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Evolution of ichnological knowledge in the Furnas Formation (Silurian-Devonian) of Parecis and Paraná basins, Brazil

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Abstract

Ichnology provides detailed information on the environmental parameters involved during deposition, serving as a basis for paleoenvironmental interpretations. To this end, ichnological analyses focus on the behavioral aspects represented by ichnoassociations, providing details of the interaction between organisms and the abiotic environment. Ichnological studies in the deposits of the Furnas Formation have been recorded since the early twentieth century, mentioning the presence of "worm tubes". The overall lack of body fossils and microfossils and the lithological uniformity have led to extensive discussions about its depositional origin. The palaeodepositional scenario of the Furnas Formation has been highlighted by the recognition of trace fossils, proposing a shallow marine setting for the unit. This review study focuses on examining the evolution of ichnological knowledge and its application to paleoenvironmental characterization in the deposits of the Furnas Formation in the Parecis and Paraná basins, Brazil, based on a review of the studies for the unit.

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1. Introduction

The Silurian-Devonian sedimentary sequence of the Paraná Basin has been gaining prominence in recent decades with the development of ichnological research (e.g., Ciguel and Aceñolaza 1986, 1989; Campanha 1985; Fernandes and Melo 1985; Siqueira 1989; Schubert 1995; Fernandes 1996; Assine 1999; Bahia et al. 2006; Netto et al. 2014; Sedorko et al. 2013, 2017, 2018a, b, c, d, 2019, 2021, 2022, 2024; Richter et al. 2021, 2023). Advances in ichnological knowledge have proven its importance (e.g., Sedorko and Netto 2024), due to itsdual nature as an object of Paleontology and Sedimentology for the application of ichnofossils in the characterization of the depositional environments. Particularly for the Furnas Formation, that is considered mostly unfossiliferous, preserving only plant remains and palynomorphs in its transitional layers to the Ponta Grossa Formation, but being very rich in this ichnofossiliferous content. On the other hand, Furnas Formation in Parecis Basin was almost no investigated regarding its ichnological content.

Until now, the state of the knowledge on the Furnas Formation (i.e. sedimentology and ichnology) is scattered in the specialized bibliography. In the general literature there are a few studies that synthetized from an historical point of view the Siluro-Devonian strata, and concentrated in the Paraná Basin (e.g. Ciguel 1996; Sedorko et al. 2013; Richter et al. 2021), without studies with this scope for Parecis Basin. These studies generally emphasized the survey of its ichnofossiliferous content and the revision of the ichnotaxonomy of trace fossil. Considering that the Furnas Formation deposits preserve

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a rich ichnofossiliferous content, this review study aims to synthesize the evolution of ichnological knowledge and its application in the paleoenvironmental characterization of the Furnas Formation in the Parecis and Paraná basins, Brazil, identifying the main phases and approaches in the evolution of the ichnological knowledge.

2. Geological Setting

The Furnas Formation is characterized by a relative lithological uniformity (conglomerates, fine- to very coarse-grained sandstones, very subordinated intercalations of mud rocks) and physical sedimentary structures at the Paraná Basin (e.g. Andrade and Camarço 1980; Petri and Fúlfaro 1983; Schneider et al. 1974), associated with a rich ichnodiversity reflecting a wide range of behavioral patterns (e.g. Fernandes 1996; Fernandes et al. 2002; Sedorko et al. 2017). These features are key elements for the interpretation of the depositional environment of the formation. The Furnas Formation deposits in the Paraná Basin are located on the northwestern and eastern borders, while in the Parecis Basin it occurs on the eastern border, correlating to the northern flank of the Paraná Basin (Felix et al. 2017). The Parecis and Paraná basins occupy a vast area of the Brazilian territory (Figure 1A).

2.1 Parecis Basin

The Parecis Basin comprises approximately 500,000 km^2 into the central-western portion of Brazil, in the states of Rondônia and Mato Grosso; accumulating more than 6,000 meters of essentially siliciclastic sediments deposited from the Neoproterozoic to the Late Cretaceous (Bahia et al. 2006). The deposition during the Paleozoic occurred with the entry of exotic sediments with progressive marine incursions on the flexed Amazonian craton (Bahia et al. 2006; Rubert 2017), leading to the deposition of the Furnas and Ponta Grossa formations (Loureiro 2016).

2.2 Paraná Basin

The Paraná Basin has an extension of approximately 1,600,000 km^2 covering portions of the Brazilian, Paraguayan, Argentinian and Uruguayan territories (Figure 1A). Due to its specificity about aspects as the geotectonic positioning and tectonosedimentary features, it is characterized as a retro-foreland basin for the Rio Ivaí and Paraná supersequences, or pericratonic syneclysis for the post-Devonian interval (Henrique-Pinto et al. 2021). The evolution of its sedimentary filling occurred in response to the tectonic and eustatic cycles

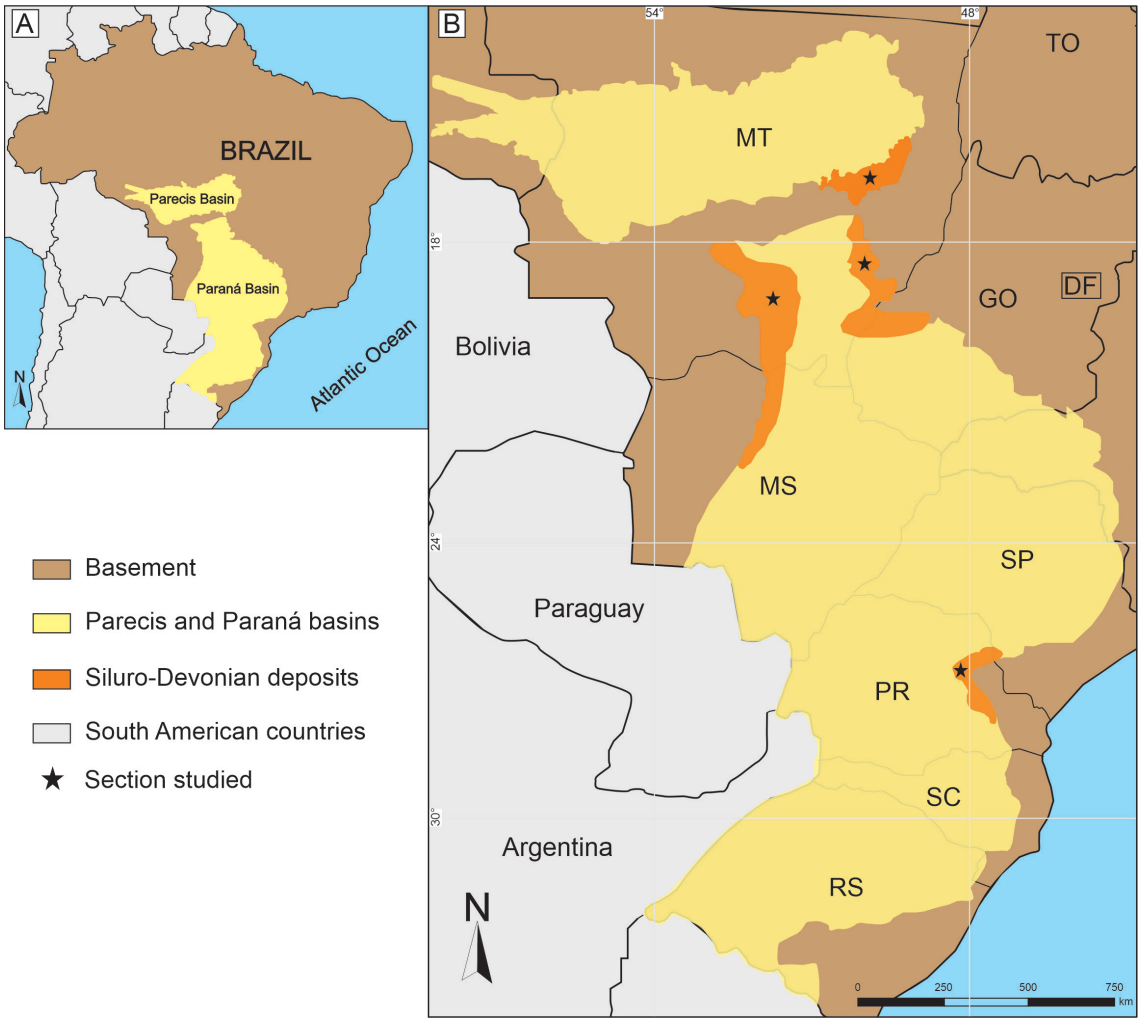

FIGURE 1. A. Location map of the Parecis and Paraná basins on the South American continent. B. Distribution of Silurian-Devonian deposits in the Parecis and Paraná basins.

associated with Western Gondwana, deposited from the Late Ordovician to the Late Cretaceous (Milani et al. 2007).

2.3 Depositional sequences

For the Paraná Supersequence (Paraná Basin), Sedorko et al. (2018a) proposed four depositional sequences in the Silurian-Devonian interval, deposited in marine environments between the Lower Silurian to Middle Devonian (Figure 1B). These sequences were referred as Lower Silurian, Siluro-Devonian, Devonian I and II. The deposits of the Furnas Formation comprise the Lower Silurian and part of the Siluro-Devonian depositional sequences of Sedorko et al. (2018a), deposited in shallow marine, tidally- and storm-influenced paleoenvironments (Borghi 1993; Assine 1999; Bergamaschi 1999; Sedorko et al. 2017, 2024; Richter et al. 2023). The lower and middle units of the Furnas Formation represent the transgressive phase of the Lower Silurian sequence, with restricted occurrences with regressive trend. The Siluro-Devonian sequence overlaps these strata, limited by an erosive surface, with a transgressive trend that culminates in the mudstones of the Ponta Grossa Formation (Assine 1996).

3. Material and Methods

This study conducts a comprehensive bibliographic research on works published between 1912 to 2024, systematically analyzing the evolution of ichnological research in the deposits of the Furnas Formation in the Parecis Basin, with a special focus on the Paraná Basin, which presents a broader number of studies. To achieve this objective, a National and international scientific journals, books, book chapters, reports, dissertations, theses, and abstracts of events were also consulted, totaling 95 researches analyzed (see Appendix A). Literature searches were constructed using online databases from research institution libraries, Google Scholar, Taylor & Francis, Science Direct, Capes Journals, Minerva UFRJ Platform, and Conference Proceedings. The research included keywords (in Portuguese or English) related to the terms “Furnas Formation”, “Ichnology”, “Trace fossils”, and “Paleoenvironmental interpretation”.

4. Results and Discussions

Based on this research, the history of the development of ichnological research in the Furnas Formation can be divided into three periods:

1. Classical Ichnology (1912 - 1942): the first observations on biogenic structures associated with “worm tubes” in the deposits of the Furnas Formation.
2. Advent of Ichnotaxonomy (1942 - 1992): most works emphasized the identification and description of ichnofossils.
3. Approach of Applied Ichnology to Paleoenvironmental Reconstructions (1992 - present): marks the application of ichnological studies as indicators of the depositional environment for the unit.

The first period is characterized by a limited number of researches, mostly focused on identifying and describing trace fossils. This factor is due to the paradigm shifts concerning to the development of ichnology as a science responsible for the recognizing of biogenic structures and interpreting their meaning in the sedimentary record (Osgood 1975). The last two periods used ichnology as an applied tool for identify ichnotaxons and, later, for paleoenvironmental characterization of the Furnas Formation.

4.1 Classical Ichnology (1912 - 1942)

The name “Grés de Furnas” was used to characterize the sandstones at the base of the Devonian sections of Paraná. Oliveira (1912, p. 34) described “the frank disagreement with the metamorphic terrains that lie to the east of the escarpments called Serrinha and Furnas” characterized by the presence of abundant “white sandstone, sometimes yellowish, coarse, often friable, that outcrops in the upper part of those escarpments”.

In addition to describing the stratigraphy of the unit, Euzébio P. Oliveira (1912, p. 35) highlighted the lack of body fossils, except for the presence of “worm tubes”, mentioning that “no fossils have been found in the Furnas sandstone, except for *Arenicolites* tubes, on the banks of the Grande stream, which falls into the Matadouro stream, a tributary of the Verde River in Ponta Grossa”.

John M. Clarke in this iconic monography (Clarke 1913, p. 64) carried out an extensive systematic review of its fossiliferous content of Paraná Basin, mentioning that, for the Furnas Formation “so far no fossils or traces of organisms have been provided, except for worm tubes, in its upper layers”. Despite the lack of detailed descriptions in the works of Oliveira (1912) and Clarke (1913), these authors started the studies that later allowed the recognition of ichnofossils.

Years later, in 1938, Frederico W. Lange identified the “first fossils found on the bank of the Pitangui River, near the Ponta Grossa Old Power Plant” (Lange 1942, p. 4). Paulino F. Carvalho (1941) provided the information for the publication of a compendium on the Devonian of Paraná Basin, and erroneously associated this finding in the sediments of the Furnas Formation with the worm tubes attributed to the ichnogenus *Arenicolites*, based on the descriptions of Oliveira (1912, 1927).

Lange (1942) found similar structures in the sandstones near the Passo do Pupo, also in the municipality of Ponta Grossa. This author describes trace fossil in two localities as “elongated, in the form of slightly undulating tubes” (Lange 1942, p. 5). Initially interpreted as “*Bilobites*” associated with the activity of annelids, crustaceans, or echinoderms. However, d’Orbigny (1842), had already synonymized the ichnogenus *Bilobites* as *Cruziana*.

The absence of superficial ornamentation and the general appearance of the burrows lead Lange to identify these structures as belonging to the ichnogenus *Fraena* Rouault 1850, denominating these “vermiform remains in the Furnas Sandstone” as the ichnospecies *Fraena furnai*. This fact makes Lange the pioneering in the description and classification of ichnofossils for the Furnas Formation.

4.2 Advent of ichnotaxonomy (1942 - 1992)

The first formal descriptions of trace fossils for the Furnas Formation, was made by Lange (1942), and started with the ichnotaxonomic discussions about the ichnospecies *Fraena*

furnai, as well as promote researches on ichnofossils in the unit in the following years (see Table 1).

The first major nomenclatural change for *Fraena furnai* was proposed by Lange and Petri (1967) without arguing the causes of this change from the ichnogenus *Fraena* to *Rouaultia* (Sedorko et al. 2013). In the same context, Fernandes and Netto (1985), based only on literature data without the analysis of the samples, proposed the modification of the designation *Rouaultia furnai* to *Didymaulichnus furnai*.

Ciguel and Acenõlaza (1986), when addressing the ichnology of the Furnas Formation in the states of Paraná and Goiás, and based on the recommendation of Häntzschel (1975), confirmed the synonymy of *Rouaultia* Roualt, 1850 to *Didymaulichnus* Young, 1972, defining it as "bilobed and smooth tracks, parallel to the bedding, with a gently curved shape, preserved in epirelief or hyporelief" (Ciguel and Acenõlaza 1986, p. 595), temporarily clarifying the nomenclatural problem surrounding the ichnofossil found by Lange (1942).

Most ichnofossils are not good chronostratigraphic markers, however, Aceñolaza and Ciguel (1987) suggested a Silurian age for the Balcarce (Argentina) and Furnas formations based on the comparison of the ichnofossiliferous association found in those units. The work of Sedorko et al. (2017) corroborated the proposal of Aceñolaza and Ciguel (1987) by recognizing ichnofossils wiht significance in the lower and middle units of the formation, associated with the "*Cruziana* Group", or "*Cruziana* Stratigraphy", as referred by Seilacher (2007). Additionally, they identified the ichnotaxa *Artrhophycus alleghaniensis* e *A. brongniartii,* which are restricted to the Lower Silurian. The authors also suggested the possibility that the ichnospecies *Didymaulichnus furnai* would be *Didymaulichnus lyelli* (Aceñolaza and Ciguel 1987).

Borghi and Schubert (1992) resumed the discussion on the appropriate nomenclature for the ichnogenus *Didymaulichnus* isp., proposing a new ichnogenus for bilobed forms at the base and unilobed at the top, *Furnasichnus*. Still on *Didymaulichnus,* Ciguel (1996) reviewed the occurrences based on holotypes and paratypes, proposing that the specimens described as *F. furnai, R. furnai and D. furnai* should be synonymized to *Didymaulichnus lyelli.* Later, Sedorko et al. (2017) synonymized *Furnasichnus* to *Didymauliponomos rowei*. Regarding ichnotaxonomy, Sedorko et al. (2017) proposed the ichnotaxon *Rusophycus acacensis* and confirmed the *Cruziana acacencis*.

Bergamaschi (1992) analyzing the deposits on the eastern edge of the basin, identified the presence of ichnofossils belonging to the *Skolithos* ichnofacies (see Table 1), interpreting the depositional environmental at the top of the Furnas Formation section as upper shoreface. However, Sedorko et al. (2013) mentioned that the patterns of ichnofossiliferous associations described by Bergamaschi (1992) would reflect structures and behavioral patterns associated with the expressions of the proximal *Cruziana* ichnofacies, since the horizontal pattern and the predominance of detritus-feeding burrows are not consistent with the *Skolithos* ichnofacies, an interpretation shared in this work.

This historical period of ichnological research in the deposits of the Furnas Formation marked the interest in the recognition of ichnofossils, as well as the beginning of the use

TABLE 1.List of studies that described the presence of ichnofossils during the "Advent of ichnotaxonomy" phase.

Author	Ichnotaxons	Locality
Ciguel and Godoy (1985)	*Palaeophycus isp.*	Serra do Purunã, São Luiz do Purunã, state of Paraná
Ciguel and Aceñolaza (1986)	*Lockeia isp.,* *Palaeophycus alternatus, Palaeophycus tubularis, Rusophycus imbricata*	States of Paraná and Goiás
Ciguel and Aceñolaza (1988)	*Conosthicus isp.*	Alagados Region, Ponta Grossa state of Paraná
Ciguel and Aceñolaza (1989)	*Conosthicus isp., Didymaulichnus furnai, Palaeophycus tubularis, Planolites isp.,* *Skolithos isp.*	Alagados Region, Ponta Grossa state of Paraná
Bergamaschi (1992)	*Didymaulichnus isp., Monocraterion isp., Palaeophycus isp., Planolites isp.,* *Rusophycus isp.*	Jaguariaíva, state of Paraná
Borghi and Schubert (1992)	*Conosthicus isp., Didymaulichnus furnai, Lockeia isp., Palaeophycus tubularis, Palaeophycus alternatus, Planolites vulgaris, Planolites isp., Rusophycus didymus,* *Skolithos isp.*	—

of Ichnology for the identification within a paleoenvironmental contexts. In addition, with the intensification of ichnotaxonomic studies after this period, there was the recognitionof a detailed and rich ichnodiversity distributed throughout the units of the Furnas Formation (Fig. 2 and Fig. 3). The locations of the ichnological descriptions are shown in Appendix B.

4.3 Approach of applied ichnology to paleoenvironmental reconstructions (1992 - present)

The Furnas Formation has already enabled discussions in different aspects about the genesis of the depositional system of its rocks (e.g. fluvial, fluvio-glacial, fluvio-deltaic, deltaic, aeolian, estuarine, tidal, shallow marine), which have led to the greatest controversies about its origin. The first interpretations of its depositional genesis derive from two distinct models: one as a marine environment (e.g. Oppenhein 1936; Carvalho 1941; Maack 1947; Almeida 1954; Sanford and Lange 1960; Lange and Petri 1967; Petri and Fúlfaro 1976, 1983; Borghi 1997), and another one as fluvial setting (e.g. Ludwig and Ramos 1965; Schneider et al. 1974; Melo 1988; Zalán et al. 1987; Mussa et al. 1996; Pereira et al. 1998; Araujo 2016; Martins et al. 2018).

According to Bergamaschi (1992), the vast majority of the paleoenvironmental interpretations were based on relatively restricted data sources (e.g. lithology, sedimentary structures, isolated surface case studies with scarce subsurface information). Moreover, most of these studies did not integrate ichnological data. In this way, several generalist models were postulated, through methodological analyses at the level of the general scale for the whole unit (Borghi 1996).

According to Assine (1999, p. 357), the factor that contributed to the difficulty of an accurate paleoenvironmental reconstruction in the deposits of the Furnas Formation was the problem resulting from the “poverty of fossils, the scarcity of interbedded pelites, the large area of occurrence and, above all, the lack of modern analogous environments”. Another limiting condition is the lack of depositional models compatible with the unit’s faciological characteristics in the geological record (Bergamaschi 1999).

Although the Furnas Formation does not have formal members, faciological contrasts in the stratigraphic succession of the unit along the basin allow the subdivision into three informal units on the Paraná Basin (Pereira and Bergamaschi 1989; Bergamaschi 1992; Borghi 1993, 1996; Schubert 1995; Assine 1996, 1999; Bergamaschi 1999). The tripartite operational division used is that of is the one proposed by Assine (1999) who, based on surface and subsurface data and gamma-ray profiles, designated the intervals of the Furnas Formation as lower, middle, and upper units.

Borghi (1993, 1994a) characterized the depositional facies, describing eleven lithofacies (ruditic, arenaceous, and pelitic), as well as the *Skolithos* and *Cruziana* ichnofacies and one biofacies (paleoflora) for the Furnas Formation. The identification of ichnofaciological signatures suggest deposition in proximal marine environments (e.g., MacEachern et al. 2007), being the basis for further studies that would attest to a shallow marine environment to the levels with the presence of ichnofossils.

The scenario of a marine environment dominated by the action of tidal waves has been discussed in previous works (Lange 1965; Bigarella and Salamuni 1967; Lange

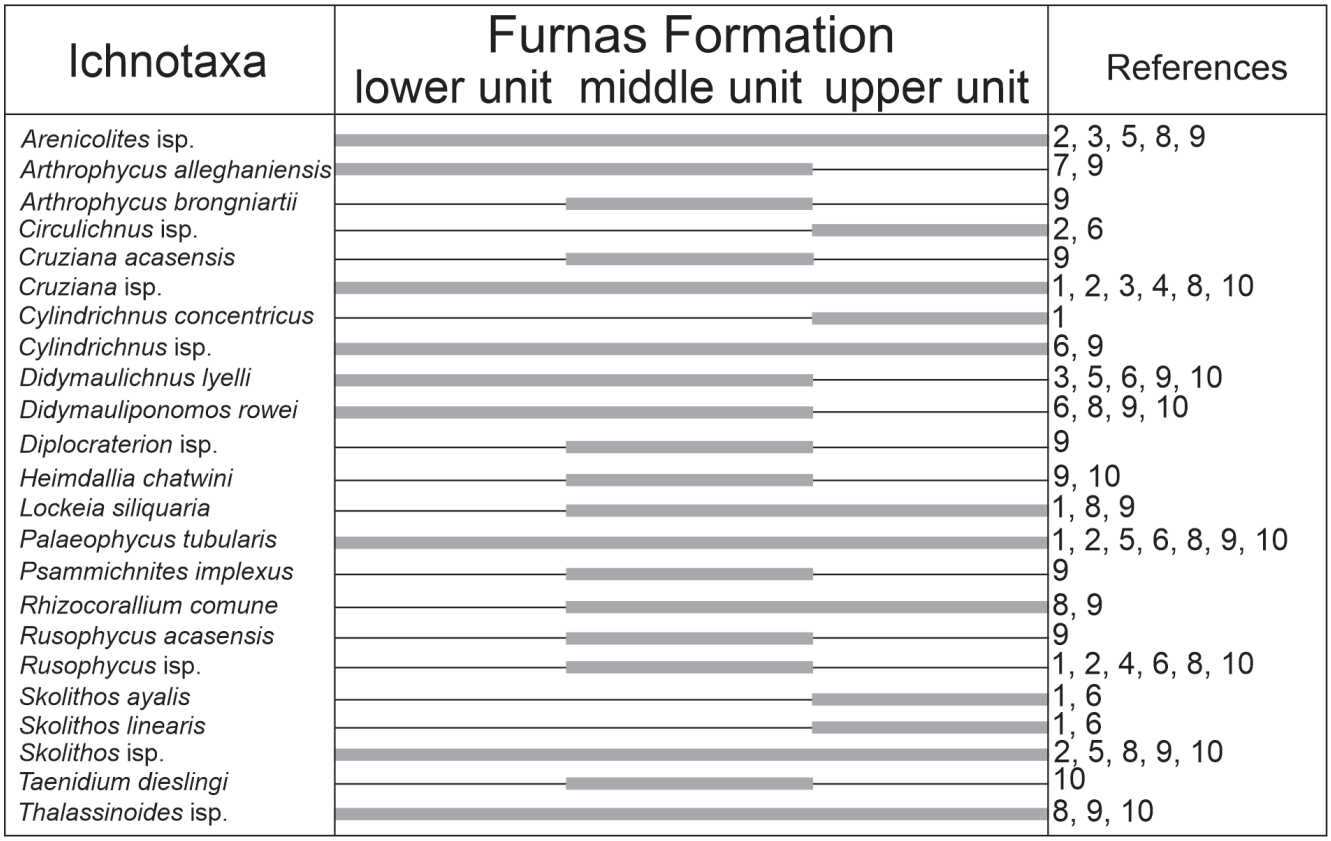

FIGURE 2. List of works by Borghi (1993)[1]; Schubert (1995)[2]]; Assine (1996)[3]; Assine and Góis (1996)[4]; Ciguel et al. (1996)[5]; Fernandes (1996)[6]; Moreira et al. (1998)[7]; Tognoli et al. (2002)[8]; Sedorko et al. (2017)[9] and Richter et al. (2023)[10] who addressed the identification and stratigraphic distribution of the main ichnotaxa of the Furnas Formation after the advent of ichnotaxonomy period.

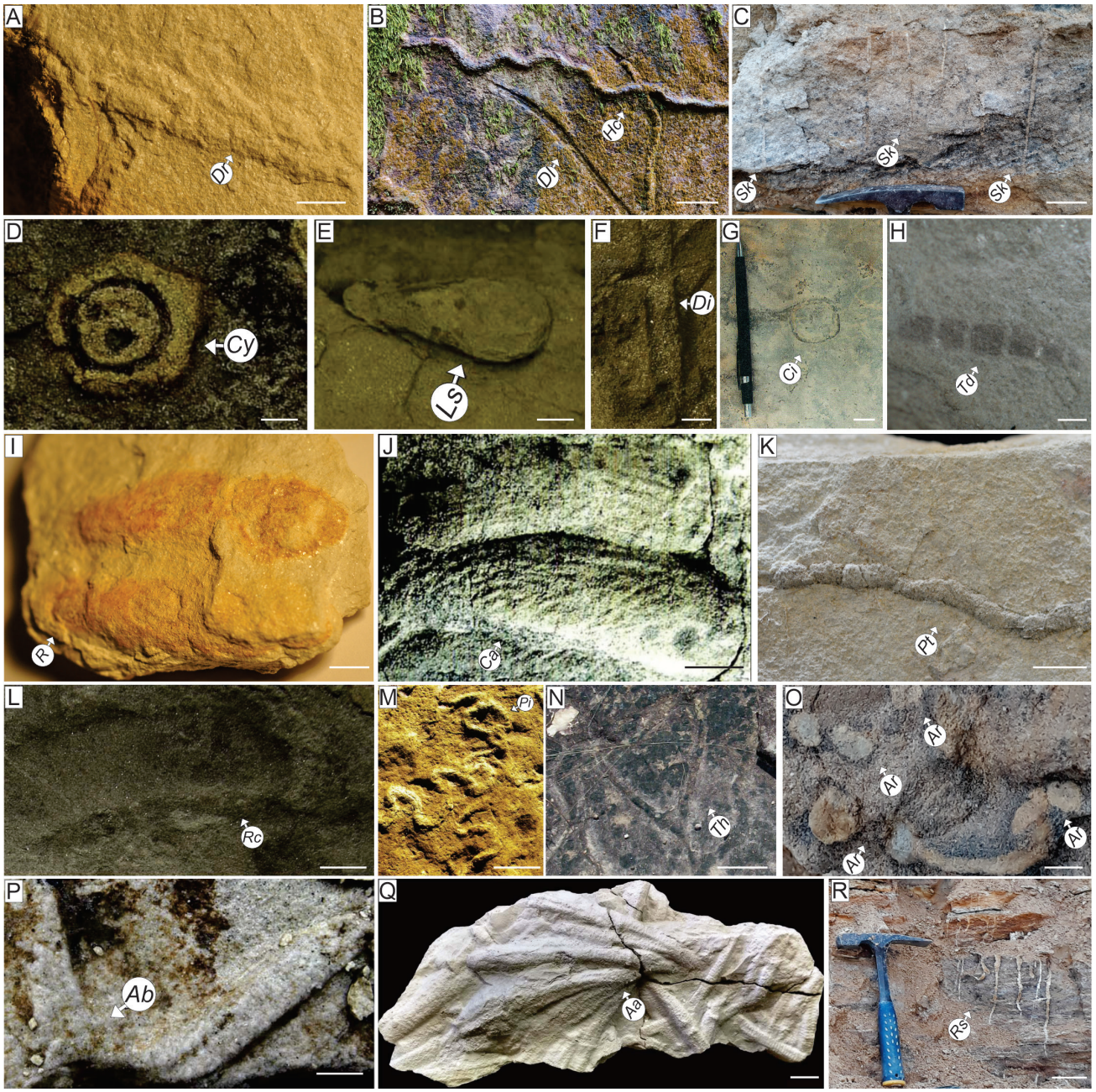

FIGURE 3. Trace fossils from Furnas Formation recorded in Paraná Basin: A. *Didymauliponomos rowei (Dr)*. B. *Didymaulichnus lyelli (Dl)* and *Heimdallia chatwini (Hc)*. C. *Skolithos isp. (Sk)*. D. *Cylindrichnus isp. (Cy)*. E. *Lockeia siliquaria* (Ls). F. *Diplocraterion isp.* G. *Circulichnus isp. (Ci)*. H. *Taenidium dieslingi (Td)*. H. I. *Rusophycus isp. (R)*. J. *Cruziana acacensis (Ca)*. K. *Palaeophycus tubularis (Pt)*. L. *Rhizocorallium comune (Rc)*. M. *Psammichnites implexus (Pi)*. N. *Thalassinoides isp. (Th)*. O. *Arenicolites isp. (A)*. P. *Arthrophycus brongniartii (Ab)*. Q. *Arthrophycus alleghaniensis (Aa)*. R. *Rosselia socialis (Rs)*. Scale = 2 cm. Modifield by Schubert (1995); Fernandes (1996); Sedorko et al. (2017) and Richter et al. (2023).

and Petri 1967; Petri and Fúlfaro 1983), highlighting Borghi (1993) who considered a depositional paleoenvironment for all the units of Furnas Formation, as a shallow marine platform associated with high-energy beaches represented by rudaceos or sandy coast where facies deposited under the dominant action of tides, resuspended by storms were preserved (Borghi 1994b).

4.3.1 Lower unit

It is arranged immediately above the discordance with the underlying units, in flat and well-defined contacts, presenting greater resistance to erosion. Faciologically, it encompasses an association of medium- to coarse-grained sandstones, sometimes conglomeratic, and less frequently, medium- to fine-grained sandstones (Assine 1996). Bergamaschi (1999) mentioned that the interval is the bearer of the most varied types of sedimentary structures, describing the presence of planar cross-stratifications, but also the occurrence of wave cross bedding, climbing ripples, parallel lamination, and herringbone cross-stratification. The biogenic sedimentary structures attributed to the *Cruziana* ichnofacies, parallel to the bedding, are recorded (Fernandes 1996). However, ichnoassociations of the *Skolithos* ichnofacies also occur as

subordinated component in sandstones bearing trough and planar cross-stratifications (Sedorko et al. 2017).

The predominant faciological context for on the base of the formation, is associated with the predominance of conglomeratic features and medium to coarse sandstones exhibiting physical and biogenic sedimentary structures. The probable deposition occurred in a coastal to shoreface system affected by strong waves and currents, marked by the reworking of sediments under coastal floodplains (sensu: Assine 1996; Bergamaschi 1999; Sedorko et al. 2017; Richter et al. 2023).

4.3.2 Middle unit

It comprises the facies of the lower interval with a decrease in the incidence and thickness of the conglomeratic bodies, as well as a slight particle size decrease of the sandstone bodies, with a predominance of the medium granulometry (Bergamaschi 1999). According to Assine (1996, 1999), lithotypes often grade to intercalations of thin layers of siltstones and/or white to light green shales, often rich in muscovites, and with ichnofossils of the *Cruziana* ichnofacies (Fernandes 1996; Sedorko et al. 2017), locally including ichnoassociations of the *Skolithos* ichnofacies (Sedorko et al. 2017).

According to Assine (1996), the lithofacies described are interpreted as a product of deposition in tidal-dominated marine environments, with the action of currents oblique to the coastline. The middle unit is characterized by ichnofossils belonging to the *Cruziana* ichnofacies (Fernandes 1996; Assine and Góis 1996; Sedorko et al. 2017; Richter et al. 2023). The presence of an increase in ichnofossils associated with the finer sediments materializes periods of lower energy, with a marked decrease or even temporary stops in sedimentary transport (Assine 1996).

4.3.3 Upper unit

It is characterized by an increase in conglomeratic levels and a tendency to increase the particle size of sandstones, ranging from medium- to very coarse-grained sandstone (Bergamaschi 1999). Assine (1996) pointed out that the upper part of the Furnas Formation, locally, encompasses features of very fine sandstones with hummocky cross-stratification, with macrofossils of vascular plants (sensu: Petri 1948; Bigarella et al. 1966; Rodrigues et al. 1989; Mussa and Borghi 1993; Bolzon et al. 1994; Mussa et al. 1996, 2002; Gerrienne et al. 2001; Milagres et al. 2007; Goñez and Gerrienne 2010). Associated with these levels, there are rare heterolithic facies, with palynomorphs whose content allowed the insertion of the top of the upper unit in the Lower Devonian (sensu: Dino and Rodrigues 1995; Dino et al. 1995; Loboziak et al. 1995; Grahn et al. 2010, 2013). Most of the lithofacies in this unit are weakly bioturbed, containing traces of the assemblage of ichnofossils representing the ichnofacies *Skolithos* and proximal *Cruziana* (Fernandes 1996; Sedorko et al. 2017). It is relevant the occurrence of dense *Rosselia* ichnofabric in upper levels of Furnas Formation from Paraná state (Netto et al. 2014) and dense occurrence of *Skolithos* in similar levels from Mato Grosso state (Sedorko et al. 2024).

The evident increase in particle size by medium- to coarse-grained sandstones, where continuous pebble surfaces are found, attests to a more energetic environment (Assine 1996) with a regressive tendency (Bergamaschi 1999). The lag deposits found in the unit were formed by marine erosion processes of winnowing, resulting from the action of storm waves (Assine 1996). In addition, these deposits record macrofossils of plants that inhabited transitional- coastal environments, associated with a predominance of vertical structures (Assine 1996; Bergamaschi 1999; Netto et al. 2014; Sedorko et al. 2017).

4.4 Ichnological evidence

The incorporation of ichnological research in the deposits of the Furnas Formation played a fundamental role for the paleoenvironmental reconstitution of the unit (e.g. Aceñolaza and Ciguel 1987; Borghi 1993; Assine and Góis 1996; Assine 1996; Bergamaschi 1999). According to Fernandes (1996), the recognition of the ichnofossiliferous content distributed in the *Skolithos* and *Cruziana* ichnofacies made it possible to attest to a shallow marine depositional system for the intervals containing ichnofossils. These ichnofacies are well distributed throughout the Furnas Formation (Sedorko et al. 2017; Fig. 3A). The ichnoassociations of the *Cruziana* ichnofacies are more frequent between the lower and middle units, while the *Skolithos* ichnofacies more frequent in the levels of the formation (Fernandes 1996).

Ichonological interpretations suggest that the deposition of the Furnas Formation occurred from a coastal system at the base of the formation that reworked alluvial sediments, and that they were drowned by tidal- influenced foreshore to shoreface facies (e.g. Borghi 1993; Schubert 1995; Assine and Góis 1996; Assine 1996, 1999; Fernandes 1996; Bergamaschi 1999; Netto et al. 2014; Sedorko et al. 2017; Richter et al. 2023). This littoral system, characterized by rudaceous tidal deposits, in areas where the fluvial inflow was intense enough to supplant the coastal reworking, can still preserve localized progradational contexts (Bergamaschi 1999).

5. Conclusions

The Furnas Formation, due to its sedimentological characteristics, consists of a monotonous uniformity of repeated sandstone lithofacies and the absence of body fossil records, with only records of plant remains and palynomorphs in its transitional layers to the Ponta Grossa Formation. Within this context, throughout the past century, the Furnas Formation has been the stage for various discussions regarding its depositional origin, based on sedimentological studies that relied on the limited data sources available at the time (i.e., lithology and physical sedimentary structures), leading to multiple paleoenvironmental interpretations. The incorporation of ichnological studies contributed to the recognition of ichnoassemblages distributed between the *Skolithos* and *Cruziana* ichnofacies, which enabled the confirmation of a shallow marine depositional system for the intervals containing ichnofossils.

The development of ichnological research within this context is well-defined in its division up until the mid-twentieth century, marked by the beginning of the first two historical periods: the “Classical Ichnology” and the “Advent of Ichnotaxonomy.” During these phases, Ichnology was used solely for the identification of ichnofossils or for reporting new occurrences in a given area or geological unit. In

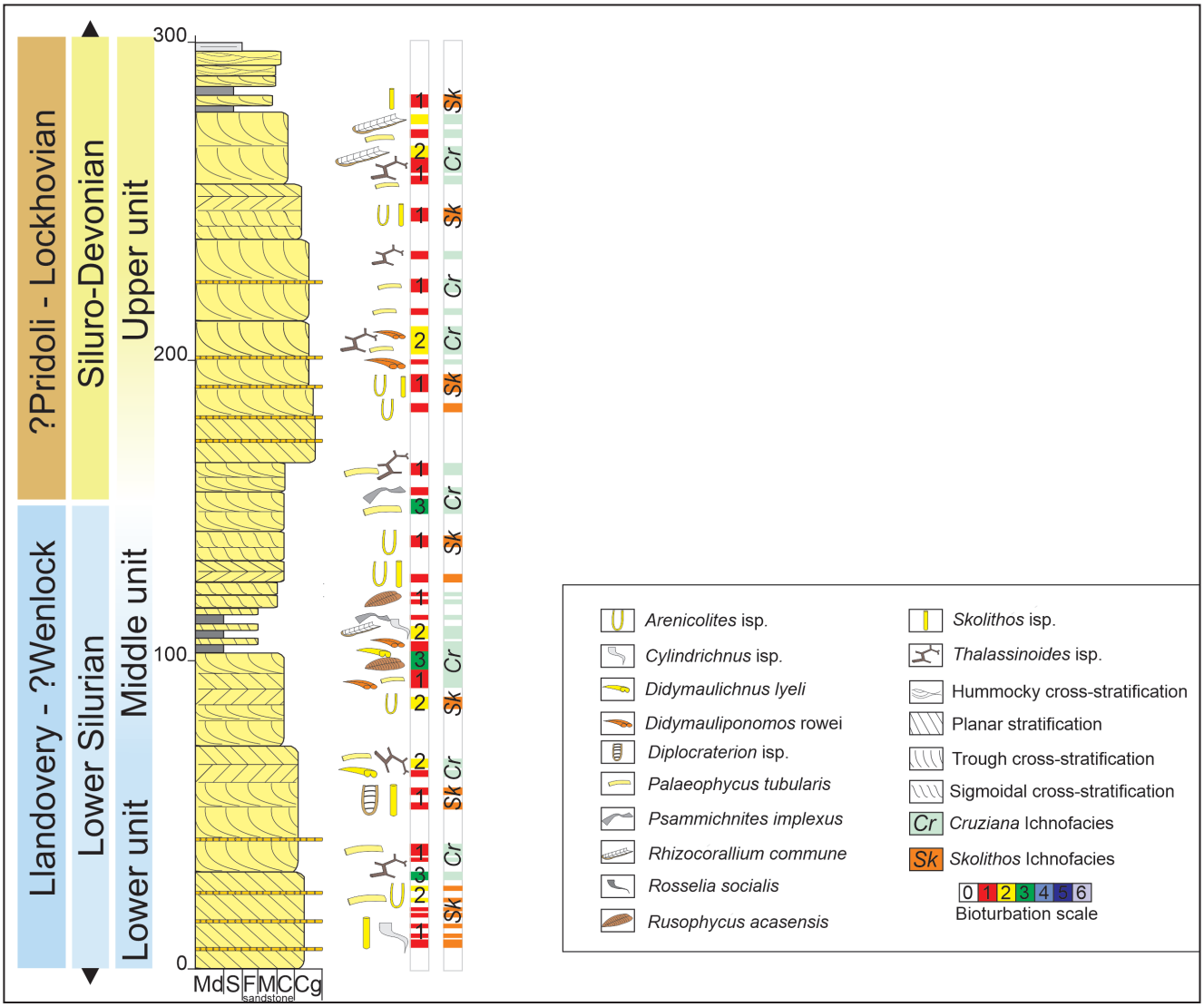

FIGURE 4. Trace fossils from Furnas Formation recorded in the Paraná Basin, based on ichnological distribution of the Guartelá Canyon Section (adapted from Sedorko et al. 2017).

contrast, the third historical period, the "Approach of Applied Ichnology to Paleoenvironmental Reconstructions," was a turning point, introducing Ichnology as an applied science. This period marked the integration of ichnological data as a key element in interpretations, aiming to understand the behaviors involved in the formation of trace structures, the significance of their morphologies, and the applications of this information in facies analysis. These interconnected factors were crucial in the advancement of scientific knowledge and enabled the elucidation of the paleodepositional origin of the Furnas Formation.

In the historical survey of this study, it was detected that most of the research presented here was developed in the Paraná Basin. While the Parecis Basin presents previous studies in relation to its ichnofossil content, new research is needed, not only for the Furnas Formation, but for all depositional sequences, especially the Silurian-Devonian interval, the focus of this study, seeking to integrate the various research methods (i.e. sedimentology, ichnology, taxonomy, taphonomy, paleometry, among others) to refine the results of the region and its correlation with the deposits of the northwestern border of the Paraná Basin.

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Authorship credits

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A - Study design/ Conceptualization **B** - Investigation/ Data acquisition
C - Data Interpretation/ Validation **D** - Writing
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