







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

Ana Beatriz Furtado-Carvalho¹ , Rodrigo Rodrigues Adôrno² , Lívia Cardoso da Silva Rodrigues¹ ,
Carolina Zabini³ 

¹UNICAMP, Institute of Geoscience, Geoscience Graduate Program, Campinas, SP, Brazil, CEP: 13083-855.

²CGA - Center of Applied Geosciences, Geological Survey of Brazil, Brasília, DF, Brazil, CEP: 70.040-904.

³UNICAMP, Institute of Geoscience, Department of Geology and Natural Resources, Campinas, State of São Paulo, Brazil, CEP: 13083-855.

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.

Article Information

Publication type: Research Papers
Received 15 May 2024
Accepted 29 August 2024
Online pub. 30 August 2024
Editor: R. S. Horodyski and H. Araújo Jr.

Keywords:
Rio Ivaí Group
Gondwana
Hirnantian
Llandovery
Vila Maria Formation
Iapó Formation

*Corresponding author
Ana Beatriz Furtado Carvalho
E-mail address:
abfurtadocarvalho@gmail.com

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

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/

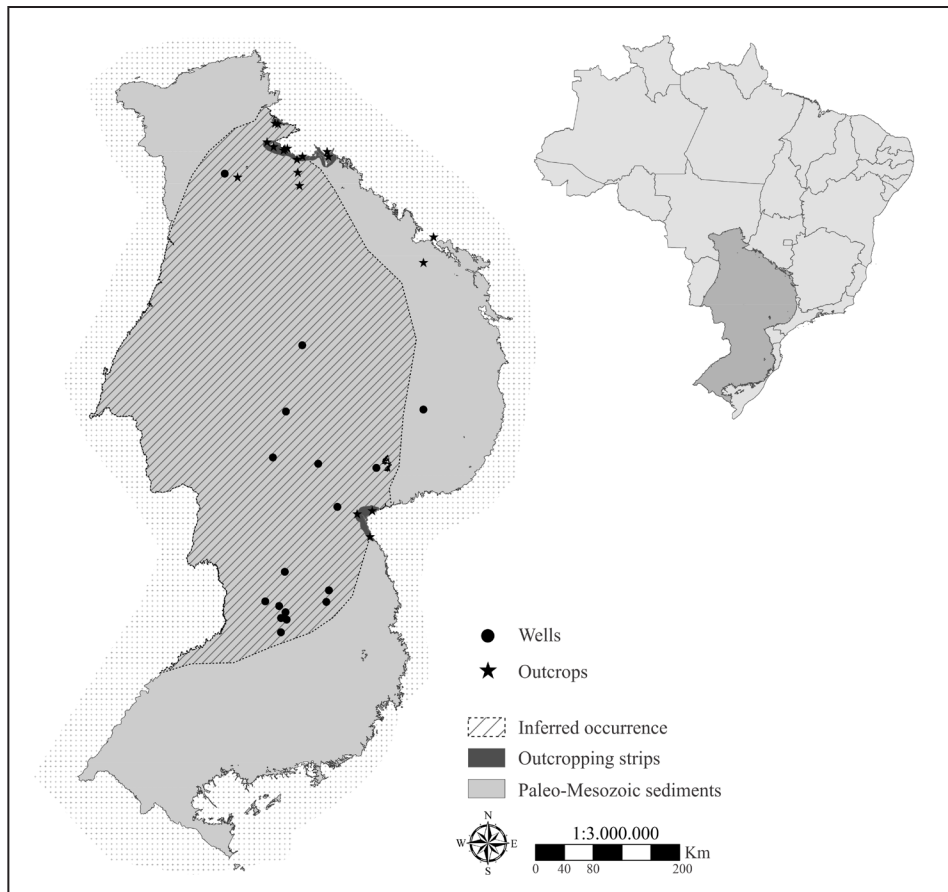


Figure 1. Simplified geologic map of the Paraná Basin in Brazil. The outcropping strips of the Rio Ivaí Group are represented in dark grey, at the northern and southeastern borders of the basin. The inferred occurrence is based on the isopach map (Milani et al. 1995).

Lower Silurian) (Assine et al. 1994; Adorno 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

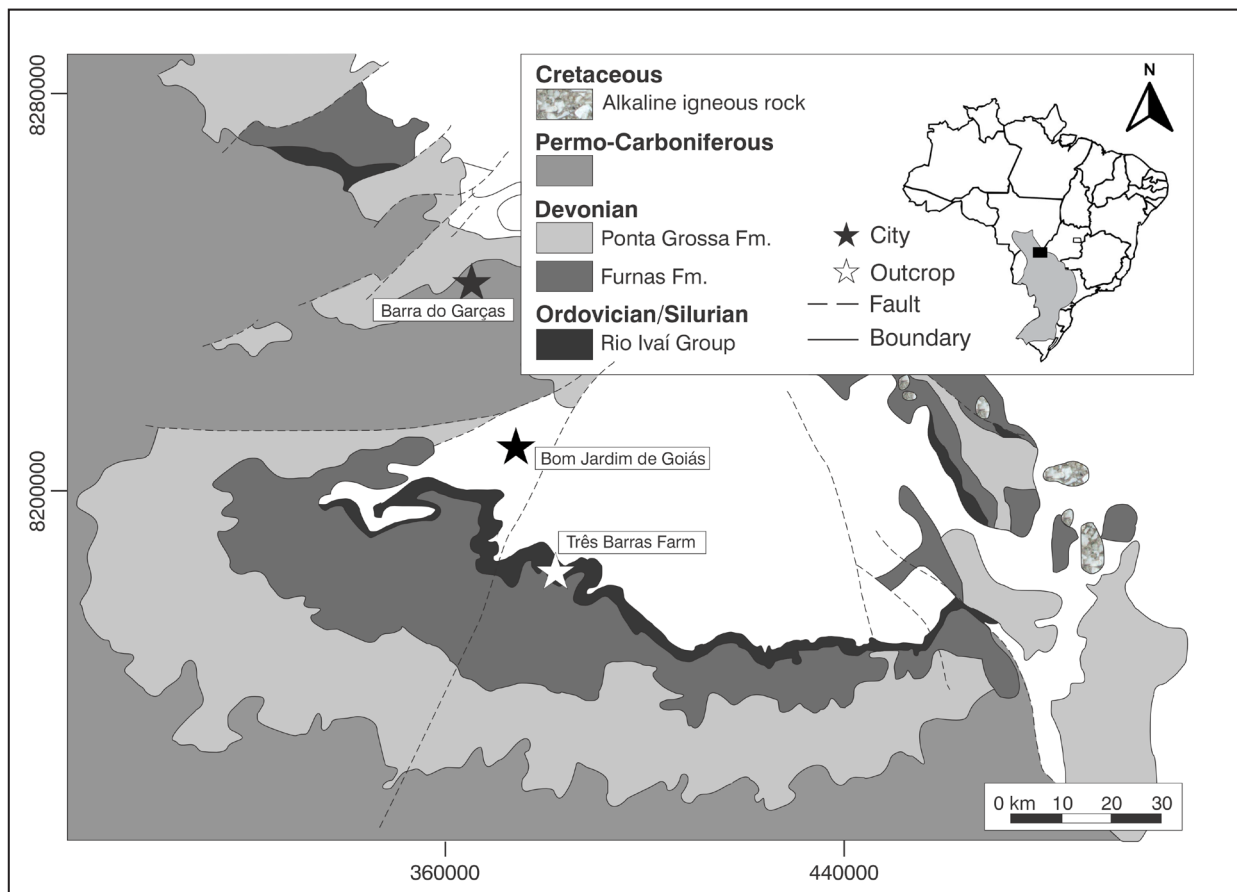


Figure 2. Geological map of the northern border of the Paraná Basin. The white star indicates the Três Barras Farm section (adapted from Adorno et al. 2016).

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 lapó 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 lapó 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 *Arthropycus 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. Cryptospores 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.

Adórno (2014) provided a new description of the section in their unpublished dissertation. Their main contribution was reporting that the lapó 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 lapó and Vila Maria formations, including ostracods, mollusk bivalves, and brachiopods.

Juvenile specimens of the ostracod *Satiellina paranaensis* Adórno 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

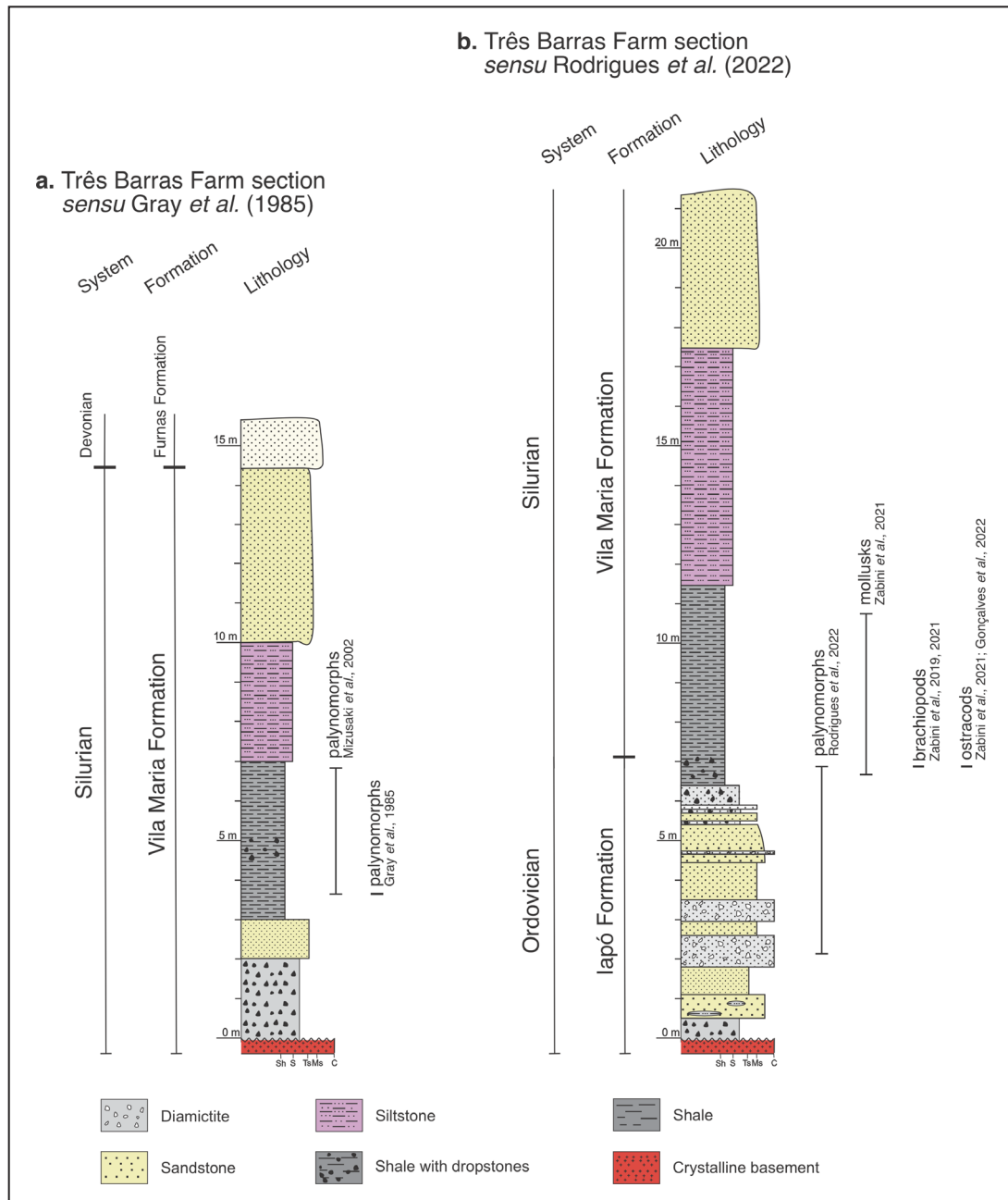


Figure 4. Stratigraphic profiles of the Três Barras Farm section proposed by different authors. a. Gray et al. (1985) described this outcrop for the first time and identified only the Vila Maria Formation of the Rio Ivaí Group. The Furnas Formation (Devonian) was not fully represented. Mizusaki et al. (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 lapó 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 lapó 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 lapó 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 lapó Formation at the Três Barras Farm, strongly suggesting the Hirnantian age to the upper layers of the lapó 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 prasinophytes, the first record of palynomorphs from the lapó 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 lapó 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					
		lapó	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	? <i>Dictyotidium</i> sp.		x	x	x				
	<i>Diexallophasis</i> sp.		x	x	x				
	<i>Dorsennidium</i> sp.	x						x	
	<i>Elektoriskos pogonius</i>			x					
	<i>Eupoikilofusa</i> sp.		x		x				
	<i>Eupoikilofusa striata</i>	x						x	
	<i>Evittia</i> cf. <i>E. dentifuculata</i>	x						x	
	<i>Helosphaeridium</i> sp.	x						x	
	<i>Leiosphaeridia</i> sp.			x					
	<i>Leiosphaeridia</i> sp. A	x						x	
	<i>Leiosphaeridia</i> sp. B	x						x	
	<i>Lophosphaeridium</i> sp. A	x						x	
	<i>Lophosphaeridium</i> sp. B	x						x	
	? <i>Multiplicisphaeridium</i> sp.		x	x	x	x			
	<i>Multiplicisphaeridium irregulare</i>	x						x	
	? <i>Pterospermella</i> sp.		x	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
	<i>Villosacapsula cf. setosapellicula</i>	x						x	
	<i>Veryhachium</i> sp.			x					
	<i>Veryhachium lairdii</i> group	x						x	
	<i>Veryhachium trispinosum</i> group	x						x	
	<i>Visbysphaera</i> n. sp.			x					
Brachiopoda	<i>Kosoidea australis</i>	x	x			x	x		
	Rhynchonelliformea	x	x				x		
Cryptospores	<i>Abditusdyadus laevigatus</i>		x		x				
	Dyads			x					
	<i>Dyadospora murusdensa</i>	x	x		x			x	
	<i>Dyadospora murusattenuata</i>	x	x		x			x	
	<i>Gneudaspora divellomedia</i>	x						x	
	<i>Imperfectotriletes patinatus</i>		x		x				
	<i>Imperfectotriletes vavrdovae</i>	x	x		x			x	
	<i>Laevolancis divellomedia</i>		x		x				
	<i>Laevolancis chibrikovae</i>	x						x	
	<i>Nodospora rugosa</i>		x		x				
	<i>Pseudodyadospora laevigata</i>	x	x		x			x	
	<i>Pseudodyadospora petasus</i>	x	x		x			x	
	<i>Rimosotetras problematica</i>	x	x		x			x	
	<i>Rugosphaera</i> sp. A	x						x	
	<i>Rugosphaera cerebra</i>	x						x	
	<i>Segestrespora laevigata</i>	x	x		x			x	
	<i>Segestrespora membranifera</i>		x		x				
	<i>Segestrespora rugosa</i>	x	x		x			x	
	<i>Sphaerasaccus glabellus</i>		x		x				
	Tetrahedral tetrad			x					
	<i>Tetrahdraletes</i>			x					
	<i>Tetrahdraletes grayae</i>	x						x	
	<i>Tetrahdraletes medinensis</i>	x	x		x			x	
	<i>Tetraplanarisporites laevigatus</i>	x						x	
	<i>Velatitetras anatoliensis</i>		x		x				
	<i>Velatitetras laevigata</i>	x	x		x			x	
	<i>Velatitetras retimembrana</i>		x		x				
	<i>Velatitetras rugosa</i>	x	x		x			x	
Fungi	<i>Tortotubus protuberans</i>	x						x	
Mollusca	? <i>Cuneameya</i> sp.		x				x		
	? <i>Paleoneilo</i> sp.		x				x		
Ostracoda	<i>Harpabollia harparum</i>	x					x		x
	<i>Satiellina paranaensis</i>	x					x		
Prasinophyte	<i>Tasmanites</i> 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, Adorno (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. Adorno 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.

Acknowledgments

A.B.F.C. would like to thank FAPESP for grant #2022/09053-9. C.Z. would like to thank FAPESP for grant #2021/12304-0. All authors thank Dr. Dermeval do Carmo for his constant help and for encouraging this manuscript to be written. The authors also thank the two reviewers who contributed with essential insight and suggestions for the improvement of this work.

Authorship credits

Author	A	B	C	D	E	F
ABFC						
RRA						
LCSR						
CZ						

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

References

- Adorno R.R. 2014. Estudo cronobioestratigráfico da Formação Vila Maria: litoestratigrafia e paleontologia do limite Ordoviciano-Siluriano da Bacia do Paraná, estados de Goiás e de Mato Grosso, Brasil Central. MSc Dissertation, Instituto de Geociências, Universidade de Brasília, Brasília, 94 p. <http://dx.doi.org/10.26512/2014.11.D.18061>
- Adorno R.R., Carmo D.A., Salas M.J., Zabini C., Assine M.L. 2016. The earliest ostracoda record from Brazil: Vila Maria Formation, Rio Ivai group, Paraná basin, Central Brazil. *Revista Brasileira de Paleontologia*, 19, 379-388. <https://doi.org/10.4072/rbp.2016.3.03>
- Assine M.L., Soares P.C. 1989. Correlações nas sequências mesopaleozoicas da Bacia do Paraná. *Acta Geol. Leopoldensia*, 29, 39-48.
- Assine M.L., Soares P.C., Milani E.J. 1994. Sequências tectono sedimentares mesopaleozóicas da Bacia do Paraná, sul do Brasil. *Revista Brasileira de Geociências*, 24, 77-89. <https://doi.org/10.25249/0375-7536.19947789>
- Assine M.L., Alvarenga C.J.S.D., Perinotto J.A.J. 1998. Formação Iapó: glaciação continental no limite Ordoviciano/Siluriano da Bacia do Paraná. *Revista Brasileira de Geociências*, 28, 51-60. <https://doi.org/10.25249/0375-7536.19985160>
- Bassett M.G., Popov L.E., Aldridge R.J., Gabbott S.E., Theron J.N. 2009. Brachiopoda from the Soom shale lagerstätte (Upper Ordovician, South Africa). *Journal of Paleontology*, 83, 614–623. <https://doi.org/10.1666/08-136.1>
- Benedetto J.L. 1986. The first typical Hirnantia fauna from South America (San Juan Province, Argentina Precordillera). In: Racheboeuf P.R., Emig C.C. (ed.). *Les Brachiopodes Fossiles et Actuels, Biostratigraphie du Paléozoïque*, 4, 439-447.
- Benedetto J.L., Cocks L.R.M. 2009. Early Silurian (Rhuddanian) brachiopods from the Argentine Precordillera and their biogeographic affinities. *Ameghiniana*, 46(2), 241-253. Available online at: <http://hdl.handle.net/11336/55350> / (accessed on 3 September 2024).
- Benedetto J.L., Halpern K., Galeano Inchausti J.C. 2013. High-latitude Hirnantian (latest Ordovician) brachiopods from the Eusebio Ayala Formation of Paraguay, Paraná Basin. *Palaeontology*, 56(1), 61–78. <https://doi.org/10.1111/j.1475-4983.2012.01158.x>
- Burjack M.I.D.A., Popp M.T.B. 1981. A ocorrência do icnogênero *Arthropycus* no Paleozóico da Bacia do Paraná. *Pesquisas em Geociências*, 14, 163-168. Available online at: <https://seer.ufrgs.br/index.php/PesquisasemGeociencias/issue/view/1393> / (accessed on 5 September 2024).
- Delabroye A., Vecoli M. 2010. The end-Ordovician glaciation and the Hirnantian Stage: a global review and questions about Late Ordovician event stratigraphy. *Earth-Science Reviews*, 98(3-4), 269–282. <https://doi.org/10.1016/j.earscirev.2009.10.010>
- Faria A.D. 1982. Formação Vila Maria - nova unidade litoestratigráfica siluriana da Bacia do Paraná. *Ciências da Terra*, 3, 12-15.
- Gonçalves L., Carmo D., Salas M.J., Adorno R.R., Meidla T., Denezine M., Rodrigues L.C.S., Assine M.L., Antonietto L. 2022. The first record of Hirnantian Ostracoda in South America: implications for the biostratigraphy and paleozoogeography of the Paraná basin. *Journal of Paleontology*, 96(2), 323–333. <https://doi.org/10.1017/jpa.2021.87>
- Grahn Y., Pereira E., Bergamaschi S. 2000. Silurian and lower Devonian chitinozoan biostratigraphy of the Paraná Basin in Brazil and Paraguay. *Palynology*, 24(1), 147-176. <https://doi.org/10.1080/01916122.2000.9989542>
- Gray J., Colbath G.K., Faria A., Boucot A.J., Rohr D.M. 1985. Silurian-age fossils from the Paleozoic Paraná Basin, southern Brazil. *Geology*, 13(7), 521-525. [https://doi.org/10.1130/0091-7613\(1985\)13%3C521:SFFTPP%3E2.0.CO;2](https://doi.org/10.1130/0091-7613(1985)13%3C521:SFFTPP%3E2.0.CO;2)
- Harlan R. 1831. Description of an extinct species of fossil vegetable, of the family Fucoides. *Journal of the Academy of Natural Sciences of Philadelphia*, 6, 289–295.
- Havlíček V., Mergl M. 1988. Two new discinid genera (Brachiopoda) from the Silurian and Devonian of the Prague Basin, Czechoslovakia. *Journal of the Czech Geological Institute*, 63, 169-172.
- Maaack R. 1947. Breves notícias sobre a geologia dos estados do Paraná e Santa Catarina. *Arquivos de Biologia e Tecnologia*, 2, 63–154. <http://dx.doi.org/10.1590/S1516-89132001000500010>
- Milani E.J., Melo J.H.G., Souza P.A., Fernandes L.A., França A.B. 2007. Bacia do Paraná. *Boletim de Geociências da Petrobras*, 15(2), 265-287. Available online at: <https://bgp.petrobras.com.br/bgp/article/view/310> / (accessed on 5 September 2024).
- Milani E.J., Assine M.L., Soares P.C., Daemon R.F. 1995. A Sequência Ordovício-Siluriana da Bacia do Paraná. *Revista Brasileira de Geociências*, 24, 301-320.
- Mizusaki A.M., Melo J.H.G., Vignol-Lelarge M.L., Steemans P. 2002. Vila Maria Formation (Silurian, Paraná basin, Brazil): integrated radiometric and palynological age determinations. *Geological Magazine*, 139(4), 453–463. <https://doi.org/10.1017/S0016756802006659>
- Puente G.S., Rubinstein C.V. 2007. The Ordovician chitinozoans from the western Gondwana margin, northwestern Argentina. In: *European Meeting on the Palaeontology and Stratigraphy of Latin America*, 4, Cuadernos del Museo Geominero, 8, 99-105.
- Rodrigues L.C., Carmo D., Assine M., Steeman P. 2022. Cryptospores of Iapó formation: the first evidence of early land plants from Late Ordovician in Paraná Basin, Brazil. *Review of Palaeobotany and Palynology*, 305, 104742. <https://doi.org/10.1016/j.revpalbo.2022.104742>
- Stanley S.M. 2016. Estimates of the magnitudes of major marine mass extinctions in Earth history. *Proceedings of the National Academy of Sciences*, 113(42), 6325-6334. <https://doi.org/10.1073/pnas.1613094113>
- Troedsson G.T. 1918. *Om Skanes brachiopodskiffer*. Lunds Universitets Årsskrift, Lund, Nabu Press, 15, 110 p.
- Truuver K., Meidla T. 2015. A Hirnantian deep-water refuge for warm-water ostracods in Baltoscandia. *Geological Quarterly*, 59(4), 738-749. <https://doi.org/10.7306/gq.1258>
- Vannier J.M.C. 1986. Ostracodes Palaeocopa de l'Ordovicien (Arening-Caradoc) Ibero-Armoricain. *Paleontographica Abteilung*, 193(5-6), 145–218.
- Zabini C., Furtado-Carvalho A.B., Carmo D., Assine M.L. 2019. A new discinoid *Kosoidea australis* sp. nov. from the Iapó and Vila Maria Formations, NE Paraná Basin, Brazil. *Historical Biology*, 33(4), 534–542. <https://doi.org/10.1080/08912963.2019.1648447>
- Zabini C., Denezine M., Rodrigues L.C.S., Gonçalves L.R.O., Adorno R.R., Carmo D., Assine M.L. 2021. Fossil diversity and taphonomy of glacial and post-glacial lower paleozoic strata, NE Paraná Basin, Brazil. *Journal of South American Earth Sciences*, 111, 103470. <https://doi.org/10.1016/j.jsames.2021.103470>