ISSN: 2447-3359

REVISTA DE GEOCIÊNCIAS DO NORDESTE

Northeast Geosciences Journal

v. 12, nº 1 (2026)

https://doi.org/10.21680/2447-3359.2026v12n1ID42566

PALEOENVIRONMENTAL CHARACTERIZATION OF THE LOWER COURSE OF THE MOURÃO RIVER, PARANÁ - BRAZIL

Caracterização paleoambiental do baixo curso do rio Mourão, Paraná – Brasil

Mauro Parolin[1]; Luan Maler de Oliveira[2]; João Cláudio Alcantara dos Santos[3]; Nelson Vicente Lovatto Gasparetto[4]

1. State University of Paraná (Unespar), Campo Mourão-PR, Brazil. E-mail: mauroparolin@gmail.com
   ORCID: https://orcid.org/0000-0003-3934-5535
2. State University of Maringá (UEM), Maringá-PR, Brazil. E-mail: luan-m@live.com
   ORCID: https://orcid.org/0000-0003-4138-7232
3. Centro Universitário Integrado, Campo Mourão-PR, Brazil. E-mail: joao.claudio@grupointegrado.br
   ORCID: https://orcid.org/0009-0008-5531-3596
4. State University of Maringá (UEM), Maringá-PR, Brazil. E-mail: gasparetto31@gmail.com
   ORCID: https://orcid.org/0000-0003-1293-4110

Abstract: This study investigates the formation of an alluvial terrace in the lower course of the Mourão River (Engenheiro Beltrão, Paraná, Brazil) through phytolith and freshwater sponge spicule analysis in a 105 cm sediment core (^{14}C: 2,426–2,957 cal yr BP; δ^{13}C = -22.3‰). Spicules and phytoliths appear from 75 cm depth; phytolith indices (Tree Cover, Aridity, Water Stress Adaptation) were established from 45 cm upward. Three phases emerged: (i) 75–65 cm: sandy-clay matrix (~40% clay), low phytolith preservation and diversity (<100), no spicules — suggesting ephemeral or absent water; δ^{13}C indicates C3 plants, mainly arboreal cover; (ii) 65–15 cm: clay-dominated (up to 60%), rising phytolith concentration and diversity (up to 220), indices pointing to more dicotyledons, mesophytic Poaceae, Podostemaceae phytoliths, and *Oncosclera navicella* gemmoscleres — alluvial plain development; (iii) 15–0 cm: clay-rich (55%), high phytolith counts (>250), no spicules or Podostemaceae — indices show xerophytic grasses and reduced tree cover, marking terrace stabilization.

Keywords: Holocene; phytolith; sponge spicules.

Resumo: O estudo analisou o processo de formação de um terraço aluvial no baixo curso do rio Mourão (Engenheiro Beltrão - Paraná/Brasil), via identificação e quantificação de fitólitos e espículas de esponjas de água doce de um testemunho sedimentar de 105 cm de profundidade (Datação ^{14}C = 2,426 – 2,957 anos cal AP. e δ^{13}C -22,3‰). As espículas e fitólitos foram registradas a partir de 75 cm, em 45 cm foi possível o estabecimento de índices fitolíticos (Cobertura Arbórea; Adaptação a Áridez e Estresse Hídrico). Foram identificadas três fases paleoambientais: i) 75 a 65 cm - areia e argila (~ 40%), baixa preservação e diversificação de fitólitos (< 100), sem espículas - período sem água/pouco tempo de residência de água, dados de δ^{13}C sugerem domínio de planta C_3, representado predominantemente por vegetação arbórea; ii) 65 a 15 cm - predomínio de argila (máx. 60%), aumento da diversificação e concentração de fitólitos da base para o topo (máx. 220), índices fitolíticos relacionados à maior proporção de dicotiledôneas (arbóreas e arbustivas), presença de Poaceae mesófilas, fitólitos de Podostemaceae e de espiculas de esponjas (gemoscleras de *Oncosclera navicella*) - formação da planície aluvial; iii) 15 a 0 cm - predomínio de argila (55%), concentração de fitólitos (> 250), ausência de espiculas e fitólitos de Podostemaceae, índices fitolóticos relacionados a presença de Poaceae xerófitas e redução da cobertura arbórea - estabelecimento do terraço.

Palavras-chave: Holoceno; fitólitos; espículas de esponjas.

Received: 02/01/2026; Accepted: 24/03/2026; Published: 06/04/2026.

1. Introduction

The state of Paraná has a complex vegetation geography. Although entirely within the Atlantic Forest biome (featuring Mixed Ombrophilous Forest, Seasonal Semi-deciduous Forest, and Dense Ombrophilous Forest), its territory also includes vegetation types typical of the Cerrado biome and open grasslands. Understanding the origin of this mosaic relies on research into paleoenvironmental reconstruction, especially from the Quaternary period. In this context, data with absolute dating and paleoenvironmental information are key to understanding Paraná's unique landscape configuration.

Floodplains are ideal locations for conducting paleoenvironmental and paleoclimatic studies, primarily because sediments there preserve structures that can serve as evaluation parameters, known as proxy data, such as pollen grains, phytoliths, sponge spicules, and diatom frustules, among others.

In this context, the objective of this study was to conduct a paleoenvironmental reconstruction of the lower course of the Mourão River, based on a sediment core obtained from its left bank, in the district of Ivailândia, municipality of Engenheiro Beltrão, in the state of Paraná, Brazil. The Mourão River has a channel that is incised along virtually its entire length; however, in certain areas of the lower course, the formation of small plains and terraces can be observed.

In order to compare and improve the paleoenvironmental understanding of the basin (e.g., LADCHUK et al., 2016; LUZ et al., 2019), as well as to attempt to establish a chronology for the formation of alluvial plains and terraces, it was decided to study the sedimentary content of a small terrace located on the left bank of the lower course of the Mourão River, using the quantification and identification of phytoliths and freshwater sponge spicules.

Phytoliths are microscopic opaline silica bodies formed within plant tissues (MEDEANIC et al., 2008). These siliceous bodies can form in the lumen and in the intra and extracellular spaces of living plants (PIPERNO, 1988). Phytoliths exhibit sizes isometric to their cell of origin, forming a "mold." (COE et al., 2012). After plant death and decomposition, phytoliths are highly resistant to degradation (PIPERNO, 1988). Composed mainly of silica, they preserve well in soils and sandy deposits — offering advantages over other proxies like pollen. In recent years, these biogenic silica structures have been widely used in paleoenvironmental reconstructions, such as in studies by Rasbold et al. (2020), Marcolin et al. (2023), Fonseca et al. (2025), among others.

Freshwater sponges (Phylum Porifera) are sessile aquatic animals characterized by porous bodies. They live attached to rocky substrates or submerged plant remains, often encrusting roots, branches, or tree trunks in seasonally flooded areas like Amazonian floodplains (VOLKMER-RIBEIRO and PAULS, 2000).

Their skeleton is made of spicules—either calcareous (marine sponges) or siliceous (marine and freshwater sponges, Class Demospongiae)—which interweave into a complex mesh that supports the body and provides structure for living cells (VOLKMER-RIBEIRO and PAROLIN, 2010).

Freshwater sponges may present three types or categories of spicules—megascleres, microscleres, and gemmoscleres (Volkmer-Ribeiro and Pauls, 2000): i) megascleres—support the skeleton and are larger in size (depending on development and sponge species, generally >100 µm) compared to other categories; ii) microscleres—smaller structures than megascleres (which may be <10 µm), occurring in the pinacoderm; however, not all sponges possess them; iii) gemmoscleres present in gemmules, generally smaller than megascleres (rarely exceeding 100 µm), and fundamental for species identification. Siliceous spicules, like phytoliths, are potentially well preserved in sediments. Spicules remain in the environment after the senile phase, when organic matter disintegrates, leaving only loose spicules within sediment particles.

Regarding paleoenvironmental reconstruction using sponge spicules, the first area studied in Brazil was the Serra dos Carajás, in the state of Pará (Volkmer-Ribeiro and Turcq, 1996). A survey conducted by Kalinovski et al. (2016) on the state of the art of scientific production in Brazil related to freshwater sponges up to early 2015 identified a total of 31 publications linking their use to paleoenvironmental reconstruction. Parolin et al. (2008) established an important milestone for the use of sponge spicules in paleoenvironmental reconstructions, as well as in sedimentology, by introducing the term spongofacies, defined as sequences in which spicules of continental sponge species predominate and indicate specific paleoenvironmental conditions. Among the more recent publications that have used sponge spicules for paleoenvironmental reconstruction are Rasbold et al. (2021), Docio et al. (2021), and Silvestre et al. (2021), among others.

2. Methodology

2.1 Study Area

The Mourão River Basin (Figure 1) is located in the central-western region of Paraná, Brazil, within the Third Paraná Plateau, specifically in the Campo Mourão Plateau subunit (MAACK, 2012). The river, which gives its name to the basin, is a left-bank tributary of the Ivaí River — the second-longest river in Paraná. According to Mezzomo (2013), the Mourão River is fifth-order, with headwaters in the municipalities of Luiziana and Mamborê. Toward its mouth, the river flows for approximately 200 km (northeastward), featuring several waterfalls and cascades, and passing through the municipalities of Luiziana, Campo Mourão, Peabiru, Engenheiro Beltrão, and Quinta do Sol, in the state of Paraná..

Geologically, the river flows over rocks of the São Bento Group – Serra Geral Formation, and it rarely crosses the Caiuá Group.

The climate is classified as subtropical mesothermal (Koppen). The average temperature in the coldest month is below 18 °C and in the hottest month above 22 °C, with hot summers, infrequent frosts, and a tendency for rainfall to concentrate in the summer, without a well-defined dry season (IAPAR, 2007).

Regarding vegetation, the Mourão River Watershed is located within the Atlantic Forest biome, with phytophysiognomy corresponding to Seasonal Semideciduous Forest (middle and lower reaches) and Mixed Ombrophilous Forest (upper reach) (IBGE, 2010). Parolin et al. (2010) indicate the presence of pockets of vegetation typical of the Cerrado biome, as well as cacti (likely a relict of drier climatic conditions in the past), in the upper portion of the basin (municipality of Campo Mourão). The original landscape has already been significantly altered in the basin due to agricultural practices, with the cultivation of soybeans, corn, and wheat predominating, in addition to eucalyptus plantations.

The sounding point is located in the district of Ivailândia in the municipality of Engenheiro Beltrão, state of Paraná (23°45’03.79” S and 52°09’48.08”W), corresponds to a small terrace (~2.5 km²) located on the left bank of the lower course of the Mourão River, 13,500 m from its mouth on the Ivaí River (Figure 1).

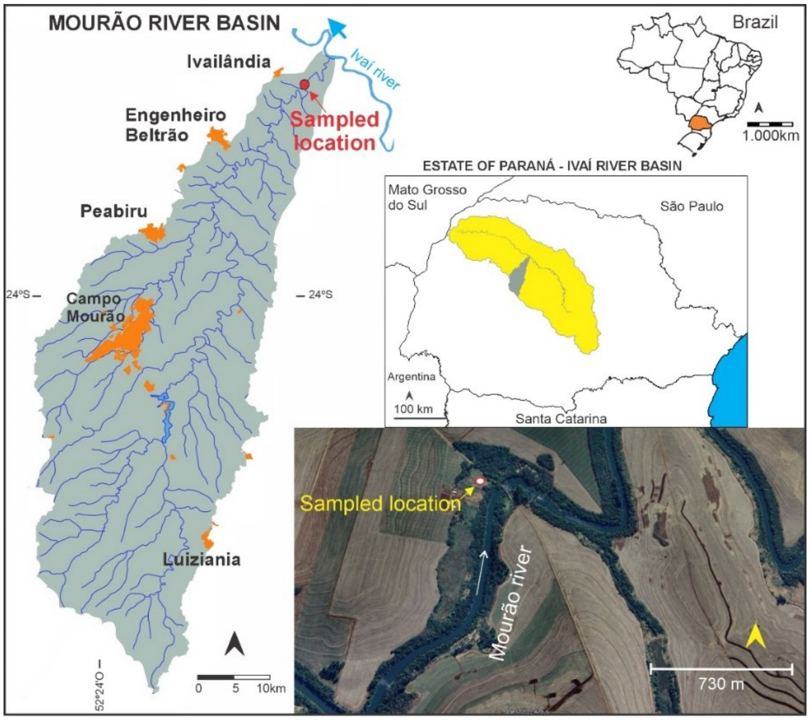

Figure 1. Location of the Mourão River watershed and satellite image highlighting the study area and from the sounding point. Source: Instituto de Água e Terra do Paraná and Google *Earth.*

2.2 Core Sampling and Laboratory Protocols

The sediment core was collected in 2023 using a 7 cm-diameter aluminum tube driven into the ground with a hammer. The core was opened at the Paleoenvironmental Studies Laboratory (Lepafe) at Universidade Estadual do Paraná, Campus Campo Mourão, where the lithology was described following Miall (1978). All phytolith and sponge spicule extraction, identification, and quantification were carried out at the same lab. After air-drying for approximately 48 hours, samples were subsampled every 5 cm.

A sample collected at a depth of 75 cm was sent for absolute dating (^{14}C/Accelerator Mass Spectrometry [AMS]) at the Center for Applied Isotope Studies at the University of Georgia in the United States; the date was subsequently calibrated using Calib 8.1.0® software (2σ – SHCal20). Carbon isotope analysis (δ13C) was also requested for the same sample.

Five samples were selected for grain size analysis (depths of 10, 25, 55, and 70 cm); the samples were chosen based on differences in color and texture when touched. The analyses were performed using the sieving method (SUGUIO, 1973).

For the extraction of phytoliths and sponge spicules, the procedures of Santos et al. (2014) were followed: i) drying in an oven (40 °C/12 h); ii) sieving of the material (Ø 0.25 mm) and separation of 10 g of material; iii) combustion of organic matter (10 g) in a muffle furnace at 500 °C for 5 h; iv) acid treatment (34% HCl) on a hot plate at 50 °C for 20 min; v) washing the resulting material with distilled water until pH stabilization (~7); vi) drying in an oven at 110 °C; vii) addition of zinc chloride (density 2.5g/cm^3) with homogenization of the material; viii) centrifugation for 3 min (1,000 RPM) to recover the supernatant; ix) washing the supernatant material with distilled water and centrifugation to remove the zinc chloride; x) preparation of permanent slides: the material was dispensed (mechanical pipette, 50 µl per sample) onto slides, which, after drying, were covered with Entellan® and a coverslip.

2.3 Microscopy and Additional Analyses

Phytolith and sponge spicule quantification was performed using an optical microscope at 40x magnification. Analysis followed absolute counting of each slide (SANTOS et al., 2014), with three slides assessed per sample to ensure reliability.

Phytoliths were identified and named in accordance with The International Code of Phytolith Nomenclature (ICPN) 2.0 (ICPT et al., 2019). In samples where morphotypes derived from the epidermis of grasses (short-cells ≥ 5%) were present, phytolith indices were determined, as shown in Table 1.

Sponge spicules were identified according to the Lepafe reference collection, as well as the works of Volkmer-Ribeiro and Parolin (2010), Volkmer-Ribeiro and Pauls (2000), among others.

The result graphs were generated using Tilia® software and enhanced with the aid of CorelDraw® software. Mapping was performed using QGIS® software.

Índice/Autores	Equação	Observação
Tree Cover Index [D/P] (ALEXANDRE et al., (1997; 1999).	**D/P** = [Spheroid ornate / (Saddle + Cross + Bilobate)] * 100.	Used to calculate the proportion of phytoliths produced by woody dicotyledons (D) and those produced by Poaceae (P).
Aridity Adaptation Index [Iph] (DIESTER-HASS et al., 1973).	**Iph** = [(Saddle/(Saddle+Cross+Bilobate)]* 100.	Used to assess vegetation adaptation to aridity. High values suggest grasslands dominated by xerophytic Poaceae and dry soil conditions. Low values indicate mesophytic Poaceae, reflecting wetter environments.
Water Stress Index [Bi] (BREMOND et al., 2003; 2005a).	**Bi** = [(Bulliform / Bulliform + Short cells + Acute bulbosus)]* 100.	Estimates plant water stress caused by low rainfall or fluctuations in the water table.

Table 1. Phytolith indices used in paleoenvironmental characterization.

3. 3. Results and Discussion

The core reached 105 cm depth (Figure 2) and revealed a Fluvic Neosol - a poorly developed soil composed of alluvial sediments. The basal layer (105–75 cm) consists of massive clay with abundant plinthite and iron concretions — indicating fluctuating groundwater — and nearly no organic matter. This lower section yielded no phytoliths or spicules. From 75 cm upward, iron concretions and plinthite become rare, and bioturbation by roots appears (60–25 cm), along with recent roots (0–25 cm) and leaf fragments near the surface (10–0 cm). Phytoliths occur from 75 cm to the top, while sponge spicules are present between 65 and 15 cm (Figures 2 and 3).

Granulometric analysis showed: i) clay content rising from 45–50% (base to 50 cm) to 50–60% (50 cm to top); ii) sand decreasing from ~40% (base to 50 cm) to ~20% (50 cm to top); iii) silt stable at ~20% throughout (Figure 2).

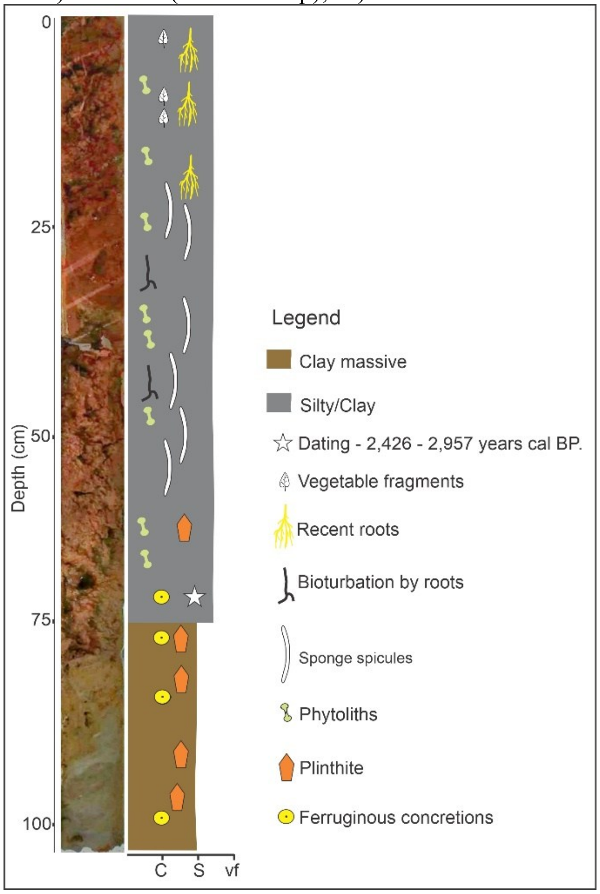

Figure 2. Sedimentological profile of the analyzed core.

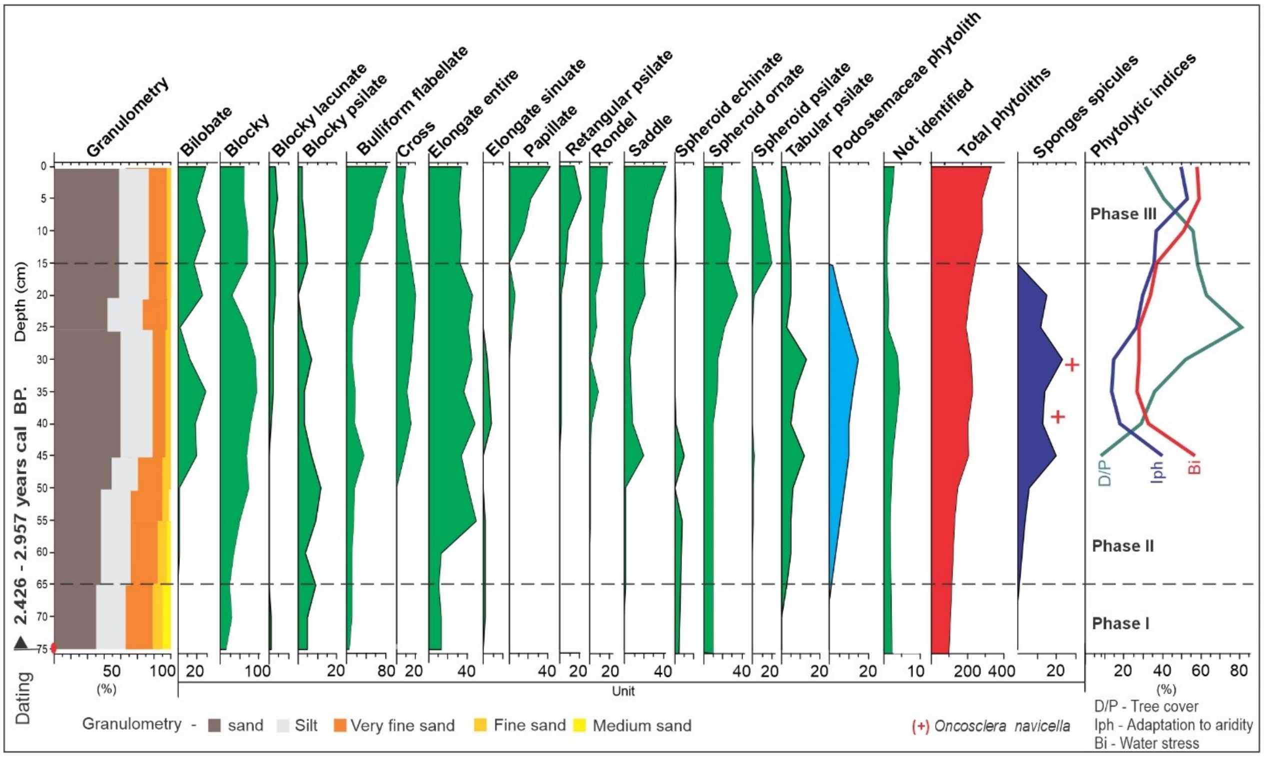

Figure 3. Core profile showing radiocarbon dating, granulometry, phytolith and sponge spicule identification/quantification, and phytolith indices.

The dated sample yielded an age of 2,670 ± 94 years, calibrating to 2,426 – 2,957 cal yr BP, indicating deposition began in the late Holocene. This suggests a sedimentation rate of ~0,027 cm/year. The $\delta^{13}C$ result at the same depth was -22.31‰, indicating a C3 photosynthetic pathway (−22‰ to −27‰), primarily associated with arboreal vegetation. It's worth noting that some grasses in humid environments also use the C3 pathway. (BOUTTON, 1991).

Phytoliths corresponding to 15 identifiable morphotypes were observed; however, they were recorded throughout the entire core, ranging from 50 to 310 units (Figures 3 and 4). The lowest concentrations (~50 phytoliths) were found at the base of the core up to 50 cm, and the larger ones (>200) in the upper portion of the core (15 cm). It was possible to calculate the phytolith indices from a depth of 45 cm to the top (Figure 2). The Tree Cover Index (D/P) ranged from a minimum of 8% at 45 cm, with an upward trend up to 25 cm, where it reached 80%, and then declined toward the top to 25%. The Aridity Adaptation Index (IPH) started at 38%, decreasing to 15% (between 40 cm and 30 cm), with a tendency to increase toward the top, reaching a maximum of 54% at 5 cm. The Water Stress Index (Bi) ranged from a maximum of ~60% (45 cm–5 cm–0 cm) to a minimum of 28% (25 cm–15 cm).

Sponge spicules were observed between 65 cm and 15 cm. Specific identification was possible based on the presence of gemmosclere of the species *Oncosclera navicella* (Carter, 1881) (Figure 3R) between 40 and 30 cm.

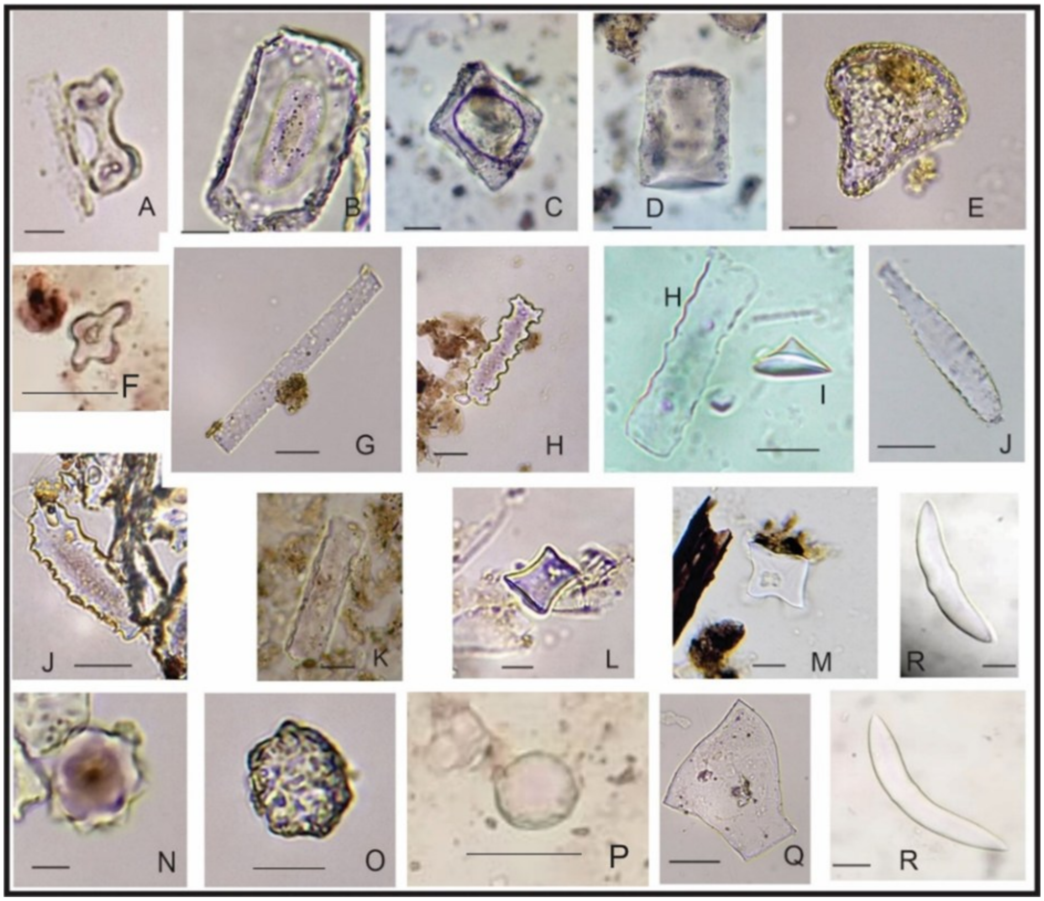

Figure 4. Photomicrographs of phytolith types identified in the sediment core: A) *BILOBATE;* B) *BLOCKY;* C) *BLOCKY LACUNATE;* D) *BLOCKY PSILATE;* E) *BULLIFORM FLABELLATE;* F) *CROSS;* G) *ELONGATE ENTIRE;* H) *ELONGATE SINUATE;* I) *PAPILLATE;* J) *Podostemaceae* phytolith*;* K) *RECTANGULAR PSILATE;* L) *RONDEL;* M) *SADDLE;* N) *SPHEROID ECHINATE;* O) *SPHEROID ORNATE;* P) *SPHEROID PSILATE;* Q) *TABULAR PSILATE;* R) Gemmosclere of *Oncosclera navicella.* Scale: 20 µm.

3.1 Paleoenvironmental Context

By integrating phytolith occurrences, phytolith indices, and sponge spicule records, three paleoenvironmental phases and an evolutionary model for the area can be defined (Figure 5).

Phase I between 75 and 65 cm - dated to 2,426 – 2,957 cal yr BP, with $\delta^{13}C$ indicating C3 - type plants and a predominance of arboreal vegetation - sand and clay are predominant (~40%), with low preservation and diversity of phytoliths (8 phytolith types and a concentration of ~100), and absence of spicules. This phase likely corresponds to a period with little to no water permanence. Phytoliths of the BLOCKY (*BLO*) and ELONGATE ENTIRE (*ELO_ENT*) types present in this phase occur in both eudicotyledons and monocotyledons and are therefore redundant (DE OLIVEIRA et al., 2025). The presence of SPHEROID ECHINATE (*SPH_ECH*) may be associated with the botanical family Arecaceae (MONTEIRO et al., 2012; PEREIRA et al., 2014; WITTEVEEN et al., 2022), whereas SPHEROID ORNATE (*SPH_ORN*) is frequently associated with woody plants (BREMOND et al., 2005b). Due to the low concentration of phytoliths, it was not possible to calculate phytolith indices for this phase.

Phase II between 65 and 15 cm - there is a predominance of clay (maximum of 60%), along with a trend of increasing phytolith diversity and concentration from the base to the top (>100 to <220 morphotypes). The occurrence of phytoliths from the botanical family Podostemaceae between 55 and 10 cm depth suggests the presence of water. According to Bove et al. (2024), the Podostemaceae family consists of annual or perennial plants that live in rivers and streams with strong currents, firmly attached to rocks and other solid substrates. The interpretation of water presence is reinforced by the occurrence of sponge spicules, also between 55 and 10 cm. The species *O. navicella* shows a preference for lotic habitats

(VOLKMER-RIBEIRO and PAROLIN, 2010) and has been recorded in the Mourão River in rapid-flow areas (SANTOS and PAROLIN, 2011). Typical grass phytolith morphotypes were identified, including BILOBATE (*BIL*), CROSS (*CRO*), BULLIFORM FLABELLATE (*BUL_FLA*), RONDEL (*RON*), SADDLE (*SAD*), ELONGATE SINUATE (*ELO_SIN*), and RECTANGULAR PSILATE (*REC_PSI*) (PIPERNO, 2006; CHUENG et al., 2018; HAYASHI and INOUE, 2022). At the base of this phase, *SPH_ECH* was recorded up to 40 cm (indicating the presence of Arecaceae), as well as *SPH_ORN*, associated with woody plants, throughout the entire phase. Analysis of phytolith indices confirms the presence of moisture, particularly the Tree Cover Index (D/P), which reaches 80% at 25 cm. High D/P values are related to a greater proportion of dicotyledons (arboreal and shrubby) (ALEXANDRE et al., 1997; 1999). The Water Stress Index (Bi) in this phase ranges from moderately low (28% – 35% across most of the interval) to moderate (56%), although the latter occurs only at 45 cm. These results suggest that this phase corresponds to the construction and/or formation of an active floodplain during the period. The relatively low Aridity Adaptation Index (Iph) (minimum of 15% and maximum of 38%) indicates the predominance of mesophytic Poaceae (Diester-Haass et al., 1973).

Phase III Between 15 and 0 cm - there is a predominance of clay (55%) and an increase in phytolith concentration (>250 morphotypes). The absence of Podostemaceae phytoliths, together with the absence of sponge spicules, indicates a period of terrace formation. A notable feature of this phase is the more significant occurrence (>20) of the PAPILLATE (*PAP*) morphotype, which is associated with grasses of the Cyperaceae family (STEVANATO et al., 2019). Phytoliths from woody plants are represented in this phase by the presence of the *SPH_ECH* morphotype (Arecaceae), which had not been observed since 40 cm depth, along with a more significant occurrence of the *SPH_ORN* morphotype. The Bi index indicates moderate water stress (maximum of 60%), a result corroborated by the Iph index, which shows an increasing trend compared to the previous phase (maximum of 56%), suggesting vegetation more adapted to aridity (xerophytic Poaceae). The D/P index shows a decreasing trend toward the top (minimum of 40%). This phase is associated with anthropogenic influence in the area, the establishment of the terrace, and the deepening of the Mourão River channel (a more erosive phase compared to the previous ones).

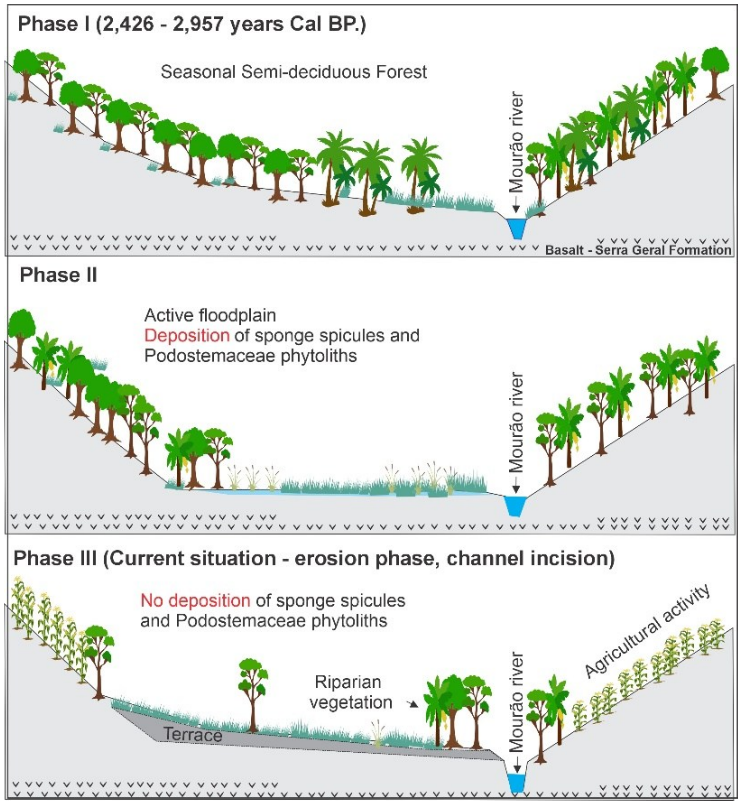

Figure 5. Evolutionary model of the Mourão River floodplain formation process.

The first paleoenvironmental study in the Mourão River Basin (upper course) was conducted by Ladchuk et al. (2016), who analyzed palynology and isotopic data ($\delta^{13}C$, $\delta^{15}N$) from peaty sediments in the Água dos Papagaios River — a tributary of the Campo River, which flows into the Mourão's left bank (7,280–3,248 cal yr BP). They suggest Cerrado vegetation has been present since the mid-Holocene, with gradual vegetation densification toward the present. Luz et al. (2019) carried out the second study, focusing on peat deposits in the Ranchinho and Água dos Papagaios rivers, plus soil samples from the Campo Mourão Cerrado Ecological Station (EECCM). Using multiproxy data (phytoliths, $\delta^{13}C$, $\delta^{15}N$), they identified a dry phase during the Late Pleistocene in Ranchinho (42,800–42,183 cal yr BP). For Água dos Papagaios, their findings align with Ladchuk et al. (2016). At EECCM, a date of 5,280 cal yr BP points to open Cerrado vegetation and increased woody cover from the mid-Holocene onward. Although the age from the lower Mourão River (2,426–2,957 cal yr BP) does not allow direct correlation with upper-basin studies, our results align with other regional Late Holocene records indicating relatively wetter conditions during this period (Table 2).

Autores	**Localidade**	**Síntese**
Rezende et al. (2018).	Japurá/Paraná.	Study conducted at Fazenda Lagoon using sponge spicules — indicates drier conditions ~13,000 years ago, with a trend toward increased humidity from ~2,180 cal yr BP to present.
Pessenda et al. (1996).	Londrina/Paraná.	Use of isotopes (^{13}C, ^{14}C) in soil to assess vegetation dynamics during the Holocene. Dates and $\delta^{13}C$ values indicate: 2,390 ± 60 yr BP / −21.3‰; 1,920 ± 60 yr BP / −21.6‰ (mix of C3 and C4 plants); 820 ± 60 yr BP / −23.8‰ — showing increasing dominance of C3 vegetation over time.
Kalinovski et al. (2016).	Rio Iapó Castro/Paraná.	Data from sponge spicules, phytoliths, $\delta^{13}C$, and $\delta^{15}N$; ages ranging from 18,371 to 2,006 cal yr BP. Show increased flooding pulses in the Iapó River beginning in the Late Holocene.
Melo et al. (2003).	Ponta Grossa.	Palynological data and sedimentary deposit analysis. Sedimentary phases dated between 2,940 and 4,750 yr BP.
Guerreiro et al. (2012).		Peat deposits from the upper Tibagi River (3,200, 2,770, and 1,340 yr BP) indicate peat formation occurred when the local base level was 2–4 meters higher than today, around 3,220 yr BP, under slightly drier conditions. Burial and incision of the peats occurred later, at ~1,340 yr BP, under wetter, near-modern climatic conditions.
Scheebell-Yebert et al. (2003).	Central region of São Paulo state.	Anthracological analyses combined with soil $\delta^{13}C$ and radiocarbon dating (~3,500–3,000 yr BP) indicate a humid climate similar to today's, with established vegetation across all four study sites in central São Paulo.
Behling (2002).	Southeast and South Brazil.	Pollen records indicate modern humid conditions — with absent or short dry periods — became established in the Late Holocene, when Araucaria forests replaced large grassland areas after ~3,000 yr BP, especially from ~1,500–1,000 ^{14}C yr BP onward.
Lessa and Angulo (1997).	Paraná and São Paulo coastal region.	Marine indicator study — shows a mid-Holocene sea-level highstand, with two secondary oscillations occurring between 4,100–3,800 yr BP and 3,000–2,700 yr BP.

Table 2. Summary of selected paleoenvironmental studies in Paraná and the Southeast and South regions of Brazil, with datings from the Middle to Late Holocene.

4. Final Remarks

Once again, phytoliths and freshwater sponge spicules prove to be reliable and valuable proxies for reconstructing paleoenvironments. The studied terrace originated at least between 2,426 and 2,957 years ago, with an active alluvial plain phase marked by the concomitant occurrence of phytoliths from the botanical family Podostemaceae and freshwater sponge spicules.

Acknowledgments

The first author thanks CNPq for the Productivity Fellowship (process 308093/2023-2) and GEMA/UEM (Grupo de Estudos Multidisciplinares do Ambiente – State University of Maringá) for logistical support. Special thanks to Dr. Sidney Kuerten, Dr. Helio Silveira, and Dr. Isabel Terezinha Leli for their valuable suggestions. In memory of Mr. Braulio Parolin, a profound connoisseur of the region.

5. References

ALEXANDRE, A.; MEUNIER, J. D.; LEZINE, A. M.; VINCENS, A.; SCHWARTZ, D. Phytoliths: indicators of grassland dynamics during the late Holocene in intertropical Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 136, n. 1-4, p. 213-229, 1997. DOI: https://doi.org/10.1016/S0031-0182(97)00089-8

ALEXANDRE, A.; MEUNIER, J. D.; MARIOTTI, A.; SOUBIES, F. Late Holocene phytolith and carbonisotope record from a latosol at Salitre, South-Central Brazil. *Quaternary Research*, v. 51 n. 2, p. 187–194, 1999. DOI: https://doi.org/10.1006/qres.1998.2027

BEHLING, H. South and southeast Brazilian grasslands during Late Quaternary times: a synthesis. *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 177, n. 1-2, p. 19-27, 2002. https://doi.org/10.1016/S0031-0182(01)00349-2

BOUTTON, T. W. Stable carbon isotope ratios of natual materials: II. Atmospheric, terrestrial, marine, and freshwater environmental. In: COLEMAN, D. C.; FRY B. (Ed.). *Carbon isotope techniques.* New York: Academic Press, v. 1, p. 173-185, 1991.

BOVE, C. P.; PELLEGRINI, M. O. O.; PHILBRICK, C. T. Podostemaceae in Flora e Funga do Brasil. *Jardim Botânico do Rio de Janeiro*. Disponível em: https://floradobrasil.jbrj.gov.br/FB194 Acesso em:12/10/2025.

BREMOND, L. *Calibration des fonctions de transfert entre assemblages phytolithiques, structures des végétations et variables bioclimatiques actuelles, pour l'intégration de la dynamique des biomes herbacés dans les modèles de végétation*. Tese de doutorado. Universidade de Direito, Economia e Ciências, Université Aix-Marseille III, 2003.

BREMOND, L.; ALEXANDRE, A.; PEYRON, O.; GUIOT, J. Grass water stress estimated from phytoliths in West Africa. J *Journal of Biogeography*, v. 32, n. 2, p. 311–327, 2005a. DOI: https://doi.org/10.1111/j.1365-2699, 2004.01162.x

BREMOND, L.; ALEXANDRE, A.; HÉLY, C.; GUIOT, J. A phytolith index as a proxy of tree cover density in tropical areas: calibration with Leaf Area Index along a forest savanna transect in southeastern Cameroon. *Global and Planetary Change*, v. 45, n. 4, p. 277–293, 2005b. DOI: https://doi.org/10.1016/j.gloplacha.2004.09.002

CHUENG, K. F.; COE, H. H. G.; FAGUNDES, M.; VASCONCELOS, A. M. C.; RICARDO, S. D. F. Reconstituição paleoambiental da área arqueológica de Serra Negra, face leste do Espinhaço Meridional (Minas Gerais), através da análise de fitólitos. *Revista brasileira de geografia física,* v. 11, n. 7, p. 2260-2275, 2018. DOI: https://doi.org/10.26848/rbgf.v11.07.p2260-2275

COE, H. H. G. Mudanças possivelmente antrópicas na cobertura vegetal na região de Búzios, Rio de Janeiro, identificadas através de análises de fitólitos. *Revista Tamoios*, v. 8, n. 1, p. 49-62, 2012. DOI: https://doi.org/10.12957/tamoios.2012.3197

DE OLIVEIRA, L. M.; LELI, I. T.; FERRREIRA, M. L.; ROMAGNOLO, M. B.; CALEGARI, M. R. Phytolith production in non-woody plants from the Atlantic Forest on islands of the Paraná River, Brazil. *Quaternary International*, v. 738, p. 109858, 2025. DOI: https://doi.org/10.1016/j.quaint.2025.109858

DIESTER-HAAS, L.; SCHRADER, H. J.; THIEDE, J. Sedimentological and paleoclimatological investigations of two pelagic ooze cores off Cape Barbas, North-West Africa. *Meteor Forschungsergebnisse: Reihe C, Geologie und Geophysik*, v. 16, p. 19-66, 1973. https://doi.org/10.1594/PANGAEA.548418

DOCIO, L.; RASBOLD, G. G.; DA SILVA, A. L. C.; PAROLIN, M.; CAXAMBU, M. G.; PINHEIRO, U. An assessment of the wealth of information given by sponge spicules as a paleoenvironmental tool: The case of two lakes in northeast (Brazil). *Journal of South American Earth Sciences*, v. 107, p. 103099, 2021. DOI: https://doi.org/10.1016/j.jsames.2020.103099

FONSECA, C. F.; BENINCA, C. G.; ISMINIO, D. A. L.; BENNERT, A.; RUIZ PESSENDA, L. C.; DE QUEIROZ, R. T.; XAVIER, R. A.; DE SOUZA, B. I.; CALEGARI, M. R.; DE SOUZA, J. J. L. L. Holocene vegetation and soil changes in the driest region of caatinga dry forest - phytolith contribution. *Catena*, v. 255, p. 109016, 2025. DOI: https://doi.org/10.1016/j.catena.2025.109016

GUERREIRO, R. L.; GASPARETTO, N. V. L.; PAROLIN, M.; STEVAUX, J. C. Distribuição e análise de sedimentos turfosos holocênicos na planície do Alto Tibagi, Campos Gerais, Paraná. RCA. *Revista de Ciências Ambientais (UniLASALLE),* v. 6, n. 1, p. 105-116, 2012.

HAYASHI, N.; INOUE, J. Vegetation transition from the terminal Pleistocene to early Holocene reconstructed from phytolith records in the southernmost part of mainland Japan. *Review of Palaeobotany and Palynology*, v. 303, p. 104681, 2022. DOI: https://doi.org/10.1016/j.revpalbo.2022.104681

IAPAR, Instituto Agronômico do Paraná. Disponível em: http://www.iapar.br. Acesso em janeiro 2015.

IBGE. Instituto Brasileiro de Geografia e Estatística. *Os tipos de vegetação no Brasil*. Rio de Janeiro: 2010.

INTERNATIONAL COMMITTEE FOR PHYTOLITH TAXONOMY. NEUMANN, K.; STRÖMBERG, C.A.E.; BALL, T.; ALBERT, R. M.; VRYDAGHS, L.; CUMMINGS, L. S. International Code for Phtolith Nomenclature (ICPN) 2.0. *Annals of Botany*, n. 124, p.189-199, 2019. DOI: https://doi.org/10.1093/aob/mcz064

KALINOVSKI, E. C. Z.; PAROLIN, M.; SOUZA FILHO, E. E. Paleoambientes quaternários da planície do rio Iapó, Castro, Paraná. *Revista Brasileira de Geografia Física*, v. 9, n. 5, p. 1543-1558, 2016. DOI: https://doi.org/10.5935/1984-2295.20160106

LADCHUK, D. P. P. T.; PAROLIN, M.; BAUERMANN, S. G. Recuperação de palinomorfos e dados isotópicos ($\delta^{13}C$ e $\delta^{15}N$) em sedimentos turfosos e seu significado paleoambiental para a região de Campo Mourão/PR. *Revista Brasileira de Geografia Física*, v. 9, n. 40, p. 1183-1196, 2016. DOI: https://doi.org/10.5935/1984-2295.20160080

LEMOS, R. C.; SANTOS, R. D. Manual de descrição e coleta de solo no campo. 3. ed. Campinas, Sociedade Brasileira de Ciência do Solo, p. 84, 1996.

LESSA, G. C.; ANGULO, R. J. A. The Brazilian sea-level curves: a critical review with emphasis on the curves from the Paranaguá and Cananéia regions. *Marine Geology*, v.140, n.1-2, p.141-166, 1997. DOI: https://doi.org/10.1016/S0025-3227(97)00015-7

LUZ, L. D.; PAROLIN, M.; PESSENDA, L. C. R.; RASBOLD, G. G.; LO, E. Multiproxy analysis (phytoliths, stable isotopes, and C/N) as indicators of paleoenvironmental changes in a Cerrado Site, Southern Brazil. *Revista Brasileira de Paleontologia*, v. 22, n. 1, p. 15-29, 2019. https://doi.org/10.4072/rbp.2019.1.02

MAACK, R. *Geografia Física do Estado do Paraná*. 4. ed. Ponta Grossa: Editora UEPG, 2012.

MARCOLIN, L.; CALEGARI, M. R.; SANTOS, L. J. C.; CAMARGO, P. B. Phytoliths, $\delta^{13}C$ and Charcoal: holocene environmental memories from a paleogully in northwestern Paraná State. *Revista Brasileira de Geomorfologia*, v. 24, p. 1-25, 2023. DOI: https://doi.org/10.20502/rbg.v24i00.2328

MEDEANIC, S.; CORDAZZO, C. V.; CORRÊA, I. C. S.; MIRLEAN, N. Os Fitólitos em Gramíneas de Dunas do Extremo Sul do Brasil: Variabilidade Morfológica e Importância nas Reconstruções Paleoambientais Costeiras. *Gravel*, v. 6, n. 2, p. 1-14, 2008.

MELO, M. S.; MEDEIROS, C. V.; GIANNINI, P. C. F.; GARCIA, M. J. PESSENDA, L. C. R. Sedimentação quaternária no espaço urbano de Ponta Grossa, PR. *Geociências*, v. 22, n. 1, p. 33-42, 2003.

MEZZOMO, M. M.; Caracterização geoecológica do trecho superior da Bacia Hidrográfica do Rio Mourão-PR: Subsídio ao planejamento da paisagem. *Geoinga*, v. 5, n. 1, p. 18-38, 2013. DOI: https://doi.org/10.4025/geoinga.v5i1.49199

MIALL, A. D. Facies types and vertical profiles models in braided river deposits: a summary. In: A.D. Miall (ed.) Fluvial sedimentology. *Canadian Society of Petroleum Geologists, Memoir*, v. 5, p. 597-604, 1978

MONTEIRO, M. R.; PEREIRA, J. S. R.; RASBOLD, G. G.; PAROLIN, M.; CAXAMBU, M. G . Morfologia de fitólitos característicos de duas espécies de Arecaceae do bioma Mata Atllântica. *Revista de Biologia Neotropical*, v. 9, p. 10-18, 2012. DOI: https://doi.org/10.5216/rbn.v9i1.19197

PAROLIN, M.; VOLKMER-RIBEIRO, C.; STEVAUX, J. C. Use of spongofacies as proxy for river-lake paleohydrology in quaternary deposits of Central-Western Brasil. *Revista Brasileira de Paleontologia*. v. 11, n. 3, p. 187-198, 2008. DOI: https://doi.org/10.4072/rbp.2008.3.05

PAROLIN, M.; GUERREIRO, R. L.; KUERTEN, S.; MENEZES, H. R. Bacias hidrográficas paranaenses. In: PAROLIN, M.; VOLKMER-RIBEIRO, C.; LEANDRINI, J. A. org. Abordagem ambiental interdisciplinar em bacias hidrográficas do Estado do Paraná. Campo Mourão: *Editora da Fecilcam*, p. 59-103, 2010.

PEREIRA, J. S. R.; MONTEIRO, M. R.; PAROLIN, M.; CAXAMBU, M. G. Characterization of phytoliths in eight species of Arecaceae in the State of Paraná, Brazil. In: Heloisa Helena Gomes Coe; Margarita Osterrieth. (Org.). Synthesis of some phytolith studies in South America (Brazil and Argentina). 1ed.New York*: Nova Publishers*, p. 49-74, 2014.

PESSENDA, L. C.; VALENCIA, E. P.; CAMARGO, P. B. D.; TELLES, E. D. C.; MARTINELLI, L. A.; CERRI, C. C.; ROZANSKI, K. Natural radiocarbon measurements in Brazilian soils developed on basic rocks. *Radiocarbon*, v. 38, n. 2, p. 203-208, 1996. DOI: https://doi.org/10.1017/S0033822200017574

PIPERNO, D. R.. Phytoliths Analysis: an Archaeological and Geological Perspective. *Academic Press, San Diego*, 1988.

PIPERNO, D. R. Phytoliths: a Comprehensive Guide for Archaeologists and Paleoecologists. *Rowman Altamira Press, Oxford,* 2006.

RASBOLD, G. G.; STEVAUX, J. C.; PAROLIN, M.; LELI, I. T.; LUZ, L. D.; BRITO, H. D. Phytoliths indicate environmental changes correlated with facies analysis in a paleo island-lake, Upper Paraná River, Brazil. *Journal of South American Earth Sciences*, v. 99, p. 102513, 2020. DOI: https://doi.org/10.1016/j.jsames.2020.102513

RASBOLD, G. G.; MCGLUE, M. M.; STEVAUX, J. C.; PAROLIN, M.; SILVA, A.; BERGIER, I. Enhanced middle Holocene organic carbon burial in tropical floodplain lakes of the Pantanal (South America). *Journal of Paleolimnology,* v. 65, n. 2, p. 181-199, 2021. DOI: https://doi.org/10.1007/s10933-020-00159-5

REZENDE, A. B.; STEVAUX, J. C.; PAROLIN, M.; GUERREIRO, R. L. Sponge spicules as proxy in Upper Quaternary lake deposits near Cianorte (PR): a tentative correlation with lakes of Central-Southern Brazil (NW Paraná and SE Mato Grosso do Sul. *Quaternary and Environmental Geosciences*, v. 9, p. 10-18, 2018. DOI: https://doi.org/10.5380/abequa.v9i2.51816

SANTOS, J. C. A.; PAROLIN, M. Distribuição de esponjas continentais no rio Mourão. *Geomae*, v. 2, n. 1, p. 13-22, 2011.

SANTOS, J. C. A.; GASPARETTO, N. V. L.; PAROLIN, M. Reconstrução paleoambiental do baixo curso do Rio Ivaí – Douradina/Paraná. Geografia, Rio claro, v. 39, n. 2, p. 337-350, 2014.

SCHEEL-YBERT, R.; GOUVEIA, S. E. M.; PESSENDA, L. C. R.; ARAVENA, R.; BOULET, R. Holocene palaeoenvironmental evolutionin the São Paulo State (Brazil), basedon anthracology and soil $\delta^{13}C$ analysis. *The*

Holocene. v. 13, n. 1, p. 73-81, 2003.

SILVESTRE, C. P.; DA SILVA, A. L. C.; DA SILVA, M. A. M.; BAPTISTA NETO, J. A.; PAROLIN, M.; MACARIO, K. C. D.; DE SOUZA, R. C. C. L.; FERNANDEZ, G. B.; AMARAL, D. F. Sedimentary facies and Holocene depositional evolution of the Maricá Lagoon, Rio de Janeiro, Brazil. *Journal of South American Earth Sciences*, v. 111, p. 103438, 2021. DOI: https://doi.org/10.1016/j.jsames.2021.103438

STEVANATO, M.; RASBOLD, G. G.; PAROLIN, M.; LUZ, L. D.; LO, E.; WEBER, P.; CAXAMBU, M. G. New characteristics of the papillae phytolith morphotype recovered from eleven genera of cyperaceae. *Flora*, v. 253, p. 49-55, 2019. DOI: https://doi.org/10.1016/j.flora.2019.03.012

SUGUIO, K. Introdução à sedimentologia. *Edgard Blucher, São Paulo*, p. 317, 1973.

VOLKMER-RIBEIRO C.; TURCQ B. SEM analysis of silicious spicules of a freshwater sponge indicate paleoenvironmental changes. *Acta Microscópica*, v. 5, n. 186, p. 187, 1996.

VOLKMER-RIBEIRO, C.; PAULS, S. M. Esponjas de agua Dulce (Porifera, Demospongiae) de Venezuela. *Acta Biológica.Venezuela*, v. 20, n. 1, p. 1-28, 2000.

VOLKMER-RIBEIRO, C.; PAROLIN, M. As esponjas. In: PAROLIN, M..; VOLKMER-RIBEIRO,C.; LEANDRINI, J. A. (Org.) Abordagem ambiental em bacias hidrográficas no Estado do Paraná. Campo Mourão. *Editora da Fecilcam*. p. 105-130, 2010.

WITTEVEEN N. H; HOBUS, C. E. M.; PHILIP A.; PIPERNO, D. R.; MCMICHAE, C. N. H. The variability of Amazonian palm phytoliths. *Review of Palaeobotany and Palynology* v. 300, p. 104613, 2022. DOI: https://doi.org/10.1016/j.revpalbo.2022.104613