vertebrates and beachrock fragments, eroded from submerged lithified paleoshorelines called *parceis*, occur on the surface of the inner continental shelf at depths between 0 and 20 meters (Martins et al. 1972; Figueiredo Jr. 1975; Figueiredo et al. 1982; Corrêa and Ponzi 1978; Caron 2014). Although modern shells and remains of other organisms also occur on the concentrations, for simplicity we refer herein only to the fossil material. Those concentrations are regarded as lag deposits (Erthal and Ritter 2020), the fragmented and abraded state of the fossils indicate reworking and concentration on high-energy nearshore settings in the past (Figueiredo Jr. 1975; Lopes and Buchmann

2008), therefore their origin can be understood in terms of past sea-level oscillations. Following the marine high stands of the marine isotope stage (MIS) 5, the global mean sea level (msl) of the last glacial period reached some -80 meters below the present during the stadial MIS 4 (71-57 ka b2k, Grant et al. 2012), then rose again to about -38 m (Pico et al. 2016) during the interstadial MIS 3 (57-29 ka b2k), reaching up to about -23 to -5 meters off southern Brazil between 47.7 and 36.2 ka BP (Dillenburg et al. 2019). The lowest sea levels of the following stadial MIS 2 (29-11.7 ka b2k) reached a minimum of -120 m during the last glacial maximum (LGM) between 26.5 and 18 ka BP (Rohling et al. 1998). As a result of periodic sea level oscillations, the shelf surface was reworked and eroded repeatedly, and its fossils mixed with younger remains, producing fossil assemblages with large time-averaging. Although sea level oscillations as the ones described above may have occurred before the Middle Pleistocene, based on ages of fossil shells found on the southern CPRS (Lopes et al. 2020d), the original geological units these remains were associated with were eroded by later marine oscillations. The contemporaneous shelf deposits are the result of the most recent postglacial marine transgression (PMT) that occurred between the latest Pleistocene-Early Holocene transition.

The PMT started around 18 ka BP as the result of the most recent deglaciation (Termination I) (Denton et al. 2010; Hulton et al. 2002). The rising sea level reworked the uppermost 3-10 meters of the continental shelf off Rio Grande do Sul (Dillenburg 1996), and large quantities of sand eroded from the shoreface by the rising sea level were transferred landward thus building the coastal Barrier IV (Caron 2014). The winnowing of sand resulting from erosion and retreatment of the shoreface left transgressive lag deposits formed of coarser material exposed on the shelf surface as large biodetrital concentrations (Figueiredo Jr. 1975). Part of the winnowed sand was probably transported offshore by currents until being deposited at depths below the influence of waves, where mechanical remobilization is minimal or nonexistent (Swift 1974; 1975; Belknap and Kraft 1981; Roy et al. 1997), forming a sheet on top of the biodetrital concentrations. The contemporaneous shelf hydrodynamics affecting the shelf bottom at depths between 8 and 24 meters rework the sand cover in the form of 4-10 meter-high and >200 km-long linear sand ridges located several km apart from each other and oriented obliquely to the modern shoreline (Figueiredo 1980). The ridges exhibit graded layers of sand and shells and migrate in response to the action of waves and currents, leaving the biodetrital concentrations exposed on the troughs between them (Figueiredo et al. 1982).

As the coast of Rio Grande do Sul is subject to micro-tidal regime (0.47 m on average), waves are the main physical mechanisms responsible for transport and erosion of sediments on the inner shelf, including the fossils, which can be characterized as palimpsests (*sensu* Swift et al. 1971, Villwock and Tomazelli 1995). The wave-driven erosive processes affecting the southernmost coast and inner shelf of Rio Grande do Sul constantly remove the sand, thus exposing fossils and *parceis* on the shelf surface. The storm waves erode and carry the fossils and fragments of the *parceis* to the beach, forming shell-dominated *Konzentratt-Lagerstätten* deposits locally known as *concheiros* or *concheiros do Albardão*, named after the lighthouse located in the northern limit of the deposits. A short vide (in Portuguese) about the *concheiors* is available at: https://www.youtube.com/watch?v=_2zoexwk6Lc.

Although the presence of fossils of Pleistocene terrestrial mammals along the beach of the southern CPRS had been reported before (Souza-Cunha 1959; Paula-Couto and Souza-Cunha 1965), according to people from the region the *concheiros* did not exist until the late 1960s. In the first systematic study the *concheiros* were described as ~5 m-wide and 5 cm-thick patches of fossil shells stretching for a few kilometers (Figueiredo 1975). However, twenty years later the *concheiros* reached a thickness of >2 meters (Asp 1996). These changes point to long-term processes influencing the formation of these deposits. Although occurring for some 40 km along the coast, the distribution and presence of the *concheiros* are variable, seemingly resulting from medium- and short-term processes as well.

As the sources of the fossil material found along the beach are the concentrations on the inner shelf, the *concheiros* represent the subaerial extension of these concentrations, as indicated by the fossils and the sediments with similar composition and grain size (Caron 2014). The beach area where the *concheiros* occur is characterized as intermediate in terms of morphodynamics and is subject to high-energy waves (Calliari and Klein 1993), especially under storm conditions that remove and transport sediments and fossils to the shore. The action of waves on the fossils at the shore produces taphonomic modifications and influences their distribution across the beach. As a result of these processes, it is possible to recognize a zoning pattern of the *concheiros*:

Lower *concheiros*: Formed of fossils accumulated on the lower part of the beach within the swash zone (foreshore), and thus subject to constant reworking by waves under fair-weather conditions. The fossils are densely concentrated (Fig.2A) and consist of a mixture of more complete and less abraded fossils (Fig. 2B), recently removed from the shelf, and others that remain for long periods under the influence of waves on the swash zone, being reduced to highly broken and abraded, mostly unidentifiable shell hash (Fig. 2C), and vertebrate fossils (Lopes and Buchmann 2008; Lopes and Ferigolo 2015). The occasional erosion of the foreshore by storm waves exposes interspersed layers of fossils and sand (Fig. 2D) that can be related to variations in hydrodynamics (e.g., storm vs. fair-weather conditions).

Upper *concheiros*: These are located on the higher part of the beach (backshore), between the berm and the incipient or front dunes. The intercalated layers of sand and fossils are thicker than those of the lower *concheiros*. The fossils include complete shells, large vertebrate remains (Fig. 2E), and highly abraded small fragments. Once accumulated on the backshore the fossils of the upper *concheiros* remain stable, being only occasionally subject to remobilization by storm waves that manage to reach the upper beach. The more frequent modifications of these fossils are caused by sandblasting that polishes the shells, erosion by washouts (*sangradouros*) draining from wetlands behind the foredunes, and episodic covering by wind-blown sand from the beach.

Shells and vertebrate fossils are not usually found behind the incipient/front dunes, except in areas where these are absent and storm waves reach further landward. Nevertheless, the smaller shell hash, in the coarse sand size range (1-2 mm), is easily entrained and carried by onshore winds due to its platy shape, forming ripples on the surface of dunes (Fig. 2F) and other sedimentary structures (Fig. 2G), and is incorporated to the large mobile dune fields farther inland.

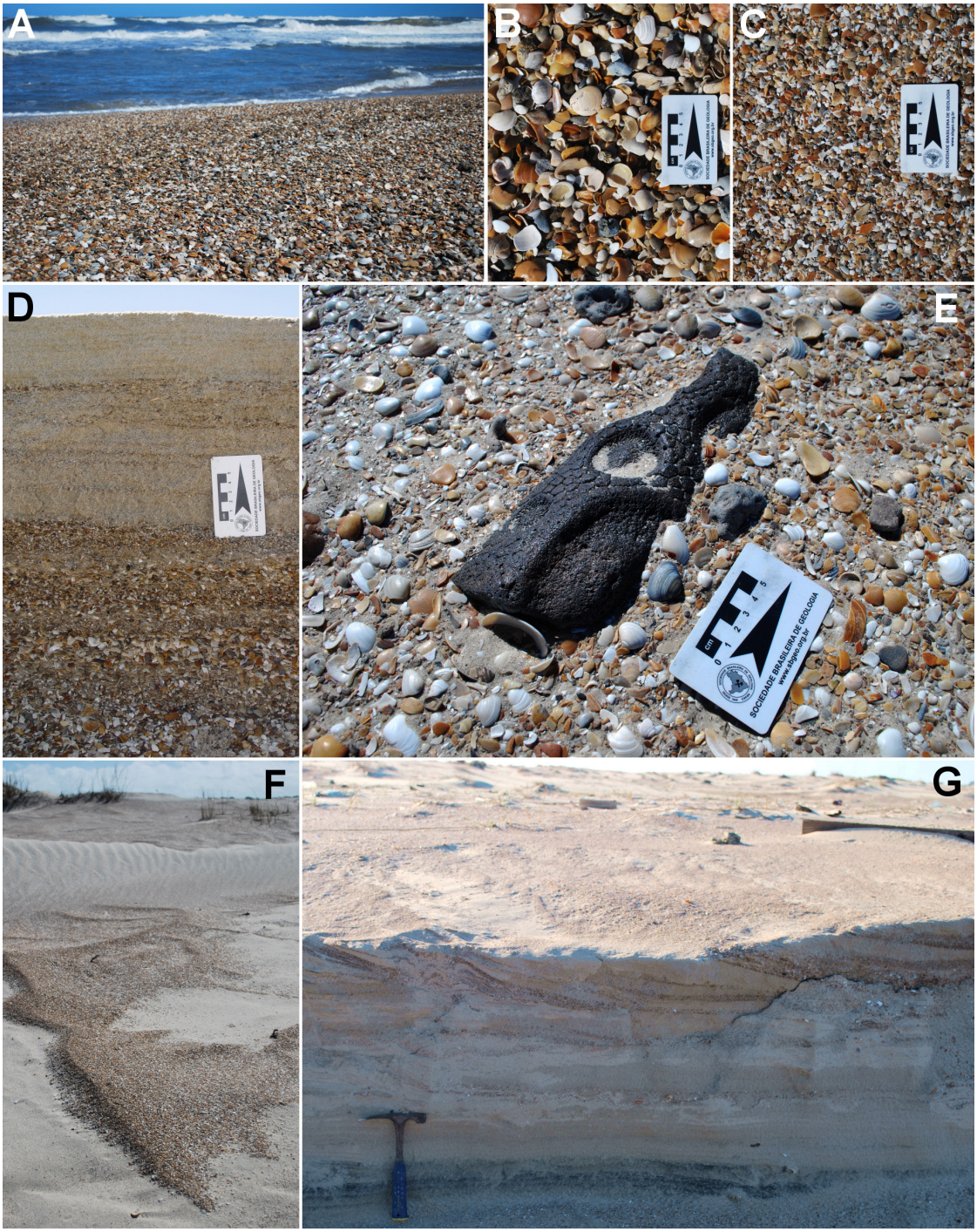

FIGURE 2 - A -A - Fossil concentration of the lower concheiros. B and C - Fossil shells photographed in the same scale showing the differences in size related to grades of abrasion and breakage. D – Interspersed layers of sand and shells exposed on the foreshore. E – Fossil of an extinct mammal (*Panocththus*) in the upper *concheiros*. F - Ripples formed of sand-sized shell hash accumulated on incipient dunes. G – Parallel- and trough cross-bedding formed of sand and shell hash layers in the upper *concheiros*.

2.1.1. The spatiotemporal dynamics of the concheiros

The upper *concheiros* are accumulated on the backshore as the result of exceptionally intense storm waves that manage to reach this area, thus remain relatively stable due to the absence of mechanical processes capable of remobilizing the fossil material. The lower *concheiros*, on the other hand, are constantly subject to wave action and, thus, are not continuous in space and time. These deposits can stretch for several kilometers but be separated by stretches of sand mostly devoid of shells that can be equally as long. One possible reason for this pattern is that fossils can be accumulated or removed at certain beach parts by concentrated wave action or due to the longshore transport that proceeds predominantly northeastwards (Lima et al. 2001).

The *concheiros* are usually exposed on the beach surface but are occasionally buried by sand. The burial is generally cyclical, following changes in wave dynamics driven by the

seasonal variations of the prevailing bidirectional winds (Tomazelli et al. 1998) that control the sediment balance on the foreshore (Fig. 3A, B). During autumn and winter, the strong waves constantly pushed ashore by southerly winds produce erosive scarps on the beach face (Fig. 3C), and the stronger storm waves can reach up to the backshore. During spring and summer the waves driven by the northeasterly winds blowing parallel to the shoreline accumulate sediments on the beach, creating a prominent berm that usually does not reach more than about 1.5 meters above the mean water line. This berm is constantly subject to overtopping by waves, producing washover deposits of sand and fossils (Fig. 3D) that bury the fossils previously accumulated on the beach. Seawater from storm waves and freshwater from the wetlands on the backshore accumulate between the berm and the incipient dunes, thus forming a type of creek or small lagoon parallel to the shore, locally called *albardão* (Fig. 3D), which gives the name to the lighthouse mentioned above. In some places, the *albardão* cuts across the berm as small *sangradouros* that can carry fossils from the upper *concheiros* back to the foreshore.

The accumulation of sand that buries the *concheiros*, however, also proceeds in longer timescales and may last for years (Fig. 4A, B). This occurs during certain periods when the beach receives more sediments than the waves can remove, resulting in the formation of a much larger berm that may reach more than two meters above the mean water line and attain widths of ~30 meters (Fig. 4C). The exact reason for this process is still unknown but may be related to the onshore migration of the linear sand banks submerged on the shelf (Figueiredo Jr. 1980; Figueiredo Jr. et al. 1982). When this high berm is present, the fossils are concentrated on the lower portion of the beach by fair-weather waves (Fig. 4C), as the only waves capable of transporting them across the berm through overwash are exceptionally high storm waves. That concentration increases the time the fossils are subject to swash and backwash action by fair-weather waves that produce mechanical abrasion and fragmentation.

The accumulation of the fossil material that forms the concheiros seems related to the sedimentary dynamics driven by wave regimes and thus varies seasonally, being more evident during autumn and winter due to the high-energy storm waves produced by southerly winds. The observation of physical processes and sedimentary features on the beach allows us to understand the formation of the concheiros as the result of cyclic events of erosion-deposition that follow a series of stages:

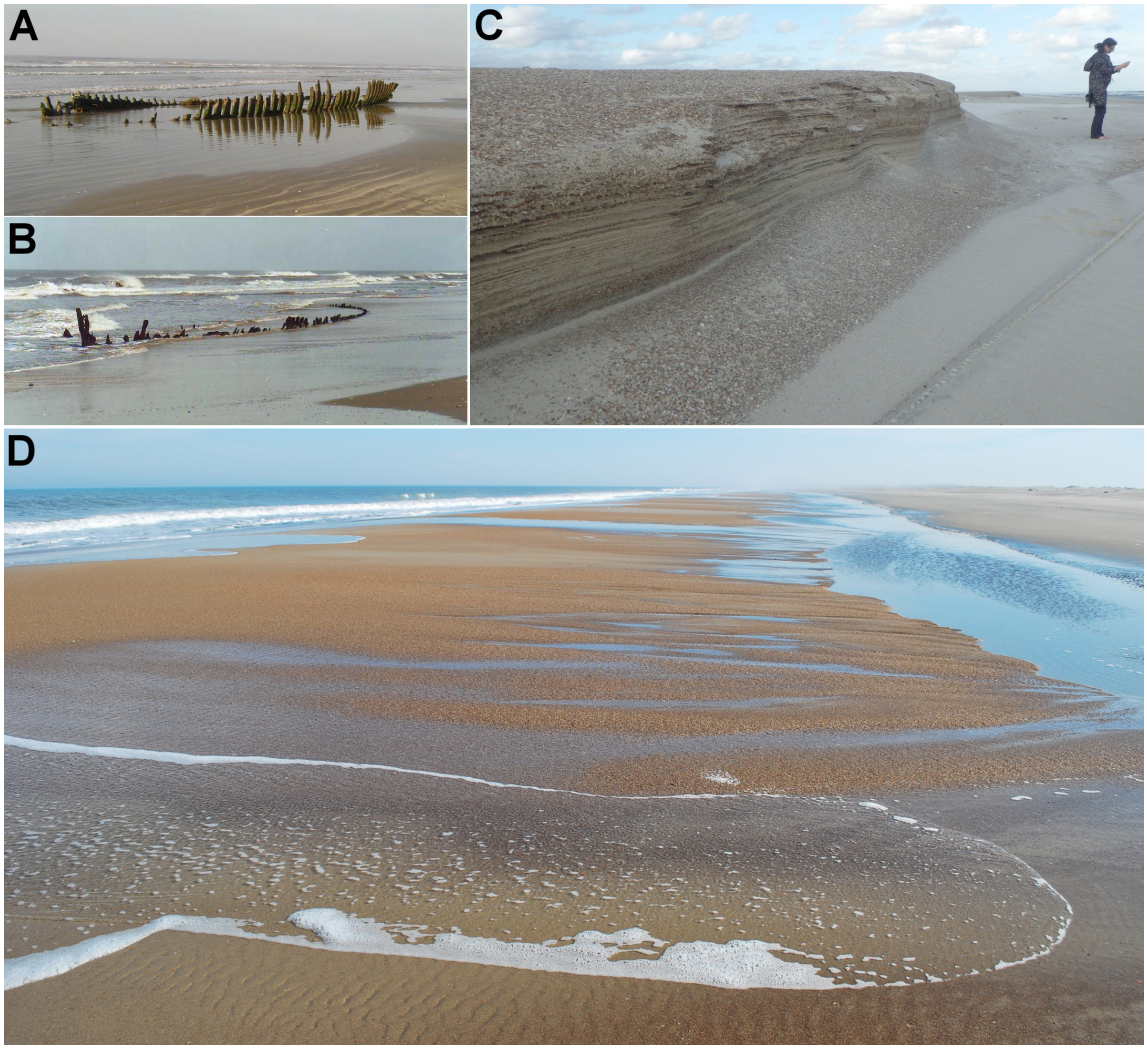

FIGURE 3 - The shipwreck 'Santa Maria' showing changes of beach sand volume between winter (A) and summer (B). C - Wave-cut erosive scarp on the foreshore. D - Berm with washover deposits of sand and shells on the foreshore, and an *albardão* formed of seawater on its rear.

FIGURE 4 - The shipwreck 'Dona Iaiá' showing increase of sand volume on the beach at the *concheiros* between 2010 (A) and 2015 (B). C - The *concheiros* in 2019 with a well-developed large berm stretching for tens of kilometers along the beach, with an *albardão* on its rear. Note the fossils concentrated on the lower foreshore (on the left) and their absence over the berm, differently from Figure 3D.

a) Under fair-weather conditions prevalent during spring and summer, sand and small fossils accumulated on the inner shoreface subject to wave action are carried to the beach. Although most fossils remain constantly moved and reworked within the swash zone, exceptionally strong waves or high tides can accumulate fossils above the mean water line, forming the lower *concheiros* on the foreshore. The sand deposited together with the fossils forms the berm (Fig. 3D), and is also carried landward by overwash or winds, thus covering the fossils on the highest part of the beach.
b) The storm events, more frequent and intense during autumn and winter, are driven by strong southerly winds that pile up water onto the shore, increase wave height and energy, and enlarge the breaker zone, thus causing waves to erode from the lower shoreface up to the foreshore. These waves rework sand and fossils that are carried to the shore, and remove sand from the foreshore. The extreme storm waves can overtop the berm and carry larger fossils up to the backshore.
c) The waves lose energy upon reaching the backshore, depositing the fossils at the foot of the foredunes or incipient dunes, and start to recede toward the sea. The returning backwash removes smaller sand grains, leaving behind lag deposits of densely concentrated fossils on the surface that form the upper *concheiros*. This is similar to one mechanism that can generate desert pavements through eolian deflation, leaving lag deposits of larger clasts (Knigh and Zerboni 2018).
b) The return to fair-weather conditions favors onshore eolian transport of sand that recomposes the berm and buries the fossils left on the foreshore by storm waves. The alternate episodes of erosion of sand/deposition of fossils and accumulation of sand across the beach are represented by the intercalated layers of fossils and sand observed on erosive beach scarps (Figs. 2D, 3C) or washout banks (Fig. 2G).

2.1.2. The fossil assemblages of the shelf and concheiros

Because the inner shelf deposits and *concheiros* result from periodic erosion of deposits and mixing of fossils of different ages, the fossiliferous assemblages exhibit large time-averaging. The fossil concentrations on the inner shelf and *concheiros* are dominated by shells of extant molluscan species, and the available radiocarbon ages range from ~200 to >30,000 years (Figueiredo Jr. 1975; Kowsmann et al. 1977; Lopes and Buchmann 2008; Ritter et al. 2017, 2023), although most of the shells display ages ranging up to 6,000 years (Ritter et al. 2017). In contrast, at water depths of 100 up to 242 meters on the outer shelf, the shelly concentrations are much older, with a median age of roughly 15,000 years (Ritter et al. 2023). The shells include from complete to fragmented and highly abraded specimens exhibiting varied

colors ranging from white, yellow, reddish, and dark gray or black (Fig. 5A), and may show encrustation by barnacles, bryozoans and polychaetes, besides traces of bioerosion by invertebrate predators and parasites (Lopes and Buchmann 2008; Erthal 2012; Lopes 2012; Ritter et al. 2019). Other fossils of marine invertebrate species include echinoderms (Fig. 5B), corals (Fig. 5C); crustaceans represented mainly by lithified ichnofossils *Ophiomorpha nodosa* (Fig. 5D) and skeletal fragments (Fig. 5E) (Rocha et al. 1975; Buchmann 1994; Lopes 2011; Freitas et al. 2020). Marine vertebrates (Fig. 5F-K) are represented by fossils of sharks, rays, bony fishes, whales, pinnipeds and seabirds (Souza-Cunha and Nunan 1980; Souza-Cunha 1982; Richter 1987; Buchmann and Rincon 1997; Oliveira and Drehmer 1997; Drehmer and Ribeiro 1998; Lopes et al. 2006; Medeiros et al. 2023). The fossils of vertebrates are strongly mineralized, dark

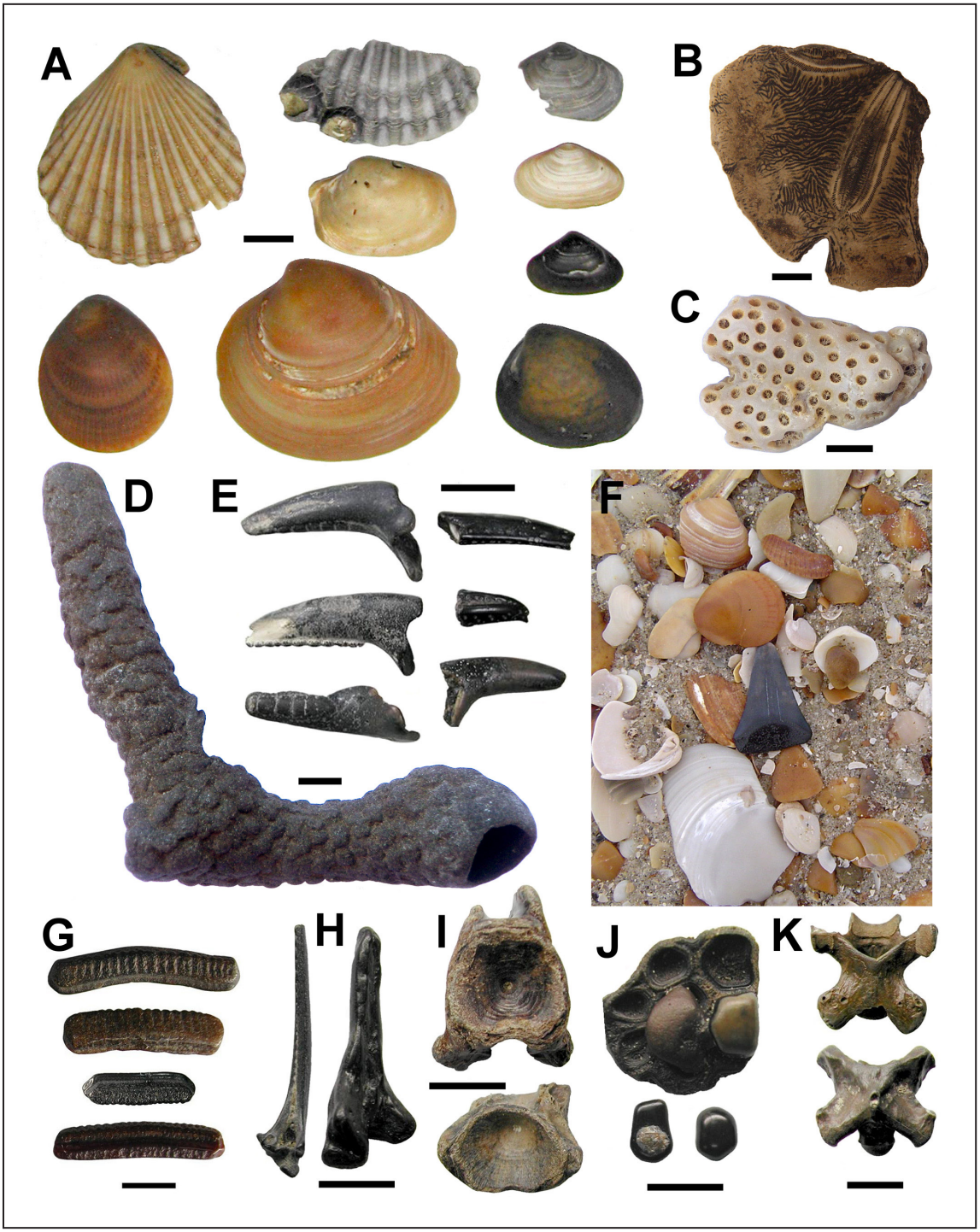

FIGURE 5 - Fossils from the concheiros: A - Mollusk shells. B - Echinoid *Encope emarginata* (sand dollar). C - Coral *Oculina patagonica*. D - Ichnofossil *Ophiomorpha nodosa*. E - Pincers of unidentified crustaceans. F - Fossil tooth of a white shark (*Carcharodon carcharias*) at the concheiros. G - Tooth plates of rays (Myliobatidae). H - Spines of unidentified teleost fishes, I - Vertebrae of cf. sciaenid fishes. J - Dental plate and two isolated teeth of *Pogonias cromis*. K - Vertebrae of seabirds cf. *Diomedea melanophrys* (scale bars = 10 mm).

reddish- to black-colored (Fig. 5F-K), probably due to the incorporation of exogenous elements as detected in fossils of terrestrial mammals from the shelf (Lopes and Ferigolo 2015). Virtually all fossils of marine vertebrates belong to species that inhabit the waters off southern Brazil, but the presence of white sharks (*Carcharodon carcharias*) and bull sharks (*Carcharhinus leucas*), characteristic of cold and tropical waters, respectively, not found in southern Brazil today, indicate variations in oceanographic conditions in the past related to glacial-interglacial cycles.

The most remarkable fossils found on the continental shelf and *concheiros* belong to terrestrial Pleistocene mammals (Fig. 6), especially large species of the megafauna (Souza-Cunha 1959; Buchmann 1994; 2002; Aires and Lopes 2012). The presence of terrestrial fossils today at water depths of up to at least 40 meters indicates that during glacial periods most of the continental shelf was subaerially exposed and occupied by terrestrial environments (Villwock 1984, Lopes and Buchmann 2010). The fossils are strongly mineralized; those found on the beach are mostly abraded and broken due to reworking by waves. In contrast, some complete specimens found on the beach were probably transported recently from the shelf deposits (Lopes and Ferigolo 2015). Their color varies between reddish, brown or black due to the incorporation of exogenous elements such as iron and magnesium. The few specimens collected directly from the shelf exhibit encrustation by marine epibionts such as corals, barnacles or bryozoans (Fig. 6A,G), whereas some specimens exhibit beachrock-like crusts (Fig. 6M) of sand and shells cemented by calcium carbonate (Lopes and Buchmann 2010; Lopes 2012; Lopes and Ferigolo 2015; Lopes and Pereira 2019).

The electron spin resonance (ESR) datings of some mammal teeth indicate Middle to late Pleistocene ages ranging from ~18 to ≥650 ka that coincide with periods of sea level lowstands (Lopes et al. 2010, 2014b). This considerable temporal mixing results from the erosion of terrestrial deposits by successive marine transgressions, which reworked and mixed fossils of different ages in the lag deposits. Because of this, the fossil mammals from the continental shelf and *concheiros* do not have stratigraphic context and cannot be correlated to any specific stratigraphic unit, although some dated remains (see Figure 8F) are chronocorrelated with fossils from terrestrial deposits (Lopes 2013; Lopes et al. 2021a). Nevertheless, the fossils from the shelf encompass a diverse fauna consisting mainly of extinct mammals such as giant sloths, glyptodonts, meridiungulates, mastodons, rodents, cervids, camelids, horses and carnivorans, and extant forms such as capybaras, jaguars, cougars and tapirs (Rodrigues and Ferigolo 2004; Rodrigues et al. 2004; Scherer 2005; Scherer et al. 2007; 2009; Pitana and Ribeiro 2007; Ribeiro et al. 2008; Lopes and Pereira 2010; 2018; Ferreira et al. 2015; Lopes et al. 2015; 2020a). Besides mammals, one fossil of a caiman (Hsiou and Fortier 2007) was also found at the *concheiros*. This diverse assemblage of terrestrial vertebrates represents different types of ecosystems and thus provides a record of environmental changes in southern Brazil during the Quaternary.

2.2. Terrestrial sites

The fossiliferous sites in onshore areas on the southern CPRS are located south of the estuary of Patos Lagoon, between Taim and the Brazil-Uruguay border (Fig. 1). The fossils include essentially the same marine and terrestrial organisms found on the shelf and *concheiros* but preserved in the Middle Pleistocene to Late Holocene shallow marine, lagoon and fluvial deposits, mainly in the subsurface, but also occur at or close to the surface in some areas. In geological terms the fossiliferous sites are part of the Barrier-Lagoon Systems II and III (Fig. 7A). The fossils have been recovered so far from three main sites: the Barrier III, Chuy Creek (Barrier II and Lagoon III) and Mirim Lagoon (Lagoon II).

2.2.1. Barrier III

The fossils preserved in deposits of the Barrier III belong to extant (and a few locally extinct) species of invertebrates that inhabit marine or lagoon environments (Bettinelli et al. 2018). These fossils are preserved in sediments accumulated

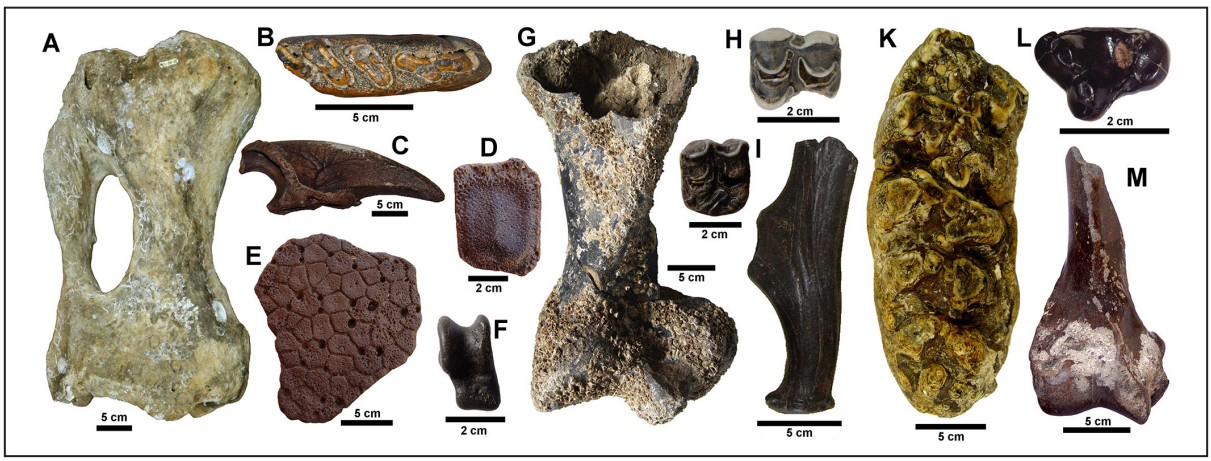

FIGURE 6 - Fossils of terrestrial mammals from the continental shelf/*concheiros*: A - Tibia and fibula of *Megatherium*. B - Partial jaw of a giant sloth (cf. *Catonyx*). C - Phalange of unidentified sloth. D - Osteoderm of a giant armadillo (cf. *Holmesina*). E - Fragment of the carapace of a glyptodont (*Glyptodon*). F - Astragalus of a proterotheriid (*Neolicaphrium*). G - Humerus of *Toxodon*. H - Tooth of a camelid. I - Tooth of a horse (*Equus*). J - Antler of a cervid (*Antifer*). K - Tooth of a mastodon (*Notiomastodon*). L - Tooth of a wild dog (*Theriodictis*). M - Humerus of a sabertooth cat (*Smilodon*), the light areas on the bone are crusts of cemented sand and shells.

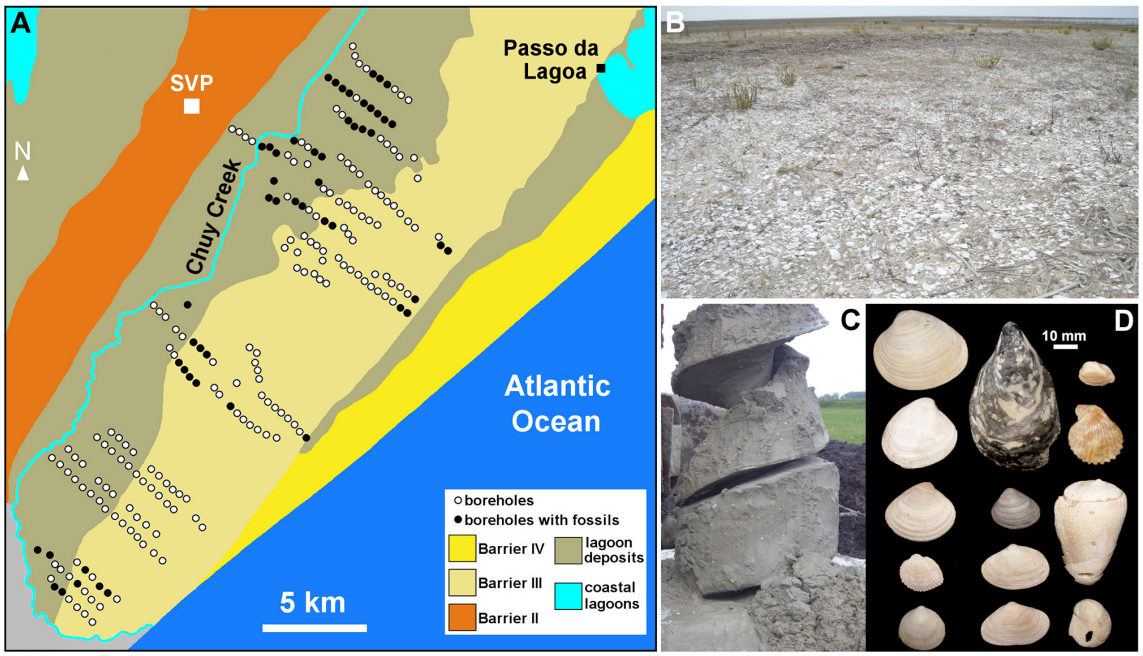

FIGURE 7 -A - Geological map of the southernmost CPRS showing the location of the onshore fossiliferous sites (excluding Mirim Lagoon). B - Fossil shells removed from the Barrier III scattered on the margin of the irrigation channel at Passo da Lagoa. C - Drilling equipment used to make the boreholes for the wind farm (shown in 7A). D - Fossil shells extracted from the boreholes.

on shallow marine (foreshore-shoreface) and lagoon margin deposits found in the subsurface on the seaward and back barrier portions of the barrier (Fig. 7A). The fossils from the seaward portion were obtained at depths of ~7 to 17 meters below the terrain surface (corresponding to altitudes of +3 to -7 meters relative to the present sea level), from sediments removed during the excavation of a channel at the locality of Passo da Lagoa (Fig. 1; Fig. 7B), and extracted by rotating drills during the installation of a wind farm (Fig. 7C) (Lopes and Buchmann 2008; Lopes et al. 2020d).

Fossiliferous deposits are widely distributed across the Lagoon System III on the back barrier (Fig. 7A), where the fossils were also extracted by rotating drills, embedded in sediments accumulated on lagoon margin environment on the back barrier, but also include material eroded from deposits of the Barrier II (Bettinelli et al. 2018; Lopes et al. 2024a). The fossils occur at depths of ~8 to +19 meters (altitudes of -6 to +5 meters), and besides mollusk shells and foraminifers they also include echinoderms and crustaceans (Bettinelli et al. 2018). The fossils are primarily unidentified fragments, but several well-preserved shells were also recovered (Fig. 7D). Most shells are white-colored due to partial dissolution by acidic water of the phreatic. However, some exhibit traces of the original color pattern and a few have preserved parts of the periostracum. The altitudes at which the shells are preserved show that the fossiliferous deposits were formed by a marine transgression that reached altitude of up to about +6 to + 7 meters relative to the current mean sea-level, consistent with the estimate of +5.1 to +7.7 meters from shoreface-foreshore deposits of the Barrier III in the northern CPRS (Tomazelli and Dillenburg 2007). The ESR ages of shells from the seaward barrier range from ~87 to 240 ka, whereas those from the back barrier are older, ranging from ~178 to 359 ka (Lopes et al. 2020d). The youngest ages are consistent with the estimated late Pleistocene (MIS 5) age of the Barrier III (Villwock and Tomazelli 1995). However, the older figures indicate the mixing with shells eroded by the MIS 5 marine transgression from the Barrier II or even older deposits.

2.2.2. Chuy Creek

This fluvial system flows along the Lagoon System III (Fig. 7A), which in geomorphological terms is a small basin bounded west and east by the Barriers II and III, respectively (Fig. 1). The creek drains from the surrounding rain-fed wetlands and was a shallow stream until being further excavated during the 1960s for irrigation purposes, thus exposing sediment layers within the Lagoon System III (Paula-Couto and Souza-Cunha 1965). The outcrops along the banks of the creek exhibit the best Middle Pleistocene to Holocene stratigraphic successions known so far in the southern CPRS. The succession exposed above the creek bed (Fig. 8A) comprises a marine deposit at the base (Fig. 8B), interpreted as deposited in shallow marine (shoreface-foreshore) environments associated with the Barrier II (Rosa 2012; Lopes et al. 2014a). This deposit contains a rich fossil assemblage dominated by mollusk shells, foraminifers, ostracods, and cirripeds, besides ichnofossils *O. nodosa*, *Rosselia* isp. and *Conichnus* isp. (Closs and Forti-Esteves 1971; Forti-Esteves 1974; Lopes and Bonetti 2012; Lopes et al. 2013b; 2020b). The shells are mostly fragmented and white-colored, and several are corroded by acidic water in the form of pitted rough surfaces (Lopes et al. 2013b). Some luminescence and ESR ages obtained in sediments and shells, respectively, point to an age of ~220 ka for the top of the marine deposit, corresponding to the interglacial MIS 7 (Lopes et al. 2014a, 2014b; 2020a), when the relative sea level reached a measured altitude of ~10 meters above the present (Rosa 2012).

The marine deposits are overlain by the Santa Vitória Alloformation (SVA), that encompasses paleosols and fluvial deposits (Lopes et al. 2021a). The fossil-bearing deposits were initially interpreted as deposited in lagoon environments and classified as a lithostratigraphic unit named `Santa Vitória Formation` (Soliani 1973; Soliani and Jost 1975). More recent studies have shown that these deposits consist of small lakes and channels of meandering-braided fluvial systems, characterized by tabular and lens-shaped, massive to laminated muddy sand facies, several exhibiting high organic content (Fig. 8C) and rounded millimetric mudclasts (Lopes et al. 2021a). The paleosols consist of massive sand with iron oxide as coatings on the grains or forming hard centimetric nodules; iron-manganese oxides occur in the form of irregular masses (Fig. 8D) or hard subspherical nodules. Pedogenic carbonates (calcretes, Fig. 8E) originally designated as 'Caliche Cordão' (Delaney 1962) occur as subspherical to irregular nodules and rhizocretions (Lopes et al. 2024b). The SVA also includes eolian (loess) deposits apparently accumulated during the stadial MIS 4 according to luminescence ages in some calcrete nodules. The calcretes associated with loess indicate a dry and probably cold climate during MIS 4, followed by warmer and wetter conditions during the following interstadial MIS 3.

The fossils found within the SVA (Fig. 8G-Q) include essentially the same Pleistocene mammals found on the continental shelf-*concheiros*, although some species from the latter have not been found so far in the SVA, and vice-versa. The species known only from the SVA include the peccary *Brasilochoerus stenocephalus* (Copetti et al. 2021), the canids *Protocyon troglodytes* (Oliveira et al. 2005), *Dusicyon avus* (Pereira et al. 2011) and *Cerdocyon* or *Lycalopex* (Lopes et al.

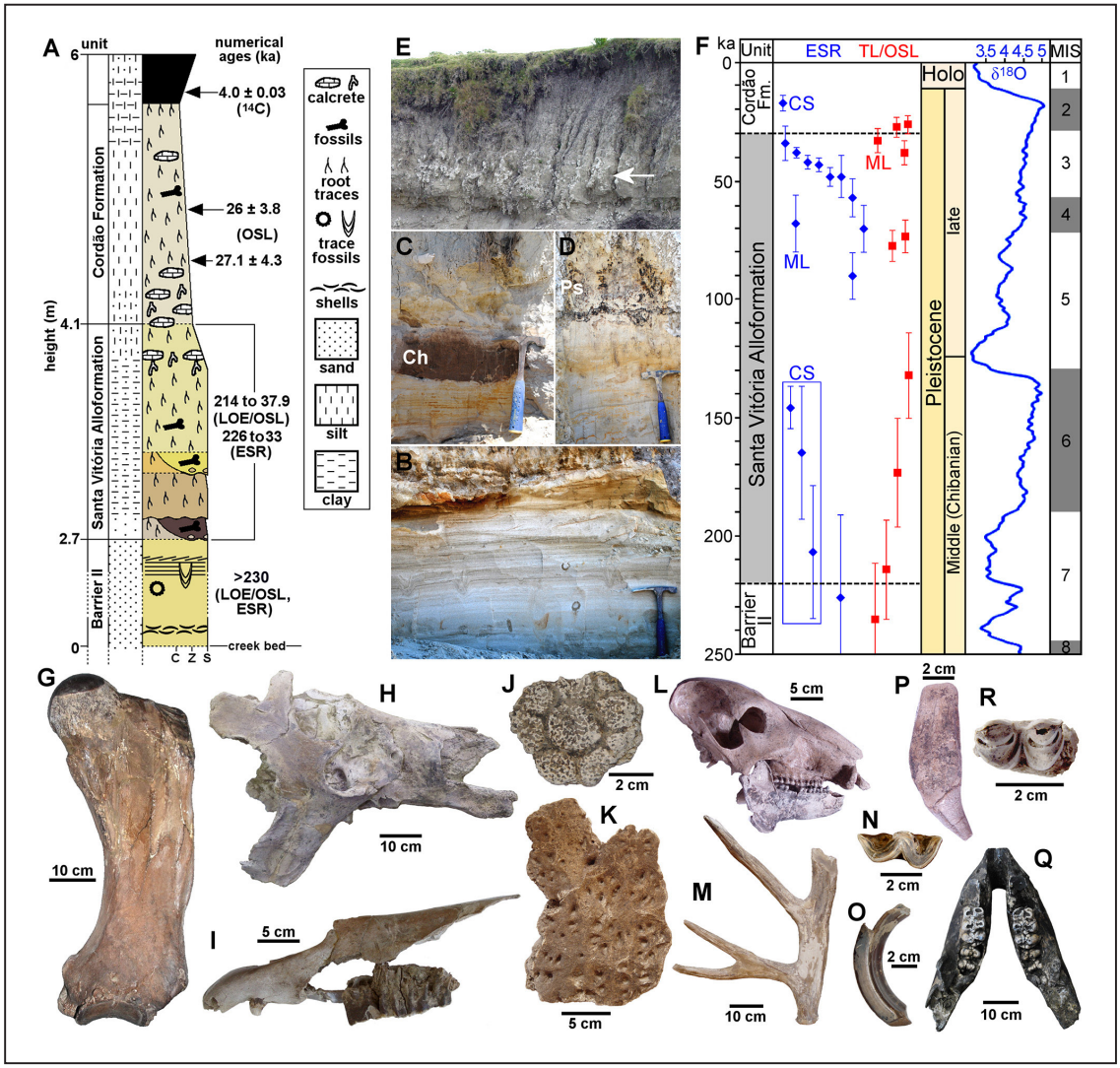

FIGURE 8 - A - Stratigraphic succession at the type section of the Santa Vitória Alloformation (modified from Lopes et al. 2021a). B - Marine trace fossils at the base of the succession. C - Fluvial channel deposit (Ch) and C - paleosol (Ps) of the Santa Vitória Alloformation. E - The Cordão Formation with calcrete horizon (indicated by the arrow) at its base. F - Chronostratigraphy of the deposits exposed along Chuy Creek based on ESR ages of fossils and TL/OSL ages of sediments from Chuy Creek, ages from Mirim Lagoon, (ML) and continental shelf (CS) are shown for comparison ($\delta^{18}O$ curve and MIS boundaries from Lisiecki and Raymo 2005). Fossils of mammals from Chuy Creek: G - Femur of *Lestodon*. H - Skull of *Megatherium*. I - Skull of *Equus*. J - Osteoderm of *Glyptodon*. K - Osteoderms of *Doedicurus*. L - Skull and jaw of *Brasilochoerus*. M - Antler of *Antifer*. N - Tooth of Macrauchenia. O - Tooth of *Toxodon*. P - Tooth of *Arctotherium*. Q - Jaw of *Notiomastodon*. R - Tooth of *Hemiauchenia*.

2015), the rodent *Holochilus brasiliensis* (Kerber et al. 2012), the ursid *Arctotherium* cf. *wingei* (Pereira et al. 2012), the giant sloth *Eremotherium laurillardi* (Lopes and Pereira 2019) and the giant armadillo *Pampatherium humboldti* (Ferreira et al. 2018), besides a stork *Ciconia* sp. (Lopes et al. 2019).

Most fossils from the SVA are either incomplete bones or unidentifiable fragments due to reworking by fluvial dynamics (Lopes and Ferigolo 2015), although complete remains can also be found (see one example in the video at https://www.youtube.com/watch?v=8ahSK3KIhyY). The fossils are generally pinkish-colored due to the incorporation of iron oxide from the surrounding sediments (Lopes and Ferigolo 2015). The weathered fossils exposed on the banks are white, whereas fossils eroded from the banks and found at the creek bottom are black. Some are encrusted by calcrete, and others exhibit crusts of muddy sand cemented by iron or iron-manganese oxides. Stable isotopes of carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) in teeth of mastodons and toxodonts indicate open grassland environments (Lopes et al. 2013a). The available ESR ages of the fossils range from ~226 to 33 ka (Lopes et al. 2010; 2014b), coherent with luminescence ages that indicate deposition of the SVA between ~220 to 30 ka b2k, thus encompassing from MIS 7 to MIS 3 (Fig. 8F) (Lopes et al. 2019; 2021a). The youngest ages from the SVA and the luminescence ages from the overlying unit allow to put the disappearance of virtually all mammalian fossils (with a few exceptions, see below) from the stratigraphic succession at an interval estimated as ~30 ka b2k that coincides with the transition from the relatively warm and humid interstadial MIS 3 to the cold and dry stadial MIS 2.

The SVA is overlain by loess deposits of the Cordão Formation (CF), formed of wind-blown silt-sized dust transported from periglacial deposits in Argentina during MIS 2 as indicated by luminescence ages of ~27 and 26 ka (Fig. 8F) obtained at its type section (Lopes et al. 2016). The loess was originally described as a pedostratigraphic unit named 'Cordão Soil Unit' (Jost 1975). The lower half of this unit exhibits a calcrete horizon thicker than the calcretes found within the SVA, which suggests a longer and drier period compared to MIS 4. The only fossils discovered so far within the CF are a few fragmented teeth of rodents, and one jaw fragment of a camelid *Hemiauchenia* (Fig. 8R) bearing one molar tooth, found at a stratigraphic level slightly above the level dated as of ~26 ka. The $\delta^{13}C$ and $\delta^{18}O$ obtained in the tooth indicate a diet of desert-adapted plants (xerophytes), comparable to modern camelids that inhabit dry steppes of Argentina (Lopes et al. 2023). The disappearance of the megafauna from the stratigraphic succession along the banks, coinciding with the accumulation of loess and aridification, as inferred from the fossil of *Hemiauchenia*, suggests that the expansion of dry environments up to southern Brazil during MIS 2 may have influenced the local extinction of the Pleistocene megafauna (Lopes et al. 2020c).

The uppermost ~1-meter-thick portion of the stratigraphic succession along the banks consists of dark brown clayey to sandy silt with bivalve mollusk shells, diatomites, phytoliths and sponge spicules that indicate expansion of wetland environments under wet and warm climate during the Holocene (Lopes et al. 2021b).

2.2.3. Mirim Lagoon

This large coastal lagoon and the terraces along its margins form the Lagoon System II, developed landward of the Barrier II (Fig. 1D). The origin of the Barrier-Lagoon System II was not precisely determined yet, having been correlated to the sea level highstand of MIS 11 (424-374 ka b2k) through correlation with marine $\delta^{18}O$ curves (Villwock and Tomazelli 1995), whereas the numerical ages from the marine deposits along Chuy Creek correlated to that system indicate it could have been formed by the MIS 7 (243-191 ka b2k) marine transgression. Being an old and large water body (>170 km-long and up to ~80 km-wide), Mirim Lagoon is also a large fossiliferous site, as shown by several fossils found at its bottom and margins that record significant environmental changes in the southern CPRS between the Pleistocene and Holocene.

In recent years, several fossils have been retrieved from the bottom of Mirim Lagoon by fishermen from the town of Santa Vitória do Palmar. These fossils include extinct terrestrial mammals such as mastodons, giant sloths, glyptodonts, toxodonts, rodents, horses and cervids (Fig. 9A-I), found at water depths between 2 and 4 meters and hundreds of meters from the lagoon margin (Lopes et al. 2020b). The presence of large (and heavy) bones of giant mammals far from the margin implies that the lagoon was much smaller in the past (Fig. 9O), considering the absence of large rivers that could have transported those remains, and the low-energy hydrodynamics today. The area occupied by the lagoon was likely reduced during past glacial periods due to a combination drier climate and relative sea levels that reached up to >100 meters below the present, thus lowering the regional base level of coastal water bodies. This interpretation is consistent with seismic data showing incised fluvial channels across the area occupied today by the lagoon (Barboza et al. 2021a).

Some fossils of terrestrial mammals have been found scattered on the lagoon shore, probably eroded from Pleistocene deposits along its margins. Other fossils were found *in situ* on an irrigation channel some 1,700 meters inland from the southeastern lagoon shore. The fossils consist of isolated elements of different species, and fragmented bones of one *Toxodon* that include a tooth dated by ESR which provided ages of ~68 ka (according to the early uptake model, EU) and ~127 ka (linear uptake model, LU) (Lopes et al. 2020b). These fossils were embedded in a muddy sand overlain by a clayey to silty sand layer exhibiting a calcrete horizon. Luminescence ages in quartz grains from one calcrete nodule show that the carbonate precipitated after ~33 ka b2k (Lopes et al. 2020b), consistent with drier conditions between MIS 3 and MIS 2 inferred from the geological records found along Chuy Creek.

The other known fossils discovered in Mirim Lagoon are marine organisms. These include a diverse assemblage of molluscan shells found along the western lagoon shore in Uruguay (Martínez 1989), whereas on the Brazilian side one oyster was retrieved from the bottom by fishermen close to the port of Santa Vitória do Palmar (Lopes et al. 2021c). Other fossils found on the shore of Santiago Spit (Fig. 1D), include teeth of bull sharks (Fig. 9J,K), a species that today occurs only in warmer areas north of Rio Grande do Sul, plus a dental plate (Fig. 9L) and one dermal buckle of rays (Lopes et al. 2020b). The vertebrate fossils also include bones of one adult (Fig. 9M) and one juvenile (Fig. 9N) of southern right whales, probably a mother and the calf that entered the lagoon during the Holocene marine incusion and became stranded at the shore.

FIGURE 9 - Fossils of vertebrates from Mirim Lagoon: A - Femur of a megatheriid sloth. B - Osteoderm of *Glyptodon*. Part of the skull (C), tooth (D), and phalange (E) of a *Toxodon*. F - Tooth of *Equus*. G - Antler of *Morenelaphus*. H - Tooth of *Notiomastodon*. I - Tooth of a rodent. J - Upper (J) and lower (K) teeth of bull sharks (*Carcharhinus*). L - Dental plate of a myliobatid ray. Humerus of an adult (M) and vertebra of a juvenile (N) southern right whales (*Eubalaena*). O - Hypothetical configuration of Mirim Lagoon during the last glacial stage (modified from Lopes et al 2020). P - Shell mining at Latinos Spit. Q - Fossil mollusk shells from Latnos Spit. R - Simulated flooding of Mirim Lagoon by the Holocene sea level high-stand, the white lines show the modern coastal configuration (PL: Patos Lagoon, SGC: São Gonçalo Channel).

The fossils of marine organisms are more abundant in the Latinos Spit (Fig. 1D). This spit consists of a series of linear sand ridges developed on the northern end of Mirim Plateau, along the southern margin of the Taim Embayment (Abreu et al. 1985; Lopes et al. 2021c). These ridges contain a ~1-meter-thick deposit close to the terrain surface, formed of densely-packed mollusk shells mined for years to obtain calcium (Fig. 9P). The shells (Fig. 9Q) are mainly of two species (the bivalve *Erodona mactroides* and the gastropod *Heleobia australis*) that today are abundant in brackish conditions in the estuary of Patos Lagoon. The fossils of marine species include the sciaenid fish *Micropogonia furnieri* (black drum or *corvina*) and several mollusks that inhabit the coast of Rio Grande do Sul today, but also include the bivalves *Anomalocardia flexuosa* and *Cyrtopleura costata*, which currently inhabit only warmer areas to the north (Lopes et al. 2021c).

The sedimentary succession described from cores (Abreu et al. 1985) and hand auger samples (Lopes et al. 2021c) at Latinos Spit and the fossils of estuarine and marine species indicate a marine incursion during the Middle Holocene, between ~8 and 3 ka ago based on radiocarbon and luminescence ages (Martínez and Rojas 2013; Lopes et al. 2021c). This incursion resulted from the marine transgression that reached ~2.5 meters above the present level between 6 and 5 ka, thus flooding large areas of the southern CPRS. Seawater entered Mirim Lagoon through the incised valley at Taim (Barboza et al. 2021a) and through the São Gonçalo Channel that connects it to the Patos Lagoon (Fig. 9R). Marine and estuarine fossils have also been discovered along the São Gonçalo Channel (Ihering 1885, 1907; Godolphim et al. 1989). The presence of extralimital species found today only to the north, and the $\delta^{18}O$ in shells from Latinos Spit indicate warmer coastal waters during the marine incursion, which favored the southward dispersion of those species, possibly taking advantage of the coastal lagoons as corridors (Lopes et al. 2021c; 2022). On the other hand, the radiocarbon ages obtained in two shells of the estuarine species indicate that the lagoon became fully fresh by ~3 ka ago because of sea level fall and the establishment of the Barrier IV that cut the connection with the ocean through Taim (Lopes et al. 2021c).

3. Potential threats and protection measures

The Quaternary fossiliferous sites of the southern CPRS represent considerable periods of time and contain fossils that show significant climate-driven changes in environments and fauna, including shifts in the distribution of marine animals in response to changes in oceanographic conditions (Lopes et al. 2013b; 2021c; 2022). The terrestrial fossil assemblages are composed of a mixture of species of tropical (Brazilian) and subtropical-temperate (Pampean) origin that can be explained by repeated latitudinal shifts of climatic zones, vegetation types and mammalian faunas (Oliveira et al. 2005; Lopes 2013; Lopes et al. 2021; 2023). The changes in terrestrial plant communities, inferred from dietary patterns of herbivore mammals, may bear relationship with the local extinction of the Pleistocene megafauna (Lopes et al. 2013a; 2020c; 2023). As the plant communities of the coastal plain belong to the Pampa biome, the understanding of the vegetation dynamics in the CPRS between the Pleistocene and Holocene based on fossil records can help to assess how the contemporaneous Pampa was established and how it responds to environmental and anthropogenic pressures, thus may contribute for its conservation and management, under the concept of conservation paleobiology (Louys 2012).

The marine and terrestrial fossils provide invaluable contributions to the knowledge of the effects of climate changes and sea level oscillations on the coastal ecosystems of southern Brazil. Obtaining information about those processes, however, requires some protection measures to either prevent or mitigate possible impacts on the fossiliferous sites derived from anthropogenic activities, thus preventing the loss of important scientific information. Under the Brazilian law, fossils and paleontological sites are considered natural geoheritage and thus are legally protected, although economic activities or constructions in fossiliferous areas can result in legal and protection issues. The large area encompassed by the fossiliferous sites implies potentially multiple threats and poses significant challenges for conservation. Nevertheless, the current land use and activities in the southern CPRS apparently have low impact potential on the deposits and associated fossils.

In the case of the fossil concentrations submerged on the shelf, there are no direct sources of impact other than the natural erosive processes acting on the shoreface-foreshore. Although some fossils have been retrieved from the shelf by fishing vessels using bottom trawls (Lopes and Buchmann 2010), the use of this fishing technique is not widespread, especially in the southernmost CPRS where the submerged *parceis* and sand banks (Delaney 1965; Figueiredo Jr. et al. 1982; Caron 2014) are obstacles for the trawls. Possible future impacts on the shelf concentration include the projected installation of offshore wind farms along the inner and middle shelf of Rio Grande do Sul at depths of up to 50 meters (https://www.sindienergiars.com.br/offshore-a-nova-fronteira-da-energia-eolica).

However, the fossil concentrations along the *concheiros* are the most impacted fossiliferous site of the southern CPRS, because cars and motorcycles are allowed to travel along the beach. Although the access to certain parts of the beach, especially along the *concheiros*, is limited to four-wheel drive vehicles, unregulated rallies and motorized tourist groups cause significant impacts on the beach, by reworking sand (Fig. 10A) that can increase beach erosion, and also by destroying fossils deposited on the beach (Fig. 10B). One proposal for the establishment of a protection area in the southern CPRS is currently under scrutiny by the federal environment protection agencies. This area encompasses not only the beach as a whole (including the *concheiros*), but also the adjacent marine environment up to the isobath of ~50 meters (Fig. 10C). Although the goal is the protection of endangered species of turtles, porpoises, sharks and rays against illegal fishing, that proposal would also ensure the protection of the fossiliferous concentrations on the shelf.

The marine fossils from the Barrier III had been known only from the irrigation channel at Passo da Lagoa (Fig. 7B) (Lopes and Buchmann 2008), but the real subsurface extent of the fossiliferous deposits became known during the installation of the wind farm on the southern CPRS (Fig. 7A). Because of the known presence of fossils in the area established for the wind farm, and the large number of wind turbines to be installed, the environmental agencies requested a preliminar paleontological survey and a rescue plan to ensure the preservation of the fossils found in the area of the wind farms. As the rescue of fossils prior to the installation of the wind turbines was not possible because of the depths (up to about 20 meters) to be reached by the foundations, an alternative approach was adopted that consisted of a monitoring program to rescue any fossils extracted by the drillings for the foundations. Although the rotating drills stirred the upper meters of the sediments, upon reaching the predetermined depth they were stopped and were retrieved, bringing to the surface undisturbed sediments containing the fossils (Fig. 7C). The environmental protection agencies were mainly concerned with the possible destruction of mammalian fossils by the rotating drills, but only two small bone fragments were recovered by the drillings. On the other hand, the drillings reached fossil-rich marine and lagoon deposits of the Systems II and III, whose extent and structure

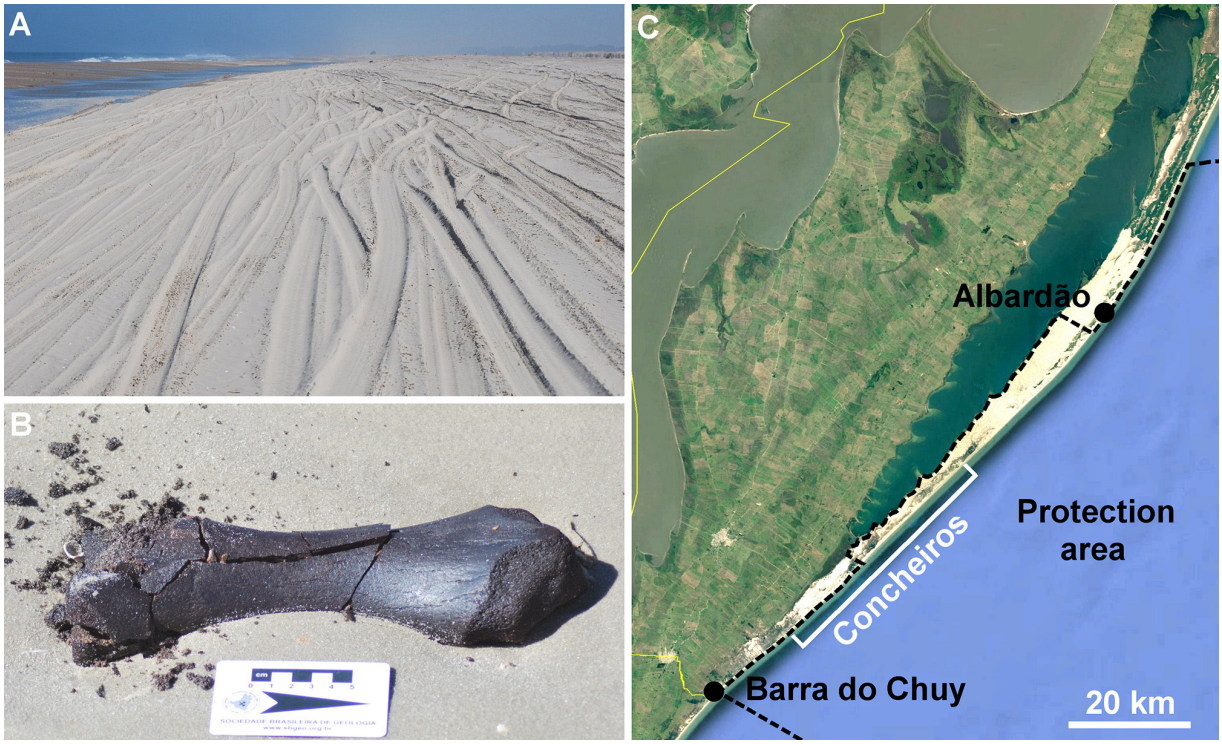

FIGURE 10 - Beach surface after the passage of a group of vehicles. B - Fossil of a giant mammal on the beach, ran over by a car. C - Google Earth image showing the proposed area (black dashed line) for a coastal and marine protection in the southern CPRS.

were unknown at the time. Together with the geological samples obtained from the boreholes, thousands of molluscan shells and other marine invertebrates were recovered across a large area (Fig. 7A). These fossils increased the knowledge of the subsurface structure and extent of the depositional Systems II and III, resulting in different scientific publications (Bettinelli et al. 2018; Lopes et al. 2020d; 2024a). The fossils were incorporated to the paleontological collection of the Museu Coronel Tancredo Fernandes de Mello, in the town of Santa Vitória do Palmar, and put on public display (Fig. 11A) as part of the scientific divulgation activities that integrated the monitoring program.

The fossil deposits along Chuy Creek are not currently under direct threat, as the creek cuts across private farmlands that use only the uppermost centimeters of the terrain for crops or pastures. In the last decade there was an increase of colluvial and alluvial sediments accumulated along most of the banks, forming deposits that are now largely covered by vegetation, which decreased erosion of the banks, thus protecting the fossils from erosion. The fossiliferous sites of Mirim Lagoon are not currently threatened, but future projects related to the Mercosul Waterway may require dredging of parts of the lagoon, which potentially can affect the fossils at its bottom. Under the Brazilian environmental laws, the water courses, lagoons, and the surrounding shores, including potentially associated fossiliferous sites, are under permanent protection. This demands that any activities to be developed around these water bodies must respect the buffer areas along the margins and may require previous environmental studies to assess the potential presence of fossils, and monitoring programs to rescue any fossil remains that might be affected.

Although the paleontological sites of the southern CPRS are not under formal protection, the *concheiros* and Chuy Creek (Lopes et al. 2009a, 2009b) are recognized as geoheritage sites of scientific and cultural importance by the Brazilian Commission of Geological and Paleobiological Sites (https://sigep.eco.br) that integrate the UNESCO World Heritage Committee. Despite the lack of formal protection for the sites, their fossils are protected in paleontological collections of universities and museums, especially the Coronel Tancredo Fernandes de Mello Museum in the town of Santa Vitória do Palmar. This museum has a collection of thousands of fossils and archaeological materials found in this area, several of which are part of a permanent exhibit that receives thousands of visitors yearly, including Brazilian and foreign tourists, schools, and universities.

Besides the public exhibition, the museum staff has been developing an educational program for more than twenty years to ensure the local people value the rich paleontological geoheritage of the region. The program includes activities with schoolchildren such as lectures and exhibitions of fossils and replicas in schools (Fig. 11B), guided tours of the museum exhibit (Fig. 11C) and simulated digging and identification of fossil replicas (Fig. 11D), besides radio interviews that reach a wide public. As a result of that program, the prehistory of the region is now included in the elementary and high school curricula; the fishermen who accidentally catch fossils from the bottom of Mirim Lagoon have donated the specimens, which are now on public display at the Mário Costa Barberena Museum, in the port of Santa Vitória do Palmar. Other people had informed the museum staff about the presence of fossils in some areas,

FIGURE 11 - A - Exhibition of fossils from the wind farms. Educational activities with schoolchildren: B - Lecture, C - Guided tour through the museum exhibit, D - Digging of fossil replicas

thus revealing new paleontological sites. Presentations for the staff working in the border post at the Brazil-Uruguay border are sometimes requested, to train the police agents to recognize fossils that may be smuggled across the border, although this had not been recorded so far. The educational program has raised the interest of the local people in the prehistory and increased the public awareness about the importance of preserving the fossils for the knowledge they provide about the geological formation and environmental changes of the coastal plain.

4. Conclusion

The southern coastal plain of Rio Grande do Sul harbors rich fossil assemblages that record important environmental changes throughout the late Quaternary. The fossils are preserved on sites distributed across a large area on both marine and terrestrial settings. Although most the fossiliferous sites are not currently under serious threat at, future developments and constructions in the area may pose risks that must be considered to establish the best measures for their protection. The protection of the sites and associated fossils is essential for their scientific relevance, but also have cultural importance as part of the geodiversity of this area and may contribute for social development through the educational value and as potential tourist attractions. Thanks to the exhibitions in local museums and associated educational activities, the local people have learned to value this geoheritage, and in turn contributed to its appreciation and preservation through identification of new fossiliferous sites and donation of fossils found accidentally.

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