https://rbgeomorfologia.org.br/
ISSN 2236-5664

Revista Brasileira de Geomorfologia

v. 24, nº ESPECIAL (2023)

http://dx.doi.org/10.20502/rbg.v24i00.2328

Artigo de Pesquisa

Phytoliths, δ[13]C and Charcoal: holocene environmental memories from a paleogully in northwestern Paraná State

Fitólitos, δ[13]C e Carvão: memórias ambientais holocênicas de uma paleovoçoroca no Noroeste do Paraná

Luciane Marcolin [1], Marcia Regina Calegari [2] e Leonardo José Cordeiro Santos [3] e Plinio Barbosa de Camargo[4]

[1]Universidade Federal do Paraná, Pós-Graduação de Geografia, Curitiba (PR), Brasil. E-mail. lucianemarcolin@hotmail.com
ORCID: https://orcid.org/0000-0002-0565-763X

[2] Universidade Estadual do Oeste do Paraná, Colegiado de Geografia, Marechal Cândido Rondon (PR), Brasil. E-mail.: marcia.calegari@unioeste.br.
ORCID: https://orcid.org/0000-0002-2146-7748.

[3] Universidade Federal do Paraná, Pós-Graduação de Geografia, Curitiba, Brasil. E-mail: santos.ufpr@gmail.com
ORCID: https://orcid.org/0000-0003-1165-6382

[4] Centro de Energia Nuclear na Agricultura- Universidade de São Paulo, Laboratório de Ecologia Isotópica, Piracicaba, São Paulo, Brasil. E-mail.: pcamargo@cena.usp.br.
ORCID: https://orcid.org/0000-0002-0696-3778

Recebido: 12/12/2022; Aceito: 20/03/2023; Publicado: 03/07/2023

Resumo: Uma parte da história ambiental do noroeste paranaense está refletida na paisagem pela presença de paleovoçorocas de grande magnitude, ao norte do rio Ivaí, cuja gênese pode estar associada à condição climática distinta da atual, ao longo do Quaternário. Estudos na região têm apontado variações climáticas ao longo do Holoceno, indicando período mais seco que o atual nas transições Pleistoceno/Holoceno e Holoceno Médio/Holoceno Superior. Embora esses estudos indiquem que as taxas de denudação forneçam uma estimativa do período de início de formação dessas feições, as condições ambientais de clima e vegetação que permitiram o desenvolvimento de tais processos ainda são pouco conhecidas. Partindo da concepção do solo como um reservatório de registros ambientais, e adotando uma abordagem *multiproxy*, o presente estudo tem como objetivo reconstituir as condições paleaombientais holocênicas que favoreceram o desenvolvimento de uma paleovoçoroca no município de Loanda, noroeste paranaense. De acordo com os resultados, o desenvolvimento dessa feição está relacionado a um ambiente com vegetação mais aberta que a atual, sensivelmente mais seco e com temperatura mais amena, durante a transição Holoceno Médio/Superior. O aumento da umidade no Holoceno Superior favoreceu, incialmente, a ampliação da erosão e, posteriormente, já com dimensões quilométricas, sua estabilização com o avanço da floresta.

Palavras-chave: Pedomemórias; Grupo Cauiá; Erosão; Reconstituição Paleoambiental

Abstract: A part of the environmental history of northwest Paraná is reflected in the landscape by the presence of paleogully of great magnitude, concentrated north of the Ivaí River, whose genesis may be associated with different climatic conditions from the current one, during the Quaternary Period. Studies in this region have pointed to climate variations throughout the Holocene, indicating a drier period than the current one in the Pleistocene/Holocene and Middle and Upper Holocene transitions. Although these studies indicate that the denudation rates provide an estimate of the beginning period of the formation of these features, the environmental conditions of climate and vegetation that allowed the development of such processes are still poorly known. Based on the conception of soil as a reservoir of environmental records, and adopting a multiproxy approach, the present study aims to reconstruct the Holocene paleoenvironmental conditions that favored the development of a paleogully in the municipality of Loanda, northwest Paraná. According to the results, the development of this feature is related to an environment with more open vegetation than today, slightly drier and with milder temperature, during the Middle to Late Holocene transition. The increase of humidity in the upper Holocene favored, at first, the enlargement of erosion and, later, already with kilometric dimensions, its stabilization with the advance of the forest.

Keywords: Pedomemories; Cauiá Group; Erosion; Paleoenvironmental Reconstitution.

1. Introduction

Erosive features found in Northwestern Paraná, north of the Ivaí River, in the municipalities of Loanda, Terra Rica, and Querência do Norte, stand out in the landscape for their dimensions, averaging over 18 km², and the size and level of conservation of the vegetation installed inside (GOULART; SANTOS, 2014; GOULART, 2020). These features represent paleogully stabilized long ago and are considered anomalous to the regional relief, characterized by morphological features of planing from successive reworkings that occurred since the beginning of the Quaternary (BIGARELLA; MAZUCHOWSKI, 1985). These paleogully differ in size, age and origin from those gullies formed after 1930, when the colonization process of the region began, and by presenting stabilized margins and covered by a Semideciduous Seasonal Forest (GOULART; SANTOS, 2014) with large trees, similar to the one that covered the region when the first settlers arrived. Some paleogully have irregular topography (>30% slope) and lakes inside, or are grouped in regional dividers, as in the municipality of Loanda, where there is a higher concentration of them, creating a peculiar roughness in the landscape (OLIVEIRA, 2021). A study by Goulart (2020) estimated that the beginning of the development of denudation processes that originated these features was still in the Lower Pleistocene. The analysis of palynostratigraphic data from three sub-basins (Rio Tibagi, Rio Piquirivaí, Umuarama) and samples from the alluvial plain of the Paraná River in the region of Porto Rico by Stevaux (1994) revealed that during the lower Pleistocene (between 2.5 and 1.0 Ma AP) the region was dominated by natural grasslands and savannas under drier climatic conditions than today.

Although we already have this estimate of the period and conditions of the beginning of the formation of these features, little is known about the climatic and vegetation conditions that contributed, a posteriori, to the evolution of these paleoflows throughout the Quaternary. The region, since the early Holocene, has undergone a widespread climatic transition. Drier-than-present phases have been identified in the Pleistocene/Holocene (14 - 8 thousand years AP) and Middle Holocene/ Upper Holocene (3.5 and 1.5 thousand years AP) transitions in Northwestern Paraná (GOLOVATI, 2015; SANTOS, 2013; STEVAUX, 2000), central-western São Paulo (SOUZA et al., 2019), and northeastern Argentina (STEVAUX, 2000), indicating synchronicity between the South and Southeast regions of Brazil.

Most of the studies carried out in Northwestern Paraná are lithostratigraphic and/or palynostratigraphic, in sediments of fluvial plains, especially of the Paraná River. These works aimed to know the evolution of the vegetation structure and the temperature and humidity conditions throughout the Holocene in the region (GOLOVATI, 2015; GUERREIRO et al., 2013; RAMÍREZ et al., 2019; RASBOLD et al., 2020; SANTOS, 2013). However, studies from pedomemories employing multiproxy approach in mineral, non-hydromorphic soil in the region are rare, except for Golovati (2015) and Santos (2013).

The advantage of using multiple proxies preserved in soils is that it yields information at different spatial and temporal scales, aiding in the understanding of past vegetation and climate conditions and environmental changes. The soils of northwestern Paraná stand out for being mineral, medium to sandy in texture, moderately acidic and of poor natural fertility (EMBRAPA, 1984). These properties added to the low soil organic matter content (SOM), in some situations, are limiting for preservation of palynomorphs. In this condition, the analysis of the phytolith assemblage, a botanical microrest preserved in soils, stands out as an important tool to investigate the evolutionary trajectory and the changes in vegetation structure throughout the Quaternary in the northwestern region. Phytoliths are microscopic opaline silica corpuscles formed in plant tissue throughout their vegetative development that, after plant death, are incorporated into soils and or sediment (STRÖMBERG et al., 2018), constituting a biotic memory of vegetation aspects (CALEGARI; VIDAL-TORRADO, 2020).

The combined use of phytoliths with other bioindicators, such as carbon (micro)fragments and stable carbon and nitrogen isotopes, has allowed to know the environmental history that some soils have experienced throughout their formation in different regions of Brazil (CALEGARI et al, 2013a; MACEDO, 2013; SILVA NETO et al., 2018) and elucidate aspects related to pedogenesis and landscape evolution throughout the Holocene, including in semiarid areas, where other proxies are rare or scarce (LISTO et al., 2022).

In view of the questions and uncertainties about paleogully in the northwestern Paraná State, this study was based on the hypothesis that the erosion process would have started around the Upper Pleistocene, according to Goulart (2020), under dry climate and open vegetation, and expanded its dimensions during periods of instability until the upper Holocene. Based on a multiproxy approach, this study aimed to identify changes in vegetation structure and, indirectly, in environmental moisture and temperature, which may have contributed to the evolution and stabilization of the erosion feature throughout the Holocene in the municipality of Loanda.

2. Study Area

The soils were described and sampled on the edge of paleogully G3 located in the municipality of Loanda, northwestern Paraná (GOULART, 2020) (Figure 1). The profiles were allocated in the upstream sector of the feature, being P1 (22°55'53.1" S; 5302'03.7" W) an autochthonous soil, on the left margin, developed from the underlying sandstone and P2 (22°57'00.9" S; 53°02'03.7" W) a soil developed from colluvial material transported from upstream. The two profiles are 2.41 km apart and P2 is located downstream on the right margin of the feature, in a steeper sector of the headland, with occurrences of small patamares formed by solifluxion and small dips.

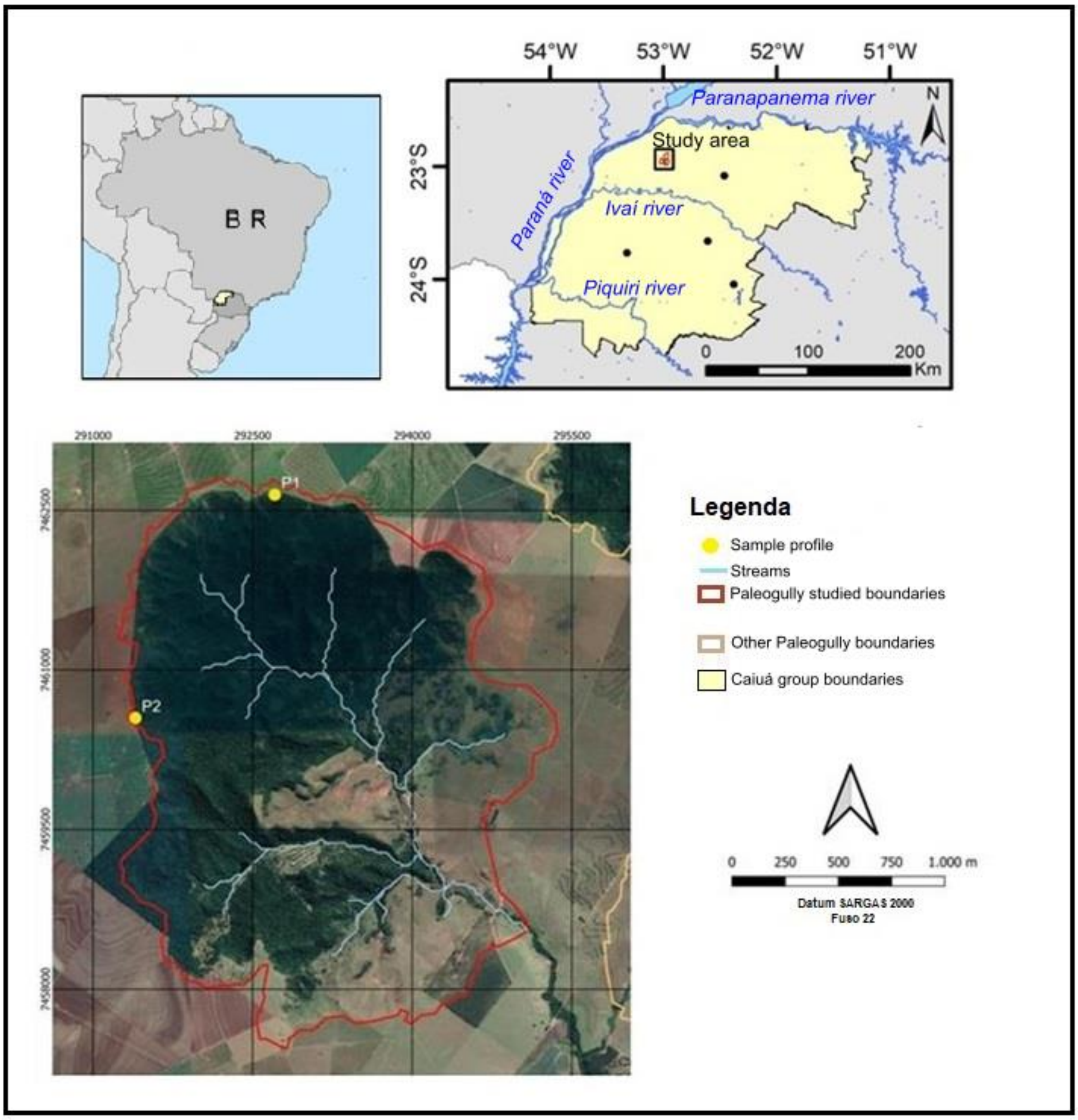

Figure 1. Location of the study area and soil sample collection profiles in the G3 paleogully.

The relief of the area has low dissection, is smooth and wavy consisting of flattened tops, convex slopes and open "V" valleys (SANTOS et al., 2006). The medium-textured Latosols and Argissols, predominant in the study area, are formed from the alteration of the Cretaceous sandstones of the Caiuá Group (FERNANDES; COIMBRA, 2000). The predominant climate is humid subtropical mesothermal (Cfa), with an average temperature of the hottest months above 22°C and the coldest months below 18°C. Rainfall varies between 1,300 and 1,700 mm, with a tendency to concentrate in the summer months, with annual averages between 450 and 530 mm (NITSCHE et al., 2019). The natural vegetation cover of the region was the Semidecidual Seasonal Forest (SSF) (ITCG, 2013) that has been replaced by temporary crops and pasture. Fragments of forest are found within the anomalous feature, covering most of the slopes, especially near the water divider (GOULART; SANTOS, 2014).

The description of soil horizons was performed according to Santos et al. (2015) in two soil profiles. Samples were collected for soil characterization and classification up to the second categorical level. Sampling for carbon isotopic analysis and phytolithic soil assembly was performed every 10 cm, from the base to the top of profiles P1 and P2. To define the phytolithic signature (fingerprinting), representative of the current vegetation, samples of litter and of the superficial soil layers (0-5 cm; 5-10 cm) were collected every 50 meters along three transects (T1, T2 and T3) of 150m length, close to the described profiles (Figure 2).

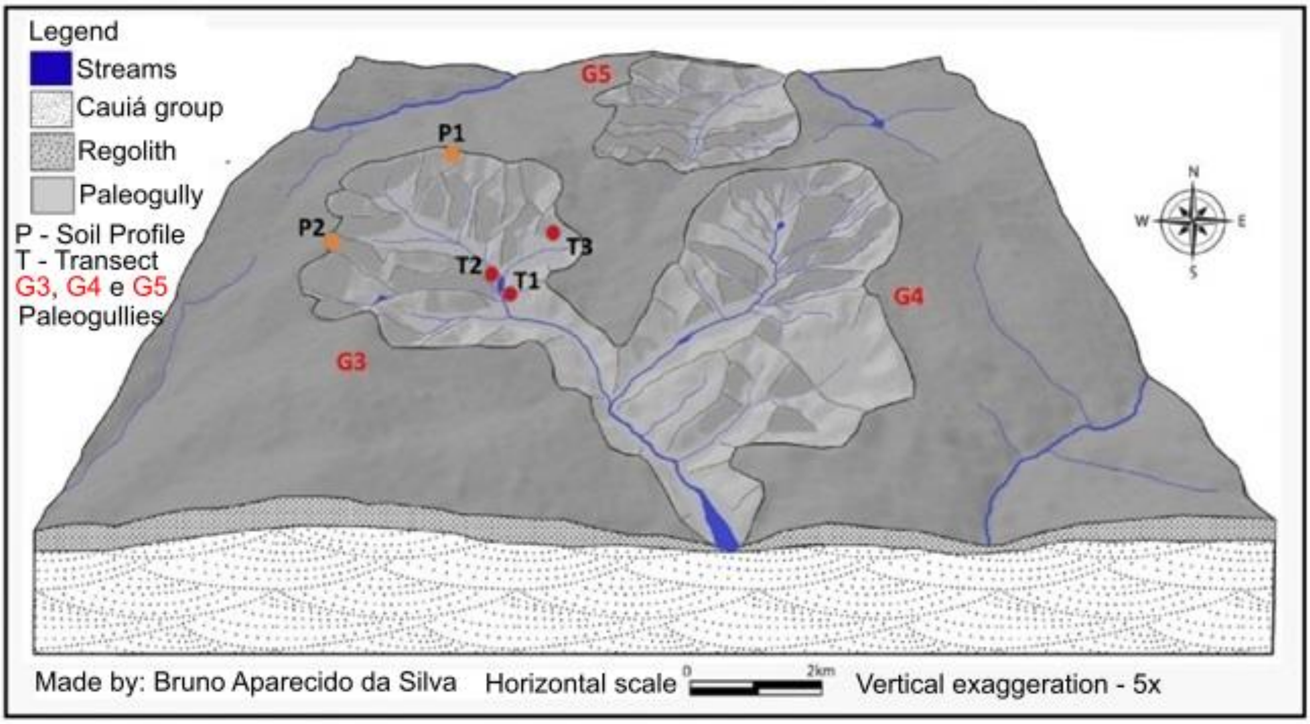

Figure 2. Block diagram showing the paleogully set and the sampling points (P: Profiles and T: Transects).

2. Materials and Methods

2.1. Analysis of soil properties

For knowledge of the phytolith preservation environment and soil characterization, granulometric, pH (acidity conditions) and organic matter content analyses were performed. The soil samples were dried, then crushed and sieved in a 20 mm mesh to obtain the fine air-dried soil fraction. The particle size fractions of the soils (clay < 2µm and silt 2-50µm) were determined by the Bouyoucos densimeter method and the sand fraction (50-2000µm) by sieving, according to Teixeira et al. (2017). The pH in KCl and in water were determined according to Teixeira et al. (2017). Organic matter content was determined according to the Walkley-Black method (TEIXEIRA et al., 1997), by obtaining organic carbon in wet oxidation with potassium dichromate ($K_2Cr_2O_7$ 1N) in sulfuric medium (LANA et al., 2016).

2.2. Quantification of soil microcarbons.

200 grams of dry soil from each horizon were weighed and sieved in 250μm mesh. The roots were removed, and the material retained on the sieve was submitted to flotation, and the charcoal fragments were collected with tweezers, dried in an oven (60°C - 24hr) and weighed on precision scales (adapted from HORN; UNDERWOOD, 2014).

2.3. Elemental composition and isotopic analyses of SOM ($\delta^{13}C$)

The determination of total organic carbon (TC) and total nitrogen (TN) content, C/N ratio and carbon isotopic analysis ($\delta^{13}C$) of soil organic matter (SOM) was performed on samples collected every 10 cm. The samples were air-dried, macerated, passed through a 0.250 mm sieve, weighed and then analyzed in an Elemental Analyzer (CarloErba - CHN 1110) coupled to a Thermo Fisher Scientific Mass Spectrometer (Finnigan Delta Plus). The results of total carbon and nitrogen concentrations are expressed in grams per kilogram (g. Kg^{-1}) of dry material from each sample. Results of the $^{13}C/^{12}C$ isotope ratio (Eq. 1) are expressed using conventional notation (δ‰ - delta parts per thousand) with analytical precision of ± 0.2‰.

$$\delta^{13}C = \left[\left(R_{sample} - R_{standard}/R_{standard}\right)\right] \times 1000 \quad (1)$$

Where: R_{sample} refers to the $^{13}C/^{12}C$ ratio of the sample; RPDB = $^{13}C/^{12}C$ ratio of the PDB standard for carbon (FARQUHAR et al., 1989).

2.4. Extraction, counting and identification of phytoliths

Extraction of burlap phytoliths followed the modified calcination procedures of Campos and Labouriau (1969) and Piperno (2006), known as "dry-ashing". The extraction of phytoliths from soil was performed according to Method 2 described in Calegari et al. (2013b). Extraction began with the removal of organic matter and iron and aluminum oxides and hydroxides covering the particles of the mineral fraction of 4 grams of soil, according to Mehra and Jackson (1960). Organic matter was removed with hydrogen peroxide (H_2O_2). The oxides were removed with DCB solution (Sodium Dithionite + Sodium Citrate + Sodium Bicarbonate). Then clay removal was performed by centrifugation (3 min - 700rpm as many times as necessary). The remaining material (silt and sand fractions) was separated from the phytoliths by densimetric flotation, using a sodium polytungstate solution ($Na_6(H_2W_{12}O_4O)H_2O$) with a density of 2.35 g/cm^3 (MADELLA; POWERS-JONES; JONES, 1998). The recovered material was used for making temporary slides in immersion oil and permanent slides with Enterlan® for identification and morphological classification of the phytolith assemblage and for quantification of morphotypes, respectively, under a trinocular optical microscope.

Phytolith count and classification were performed according to Carnelli et al (2001). A minimum of 300 phytoliths were counted per burlap sample and a minimum of 200 phytoliths with taxonomic significance and size greater than 5μm were counted in the soil samples. Phytoliths smaller than 5μm are difficult to identify and usually represent fragments of larger corpuscles, (EPSTEIN, 2001). Morphotypes were described and named according to International Code for Phytolith Nomenclature - ICPN 2.0 (ICPT et al., 2019).

To express taxonomic significance the morphotypes were organized according to the producing groups: Trees (SPHEROID ORNATE), morphotype produced by: **Woody plants**, predominantly arboreal life forms (BREMOND et al , 2005; MERCADER et al., 2009; Souza, 2019;); **Trees/Shrubs** (ELIPSOIDAL PSILATE, POLYGONAL EPIDERMIC CELL, SPHEROID PSILATE, TRACHEARY, TABULAR, TABULAR SULCATE), morphotypes produced by non-monocotyledonous plants - woody and non-woody, of tree and shrub life forms (RUNGE, 1999; MERCADER et al, 2009; CECCHET, 2012, FELIPE, 2012, RAITZ, 2012, SOUZA, 2019; MOZER, 2019); **Palms** (SPHEROID ECHINATE) diagnostic morphotype of the Arecaceae family (MARCOTE-RÍOS and BERNAL, 2001; MARCOTE-RÍOS et al., 2016; MACEDO, 2013; BENVENUTO et al, 2015; HUISMAN et al, 2018; SOUZA, 2019); **Total Poaceae** (herbs) (Panicoid, , Pooid, Chloridoid, ELONGATE DENTATE, BLOCK, BULLIFORM FLABELLATE) morphotypes produced by plants of herbaceous life form (TWISS, 1987; 1992; RAITZ, 2012; CALEGARI et al., 2017c) , **Indefinite Family** (ELONGATE and ESTOMATE), morphotypes with a high degree of redundancy, produced by plants of different families and life forms.

2.5. Phytolithic indices

The environmental intepretations and the significance of the phytolith assemblage were established through the relationship between the different groupings of morphotypes, which express the producing taxa and their ecology. These relationships are expressed in the different phytolith indices available in the current literature (STRÖMBERG et al., 2018). Four indices were applied, based on grass and tree phytoliths. They are:

a) Index of Adaptation to Aridity/Humidity - Iph (DIESTER-HAAS et al., 1973; TWISS, 1992; BREMOND et al., 2005). It is based on the ratio of the amount of phytoliths of Chloridoideae versus Chloridoideae + Panicoideae (TWISS, 1992). It expresses the percentage of Chloridoideae among C_4 grasses (Eq. 2).

b) Iph %= [(SADDLE / (SADDLE+CROSS+BILOBATE short cell)]×100 (2) Climatic Index (Ic): (TWISS 1987, 1992) estimates the relative proportion of C_3 grasses in North American grasslands. It is defined from the relationship between Pooideae morphotypes versus Pooideae + Chloridoideae + Panicoideae morphotypes (Eq.3)

c)

$$\mathrm{IC\%} = \left(\frac{\textsc{Rondel} + \textsc{Trapeziform polylobate} + \textsc{Trapeziform}\ \text{short cell}}{\textsc{Rondel} + \textsc{Trapeziform polylobate} + \textsc{Trapeziform}\ \text{short cell} + \textsc{Saddle} + \textsc{Cross} + \textsc{Bilobate}\ \text{short cell}} \right) \times 100 \quad (3)$$

c) Arboreal Cover Index (D/P): (adapted from Alexandre et al 1997 and Neumann et al. (2009), consists of the ratio between phytoliths of arboreal dicotyledons (D) (SPHEROID) and phytoliths of Poaceae (P) (Eq. 4). In this adaptation, the SPHEROID PSILATE was included for arboreal dicotyledons because they have been found in abundance in woody plant samples of arboreal life form in reference collections prepared in Brazil (RAITZ, 2012; FELIPE, 2012; SOUZA, 2019; MOZER, 202); and only the short cells of C_4 grasses were kept representing Poaceae.

$$\mathrm{D/P} = \frac{\textsc{Spheroid}\ (\textsc{psilate} + \textsc{rugose})}{\textsc{Rondel} + \textsc{Trapeziform} + \textsc{Polylobate} + \textsc{Saddle} + \textsc{Cross} + \textsc{Bilobate}\ \text{short cell}} \quad (4)$$

d) The water stress index (Fs) is calculated according to BREMOND et al., (2005), by the ratio between the BULLIFORM FLABELLATE morphotype and the sum of all grass phytoliths except ELONGATE (Eq.5).

$$\mathrm{Fs} = \frac{\textsc{Bulliform flabellate}}{\textsc{Saddle} + \textsc{Cross} + \textsc{Bilobate} + \textsc{Trapeziform}\ \text{short cell} + \textsc{Trapeziform polylobate} + \textsc{Bulliform flabellate} + \textsc{Acute bulbosus}} \quad (5)$$

2.6. ^{14}C Dating

Four samples were sent to the Radiocarbon Laboratory of the Federal Fluminense University (LAC UFF) for dating, two from P1 (60-70 cm and 680-690 cm) and two from P2 (60-70 cm and 130-140 cm). The 680-690 cm sample from P1 did not have enough carbon content to be measured. The dates of the samples with their respective codes are presented in conventional radiocarbon ages in years before present (BP) (STUIVER; POLACH, 1997) and calibrated, with 95.4% reliability (cal. years AP), the present being 1950 (PESSENDA et al., 1998).

2.7. Statistical Analysis

The results of the phytolith count were organized in tables with absolute values of the identified phytolith count, to determine the percentages of each morphotype and taxonomic classes of phytoliths. The grouping analysis by similarity, used in the paleoenvironmental interpretation, was carried out using CONISS, which is a program that performs the grouping analysis stratigraphically, delimited by the incremental sum of squares method (GRIMM, 1987) and is embedded in the Tilia program. The results were organized in distribution graphs of the percentages of each morphotype and the dendrogram indicating the hierarchical groupings among the samples. To explain the dendrogram groupings, principal component analysis (PCA) was performed using Minitab software. Pearson's correlation was performed between charcoal fragments and phytoliths of woody plants. Mean test (Tukey test) was performed on the phytolith assembly data from the transects, using Minitab software.

3. Results

3.1. Soil Attributes

P1 is a soil developed from the alteration of the underlying sandstone, belonging to the Caiuá Group. It is 740 centimeters deep and has a vertical sequence of A, AB, and Bw horizons, which is subdivided into eight subhorizons for maintaining the attributes of latossolic B (Table 1). It presents a dark reddish brown color, with a variation in hue, from the top to the bottom of the profile, from 5YR 3/3 to 2.5 YR 3/4. P2 is shallower (190 cm), and is a soil developed from colluvial material mobilized from upstream, already pedogenized. It presents a vertical sequence of horizons A, 2AB, 2BA, 3Bw1, 3Bw2, and 4BC and a reddish brown color, varying from 2.5YR 2.5/4 in the A horizon to 2.5YR 3/4 in the underlying horizons. Both profiles present well drained soils, with good macroporosity (structural and biological) and biological activity, of fauna (termites and ants) and roots, more abundant in the A horizon. P2, in general, showed greater biological activity of termites and ants, with the presence of empty channels and galleries filled with looser material.

Table 1. Morphological, physical and chemical attributes of soils in reference profiles, in an anomalous feature in the municipality of Loanda, Northwest Paraná

Horiz.	Deep. (cm)	Cor Munsell (wet)	Clay	Silt	Sand*	S/A	pH		Delta pH	OM	C
			--------------g.kg^{-1}------------				H_2O	KCl		%	g.kg^{-1}
				Profile 1: Haplic Ferralsol							
A	0-13	5YR3/3	260	62	678	0,24	5,3	4,7	-0,6	10	0,6
AB	13-43	5YR3/3	262	63	675	0,24	6,4	4,6	-1,8	9,3	0,5
Bw1	43-100	2,5YR3/4	272	15	713	0,06	5,9	4,5	-1,4	5,3	0,3
Bw2	100-200	2,5YR3/4	274	13	713	0,05	5,8	5,1	-0,7	3,3	0,2
Bw3	200-300	2,5YR3/4	287	13	700	0,05	4,9	4,3	-0,6	2,6	0,2
Bw4	300-400	2,5YR3/4	287	25	688	0,09	4,9	4,3	-0,7	1,9	0,1
Bw5	400-500	2,5YR3/4	287	13	700	0,05	5,2	4,4	-0,8	3,3	0,2
Bw6	500-600	2,5YR3/4	274	38	688	0,14	5,1	4,3	-0,8	1,2	0,1
Bw7	600-700	2,5YR3/4	300	13	687	0,04	5,1	4,3	-0,8	0,5	0
Bw8	700-800	2,5YR3/4	300	25	675	0,08	5,3	4,3	-1	0,5	0
				Profile 2: Haplic Ferralsol (Colluvic)							
A	0-25	2,5YR2,5/4	113	21	866	0,19	6	5,2	-0,8	7,9	0,5
2AB	25-55	2,5YR3/4	90	312	599	3,48	5,5	4,6	-0,9	5,3	0,3
2BA	55-70	2,5YR3/4	158	128	714	0,81	5,4	4,3	-1,1	4	0,2
3Bw	70-100	2,5YR3/4	186	98	716	0,53	5,6	4,4	-1,2	3,3	0,2
3Bw2	100-160	2,5YR3/6	106	160	734	1,51	5,8	4,5	-1,3	4	0,2
4BC	160-200	2,5YR3/6	40	383	577	9,47	6,3	4,9	-1,4	6	0,4

* Particle size fractions: Clay< 0.002 mm; Silt: 0.05 to 0.002 mm; Total sand: 2 to 0.05 mm.

P1 is more clayey and in P2 clear vertical variations in clay and silt fractions are observed, which signals a lithological discontinuity, between 25 and 55 cm and between 70-100 cm depth. These variations mark former colluvial levels, which contributed as parent material for this soil. Chemically the two profiles are very similar (Table 1). They present acidity ranging from strongly to moderately acidic (pH between 4.2 and 6.4). The calculated pH delta was negative in all horizons, decreasing from the top to the bottom of the profiles, ranging between 0.6 and 1.8 in P1 and 0.8 and 1.4 in P2. The organic carbon (C) and organic matter (O.M) contents in general are low (Table 1) and the highest contents are found in the superficial horizons, respectively 0.6% and 10% in P1 and 7.9% and 0.5% in P2. The irregularities in the vertical distribution of morphological, chemical and physical attributes observed in P2 corroborate the existence of lithological discontinuities in the profile, related to the past colluvial process, whose macromorphological properties have already been obliterated by pedogenesis over time.

3.2. Elemental composition, isotopic data of SOM (δ13C, 14C) and coal fragments

Table 2 shows the ^{14}C ages of humin from the soils. The ages decrease from the bottom to the top. The humin from the 60-70 cm samples indicated Upper Holocene (~2,201 Cal yr BP) age at P1, and Middle Holocene (~5,800 Cal yr BP). At P2, the 130-140 cm sample showed early Middle Holocene age (~7800 Cal years BP).

Total carbon (TC) contents, in general, decrease in depth in both profiles (Figure 3). In P1, values are lower (<5.5 $g.kg^{-1}$) and have a more linear vertical distribution, with subtle changes at 40 cm and 340 cm depth, where decreases and increases in TC content are observed, respectively. In P2, the values are higher (between 30.6 and 4.4 $g.kg^{-1}$) and evidence of discontinuity is observed at depths of 60, 100 and 150 cm, where the contents increase, defining a non-linear pattern of distribution of this element in the soil profile. The C/N ratio follows the same trend as the distribution of total C, corroborating the non-linear pattern at P2 and with lower and more linear values at P1.

Table 2. ^{14}C dating ages of the humin fraction in relation to the depth of the soils of Profiles 1 and 2, Loanda - PR.

Sample ACUFF[1]	Profile	Age ^{14}C (years BP)	Calibrated Ages (95.4% probability, 2 σ)	
			Cal years BP	Cal years BP*
210015	P1 60-70	2111±26	2317-2225 2159-2085	2201
210016	P2 60-70	5046±30	5896-5653	5775
210017	P2130-140	6965±31	7846-7674	7760

[1] Sample code at UFF's Radiocarbon Laboratory. * Average of calibrated ages

The isotopic values of $\delta^{13}C$, presented in Supplementary Information (SI-1), do not indicate vegetation change over time represented in these profiles. The vegetation was always forested in both profiles, presenting phases of greater openness, but that do not configure a vegetation change. Both profiles presented isotopic depletion in depth. P1 presented variations in isotopic values between -21.64‰ and -25.30‰ at depths of 30 cm to 320 cm and -25.18‰ at 680 cm. In the P2 profile, the isotopic values observed were -22.42‰ at 30 cm, -23.23‰ at 90 cm, -25.84‰ at 150 cm, and -24.34‰ at the base of the profile.

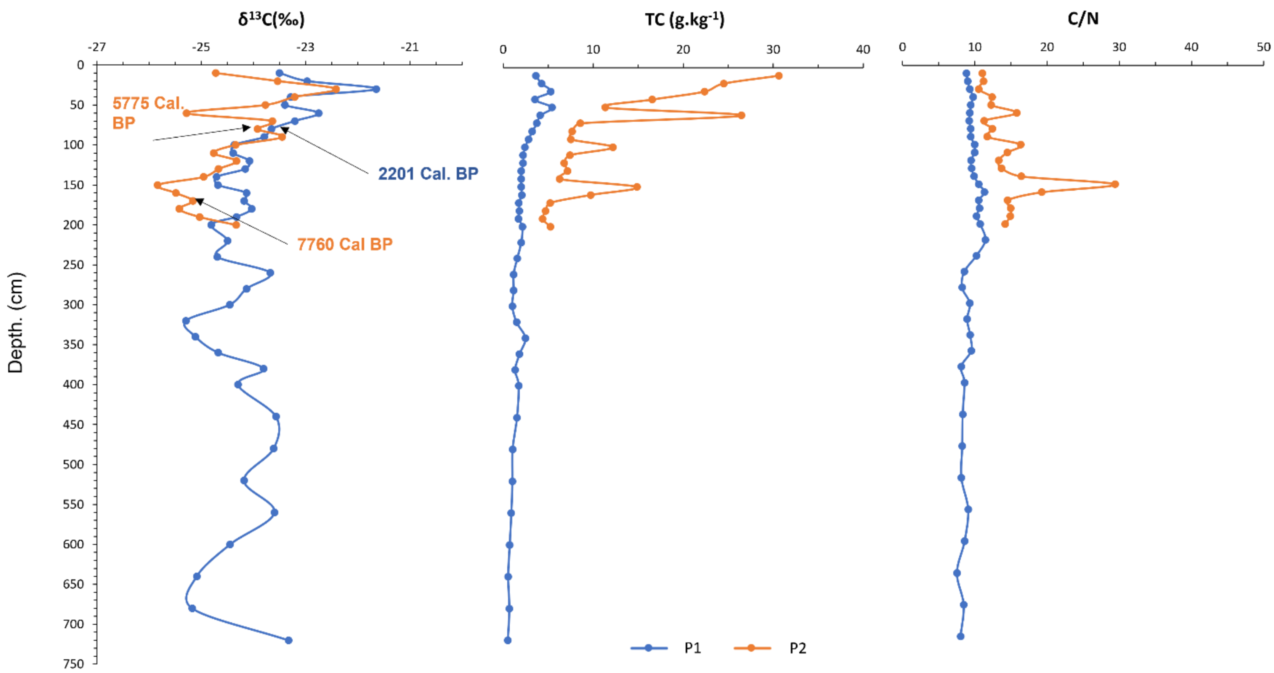

Figure 3. Vertical distribution of C and N isotopic values, C/N ratio and 1^{14}C dating of the SOM of soil profiles from paleogully G3 - Loanda (PR).

3.3. Phytolith Assemblage

In the current vegetation assemblage, represented by the transect samples, 16 morphotypes were identified (Figure 4), composed predominantly of phytoliths of Poaceae (BILOBATE, and POLYLOBATE-Panicoideae/C4, BULLIFORM FLABELATTE and ELONGATE DENTATE); of Eudicotiledoneae (SPHEROID PSILATE and SPHEROID ORNATE; ELLIPSOIDAL PSILATE, POLYGONAL, TABULAR) and of Arecaceae (SPHEROID ECHINATE). STOMATE and ELONGATE, with no specific family, are also part of the assemblage (more details are given in Supplementary Information SI-2).

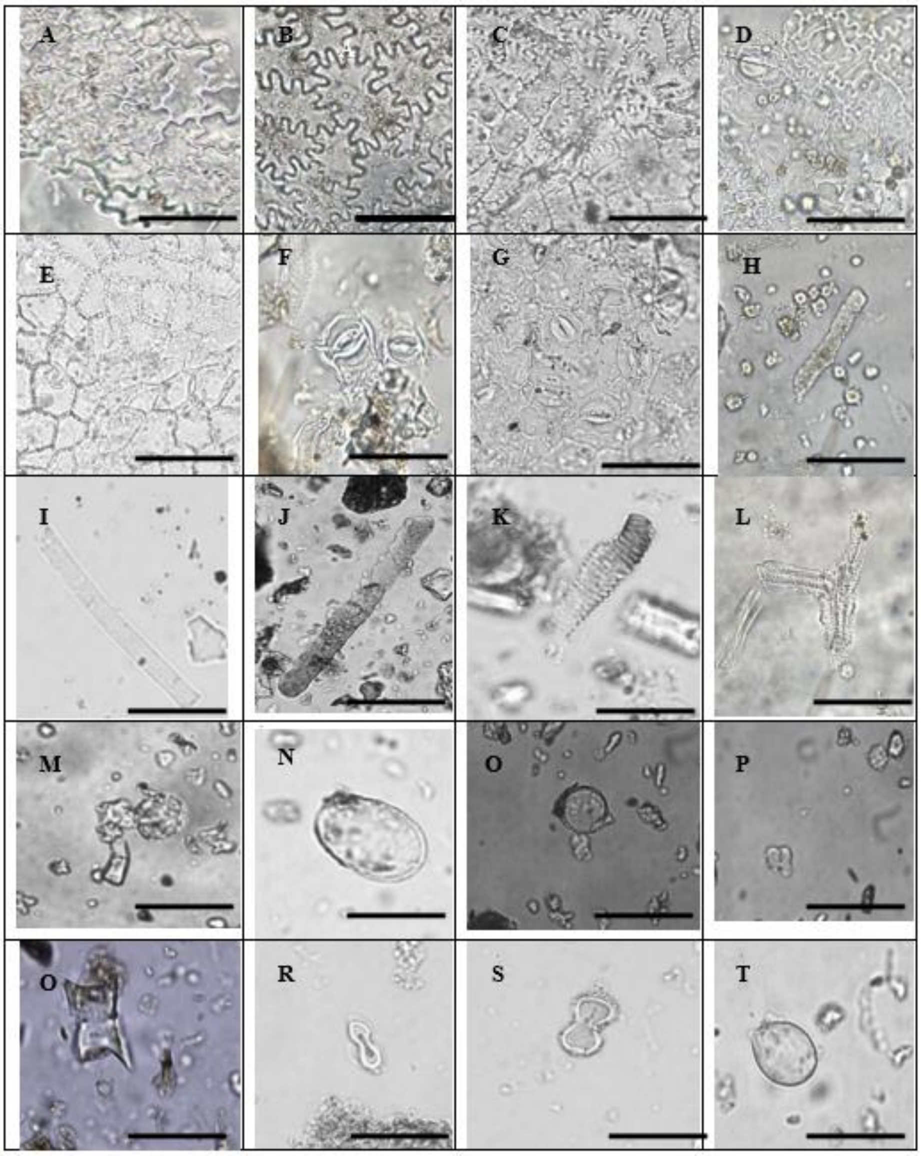

Figure 4. Morphotypes found in litter and soil profiles (P1 and P2), in an anomalous feature, in Loanda (PR). A-G Articulates of Eudicotyledonous phytoliths; F, G) STOMATE; H-J) ELONGATE; K-L) TRACHEARY; M-O) SPHEROID PSILATE; P) Unidentified; Q-S) BILOBATE; T) Cystolith (non-phytolith). Bar= 10 μm

In the profiles this same assemblage was maintained, however presenting a lower diversity of morphotypes in depth. The relative frequency of taphonomized morphotypes and morphotypes of indiscriminate families increased at depth, to the detriment of identifiable phytoliths. At P1, from 300 cm and above no phytoliths were found that were larger than 5μm in size and identifiable shape, nor were they fragmented or corroded, so samples below this depth were considered sterile in phytoliths. In P2, the sterile samples were found throughout the profile, more contiguously between 110 cm and 190 cm. The composition and distribution of the phytolith assemblages in the profiles were organized in graphs.

Principal component analysis (PCA) was performed using 10 variables, representing the phytolith-producing taxonomic groups (Herbs; Palms; Trees; Trees and Shrubs), articulated phytoliths (Art), indiscriminate (Indisc), unidentified (NI) and tafonimized (Taf) morphotypes, the amount of charcoal (coals) and the C/N ratio (CN). In P1 the sum of the first four principal components accounts for only 72.2% of the variance among the samples. PCA-Axis 1, (Moisture) accounts for 24.4% of the total variance among the samples and PCA-Axis 2, which represents the temperature variation, account for 21.1% of the variance along the profile. The moisture variation indicated in PCA-Axis1 is defined by the predominant presence of herb (variable) morphotypes (mostly mesic grasses) and trees, and to a lesser extent, tafonomized (Taf) morphotypes (morphotypes that show some sign of chemical, physical, or temperature change-fires, Parr, 2006) and unidentified, due to the high degree of physical or chemical change that made it impossible to identify the shape; indicating movement in the profile and/or long time in the profile) (positive quadrant) and by the variables trees and shrubs (life forms indicative of moisture in the environment), articulated (Art) and the morphotypes with no taxonomic significance (Indisc) (negative quadrant). The PCA - Axis 2, which reflects the temperature variation in the environment is influenced, in the positive quadrant, only by the Palm morphotypes (in general, these are plants associated with tropical and subtropical environments, and well-drained soils, LIMA et al., 2003) and the amount of charcoal indicative of the occurrence of fires, associated with drier conditions (GOUVEIA et al. 2002) , and, in the negative quadrant, by the morphotypes of trees and shrubs (life forms indicative of moisture in the environment), articulated (Art) (in general indicate good preservation of organic matter in the soil and low degree of soil movement/revolving, CALEGARI et al.,2013a), without taxonomic significance (Indisc.) and unidentified (NI) (Figure 5).

At P2 the sum of the first four principal components accounts for only 87.9% of the variance among the samples. The PCA-Axis 1, (Moisture) is responsible for 42.4% of the total variance among the samples and the PCA-Axis 2, which represents the temperature variation, correspond to 17.6% of the variance along the profile. In PCA-Axis1, considering the significance of the variables presented in P1, the moisture variation is defined by the predominant presence of Palms morphotypes (variables), C/N ratio and tafonomized (Taf) in the positive quadrant and by the variables trees and shrubs and the articulated (Art) that in general indicate good preservation of organic matter in the soil and low degree of soil movement/revolvement (CALEGARI et al.,2013 a) and, in smaller proportion the morphotypes without taxonomic significance (Indisc) in the negative quadrant). The PCA - Axis 2, which reflects the temperature variation in the environment is influenced, in the positive quadrant, only by the morphotypes of herbs and unidentified phytoliths, and in the negative quadrant by the C/N ratio and by morphotypes of trees, trees and shrubs, indiscriminate and articulate (Art.) (Figure 5).

3.3.1. Phytoliths Zones

Cluster analysis and Principal Component Analysis (PCA) differentiated three phytoliths zones that are repeated in both profiles. The zones and their respective phytoliths assemblages consider the average of the values of the main characteristics in each profile.

In P1, the phytolith assemblage of the current vegetation (0-10 cm soil and the litter) represents the reference, for interpretation of the underlying zones. Developed under Cfa climate conditions, the current SSF assemblage is composed of phytoliths of herbaceous plants (13.7±1.8) being 8.7(±1) diagnostic phytoliths of grass short cells (GSCP). Tree and shrub and palm morphotypes accounted for 34.6% of the assemblage. The results of the phytolith analysis are congruent with the isotopic results that showed a $\delta^{13}C$ value of -22.8‰, which signals vegetation with a mixture of C_3 and C_4 plants (Figure 5).

From the bottom to the top, three phytoliths zones were identified (Figure 6) thus characterized:

Zone I (200-120 cm): groups part of the B ferralic horizon samples and presents the $\delta^{13}C$ value that signals a vegetation with a predominance of C_3 plants (-24.3‰).

The predominance of C_3 plants was corroborated by the phytolith assemblage that presents about 47% of these as forest indicators (Eudicots and Palms). It presents few charcoal fragments (1g.kg^{-1}). This zone was subdivided into subzones Ia and Ib, due to intra-zonal variations:

Zone Ia (300-160 cm): The phytolith assemblage in this zone is composed of morphotypes produced by of herbaceous species (32.9% ±2.6), 18.8% (±1.9) of which are taxonomically significant short grass cells (Panicoid, Pooid and Chloridoid), 12 % (±5.4) of Arecaceae (Palms) (SPHEROID ECHINATE) and 14.7 % (±6.3) of arboreal Eudicots (SPHEROID ORNATE) and 12.3 % (±2.5) of arboreal and shrub Eudicots. The rest of the assemblage is composed of phytoliths with a high degree of redundancy. The calculated indices showed values (mean) of 2.1 (±1.4) for the D/P index and 1 (±0.8) for FS. The IC and Iph showed a value of 0.1.

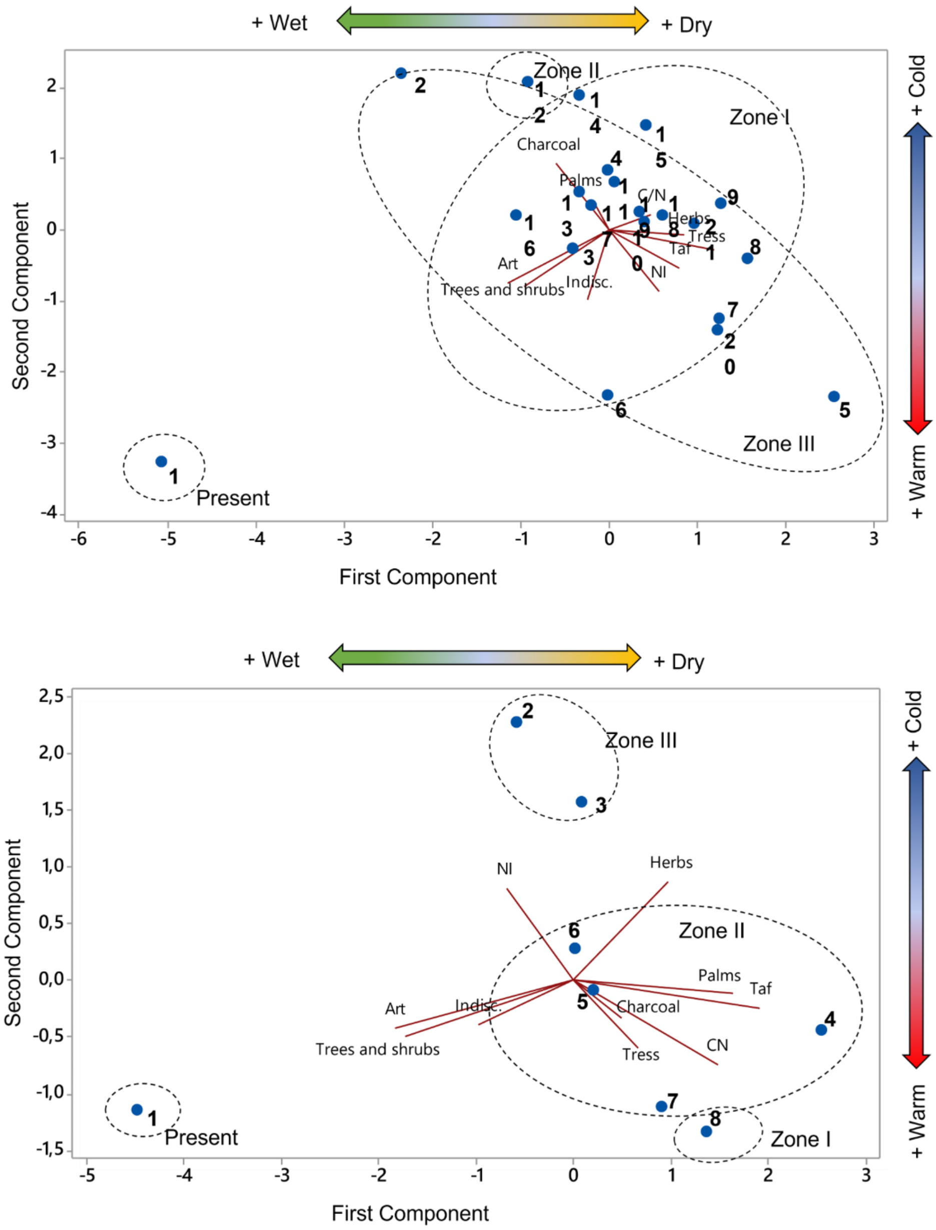

Figure 5. Principal Component Analysis of the phytolith assemblage of P1 and P2, in Loanda (PR). The ellipses in dotted line gather the samples that compose each phytolith zone. Eigenvectors indicate the names of the producing groups and plants; Arabic numbers indicate the samples **(P1**: **1** - Litter, **2** - 0-10 cm, **3** - 10-20cm, **4** – 20-30cm,**14** – 120-130 cm, **15** - 150-160 cm, **17** – 170-180cm**, 18** – 190-200 cm, **19** – 250-260 cm, **20** – 270-280, **21** – 290-300 cm; **P2**: **1** - Litter, **2** - 0-10 cm, **3** - 10-20cm, **4** – 50-60 cm, **5** – 60-70 cm, **7** – 100-110 cm, **8** – 180-190 cm).

Zone Ib (160-120 cm): Gathers samples from the B ferralic horizon that show phytolith assemblage composed of morphotypes produced by herbaceous species (24.2%± 3.4), of which 10.8% (±1.9) are short-celled grasses of taxonomic significance (Panicoid, Pooid and Chloridoid), 13 % (±13) of Arecaceae (SPHEROID ECHINATE) and 26.9 % (±9) of arboreal Eudicot (SPHEROID ORNATE) and 17% (±4.1) of arboreal and shrub Eudicot. The rest of the assemblage is composed of redundant phytoliths with no specific family. The isotopic value is -24.1‰ and1.6 g.kg^{-1} of charcoal fragments were found. The IC, Iph and FS showed null value, and the D/P showed value 1.5 (±2).

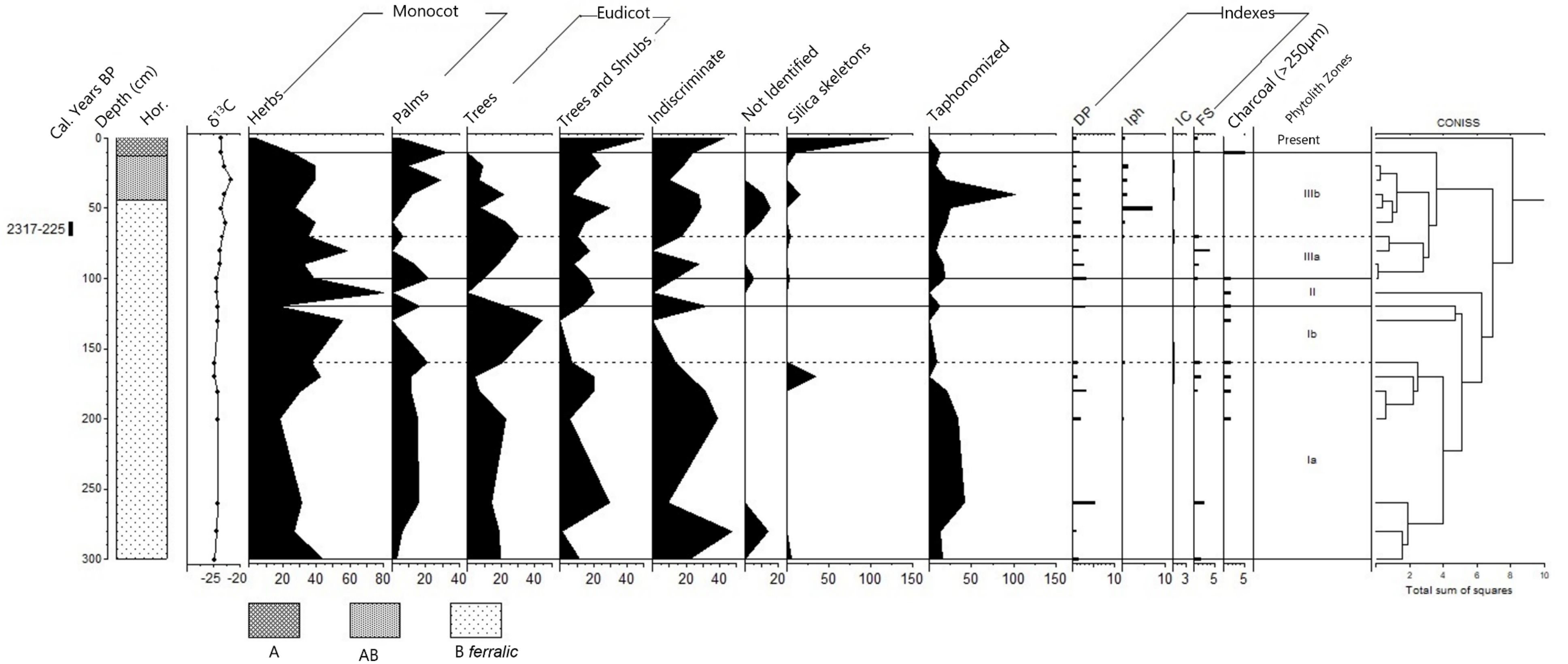

Figure 6. Relative frequency distribution of phytolith assemblage, phytolith indices and charcoal fragments from P1, in paleogully, Loanda, PR.

Zone II (120-100 cm) - still corresponds to samples from the B ferralic. It represents a transition zone, marked by the increase of phytoliths produced by plants of the herb and tree and shrub groups to the detriment of those diagnostic of woody tree plants (SPHEROID ORNATE) and palm trees (SPHEROID ECHINATE). Isotopic values and the amount of charcoal fragments remained similar to the underlying zone, respectively, (-24.4‰ and 1.6 $g.kg^{-1}$). The indices also showed little variation.

Zone III (100-10 cm) - this zone is composed of samples from the top of the B ferralic horizon and the BA horizon. The phytolith assemblage is marked by morphotypes from herbaceous plants that represent 37.6% (±2.3) of the assemblage, trees (17.7% ±9.3), trees and shrubs (33.6% ± 1.8) and palm trees (Arecaceae-9.5% ±8.3). The rest of the assemblage consists of redundant phytoliths with no defined family (1.6%). The mean isotopic value is -23‰, with no charcoal fragments. Intra-zonal variations conditioned the subdivision of this zone.

Zone IIIa (100-70 cm) - Presents phytolith assemblage with a trend of increasing herbaceous phytoliths (41.6% ±2.2) at the expense of shrub (12.1 ±1.5) and palm (6.3%) morphotypes. GSCP and tree plant morphotypes are predominant in this zone, respectively 22% (±15) and 25.2 (±9.1). The assemblage is further composed of phytoliths from herbaceous plants (41.6% ± 2.5), of which 4.2% are from the subfamily Panicoideae, 8.1 % from Pooideae/Danthanoideae and 0.4% from Chloridoideae and by redundant phytoliths within the Poaceae family (28.9%); the assemblage still features palms (20.7%) and the rest are redundant phytoliths, from the No defined family group (12.5%). The value of $\delta^{13}C$ is -23.6‰ and of the indices are 2 (D/P), 0.3 (CI), 1.83 (Fs) and 0.7 for Iph.

Zone IIIb (70-10 cm) - Begins in the middle/upper Holocene transition, around 2,201 cal. BP and extends to approximately 400 cal years BP. It presents the assembly that marks the decrease of herbaceous plant phytoliths (35.3% ±1.5), especially in the basal samples. Decrease was also observed in morphotype diagnostics of grass subfamilies (GSCP) (15.5% ±1.4). Trees represent 13.5% (±9.1) of the assembly and palms 11.3% (±9.2) and the rest, about 39%, are redundant morphotypes that make up the No defined family group. The $\delta^{13}C$ is similar to that of the current vegetation (-22.7‰), as is the value of the D/P (1.7), IC (0.1) indices. The FS was null for this subzone and the Iph was the highest in the entire profile (2.1).

In P2, the assembly of the present SSF (burlap and 0-10 cm) is composed of herbaceous plant phytoliths (21.3 ±11.5), with 19.3(±12.8) morphotypes being diagnostic of GSCP. Tree and shrub and palm morphotypes represent 66.4% of the assemblage and the remaining 12.3%, represents those redundant morphotypes, belonging to the No defined family group. This assembly shows a coherent relationship with the carbon isotopic values (-24.7%), which signals a vegetation with plant mixture, with a predominance of C_3 plants (Figure 5).

From the bottom to the top of P2, three phytolith zones were identified (Figure 7), with the following characteristics:

Zone I (200-110 cm): composed of the 3B ferralic2 and 4BC horizons (Table 1), presents an isotopically depleted $\delta^{13}C$ value of -24.8‰. The assemblage corroborates the isotopic data with a predominance of phytoliths from arboreal (9% ±10.1) and arboreal and shrub plants (37.9% ±8.8). Phytoliths from herbaceous plants comprise 28.1% (±45) of the assemblage, with 22.9% (±5.2) being GSCP. Morphotypes from the No defined family group represent 25% of the assemblage. Notably few charcoal fragments (<1$g.kg^{-1}$) were found in the zone.

Zone II (110-20 cm): This zone encompasses part of the Lower Holocene, corresponding to samples from horizons 3B ferralic, BA and 2AB m dating between approximately 7,100 and 5,775 Cal BP. The identified phytolith assemblage.

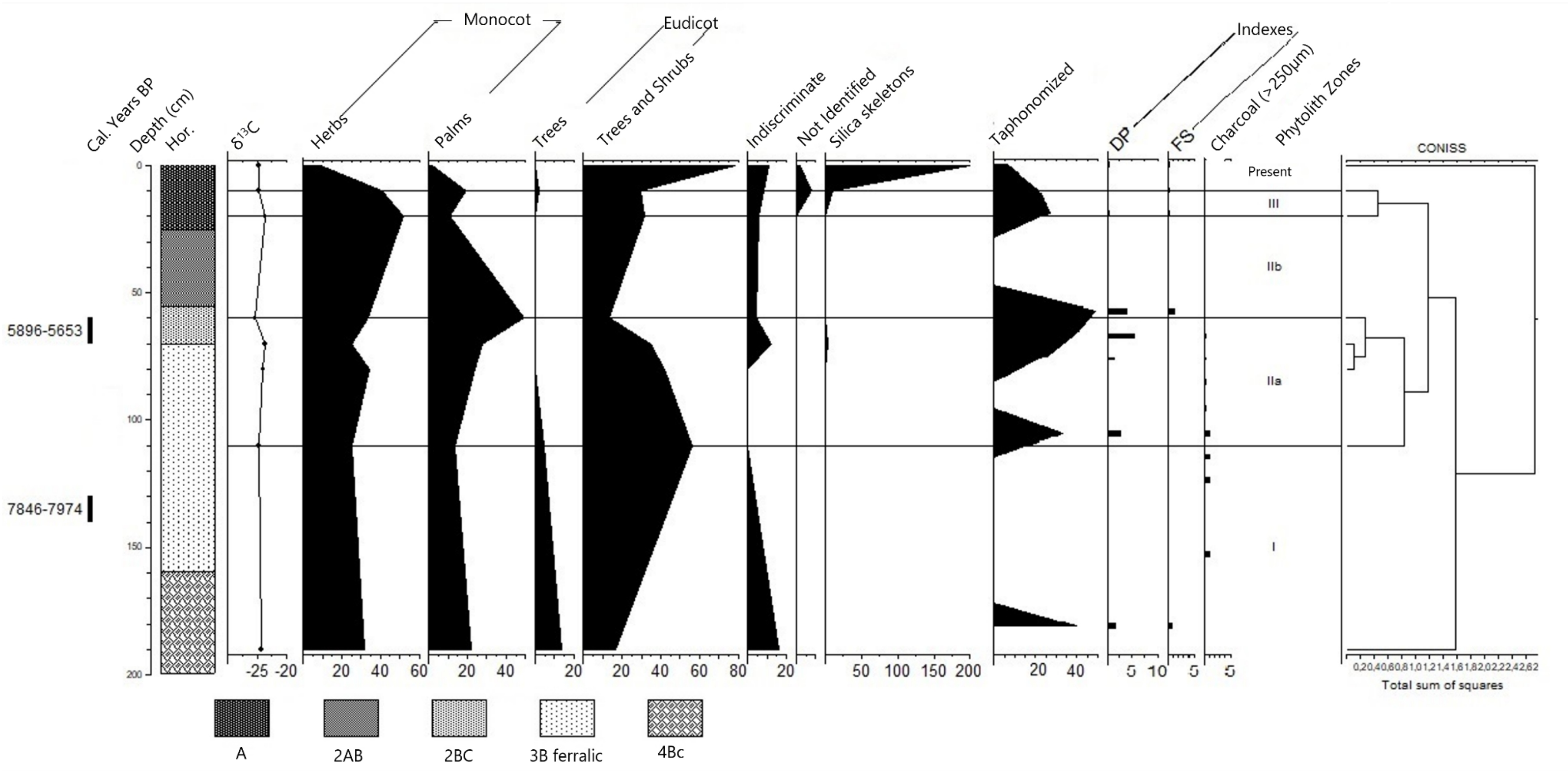

Figure 7. Relative frequency distribution of phytolith assemblage, phytolith indices and charcoal fragments from P2, in paleogully, Loanda, PR)

The identified phytolith assemblage is mainly composed of SPHEROID ECHINATE palms (34% ±37.9), followed by 30.7 % (±7.1) of herbaceous plants and 20.1 (±5.8) of indiscriminate trees and shrubs. The remaining 15.2% the rest are from redundant morphotypes of the No Defined Family group. Among the herbaceous phytoliths, the GSCP morphotypes represent 29.4% (±8). The calculated indices for phytolith analysis are 1.5 (±2.1) for the D/P index, 0.2 (±0.5) for FS and null for IC and Iph.

Given the variations observed among the assemblage values, this zone was subdivided into:

Zone IIa (110-60 cm): The assemblage is composed of phytoliths from herbaceous plants (33.7%±5.7), trees and shrubs (25.61 ±6.9) and palms (26.1% ±26.8). GSCPs represent 27.0 (±6.5) of the assemblage, while 14.6% are redundant morphotypes with no defined family. The value of $\delta^{13}C$ is -24.1‰ and of the indices are 2 ,2 (D/P) and 0.3 (FS), the others are null.

Zone IIb (60 cm -20 cm): It begins at the end of the Middle Holocene about 5775 cal. BP and presents an increase of phytoliths of herbaceous plants (33.7% ±8.3), marked by the predominance of GSCP. Indiscriminate tree and shrub morphotypes represent 10.2% (±2.7) of the assemblage, while palm morphotypes show expressive increase compared to all other zones in this profile (49.0%). Only 7.1% are morphotypes of the No defined family group. The $\delta^{13}C$ remained the same as in the underlying zone (-24.1‰). The values obtained for the indices are 1.3 (D/P), 0.4 (FS). The others were null.

Zone III (20cm -10 cm): Corresponds to samples from the upper part of the 2AB horizon, dated approximately 1925 cal years BP. It shows an increase of phytoliths from herbaceous plants (51.8% ±6.9) and of short cells, mainly Panicoid (21.1%). Phytoliths from palms account for 11.1%, while arboreal and shrubs account for 31.7% (±9.2). Redundant phytoliths make up 4.5% of the assemblage. The $\delta^{13}C$ value is -23‰ and of the phytolith indices are 0.2 (SD), 0.1 for FS and Iph and null for IC.

3.4. Correlation between phytolith assemblage and charcoal fragments in soil

Charcoal fragments larger than 250μm were found at different depths in both soil profiles studied (Figure 8 and 9). In P1, the highest concentration of fragments occurred in B ferralic 1 (4.6 g.kg-1) and B ferralic 2 (1.58 $g.kg^{-1}$), while in P2, they were found in all sampled horizons, decreasing towards the base of the profile, varying nonlinearly from 0.14 $g.kg^{-1}$ (A horizon) to 0.02 g.kg-1 (BA horizons). Figure 8 presents the distribution of the sum of woody plant morphotypes, burned phytoliths, and charcoal fragments by horizon. Phytoliths produced by woody plants (SPHEROID ORNATE and PSILATE and ELIPSOID PSILATE) were found in all assemblages in P1 and in P2 SPHEROID ORNATE was found only in the litter samples.

Burnt phytoliths were observed up to 300 cm in P1 and only up to 110 cm in P2. Effect of fire (color variation and deformations in morphotypes) was observed predominantly in phytoliths produced by grasses in both profiles. The correlation coefficient (Pearson) between charcoal fragments and woody phytoliths was 0.84 (P1) and 0.72 (P2). When correlated with the burned phytoliths, the charcoals showed values of -0.18 (P1) and -0.34 (P2). The coefficient of determination (R2) was, respectively, for P1 0.59 and 0.08 and for P2 0.69 and 0.20 (Figure 9).

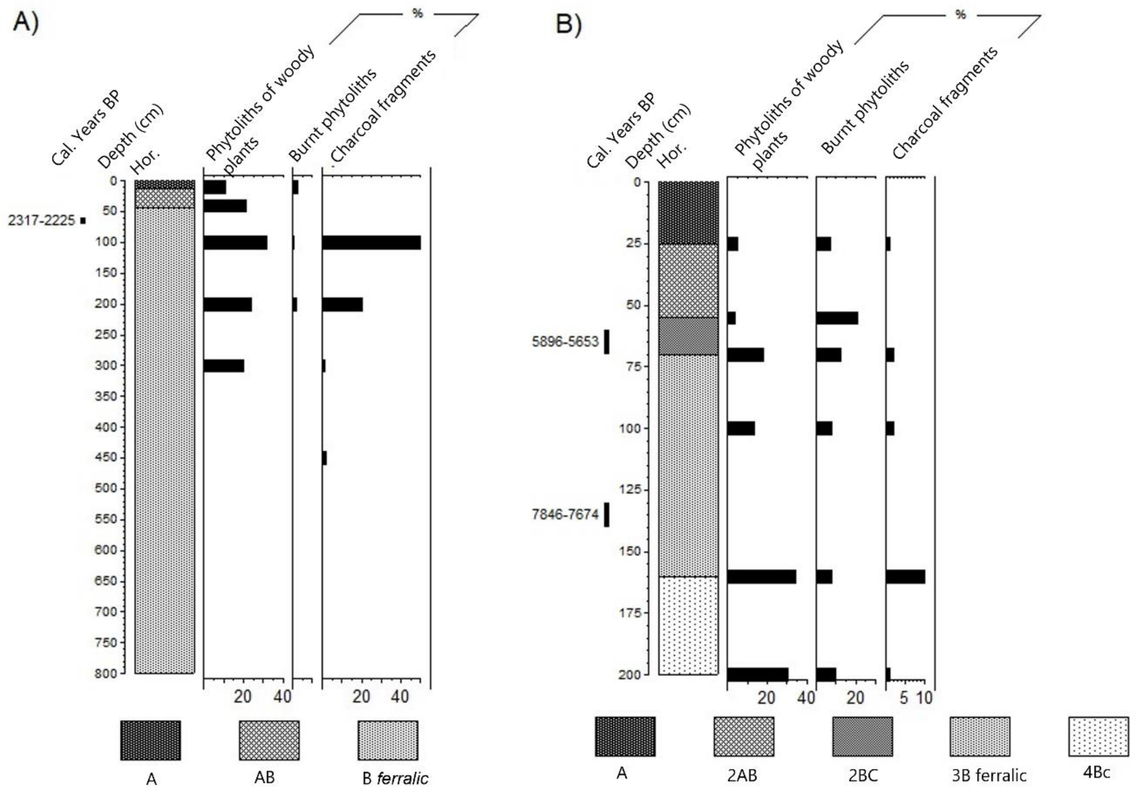

Figure 8. Distribution between woody plant phytoliths, burned phytoliths and charcoal fragments from P1 (A) and P2 (B), in anomalous features, Loanda (PR).

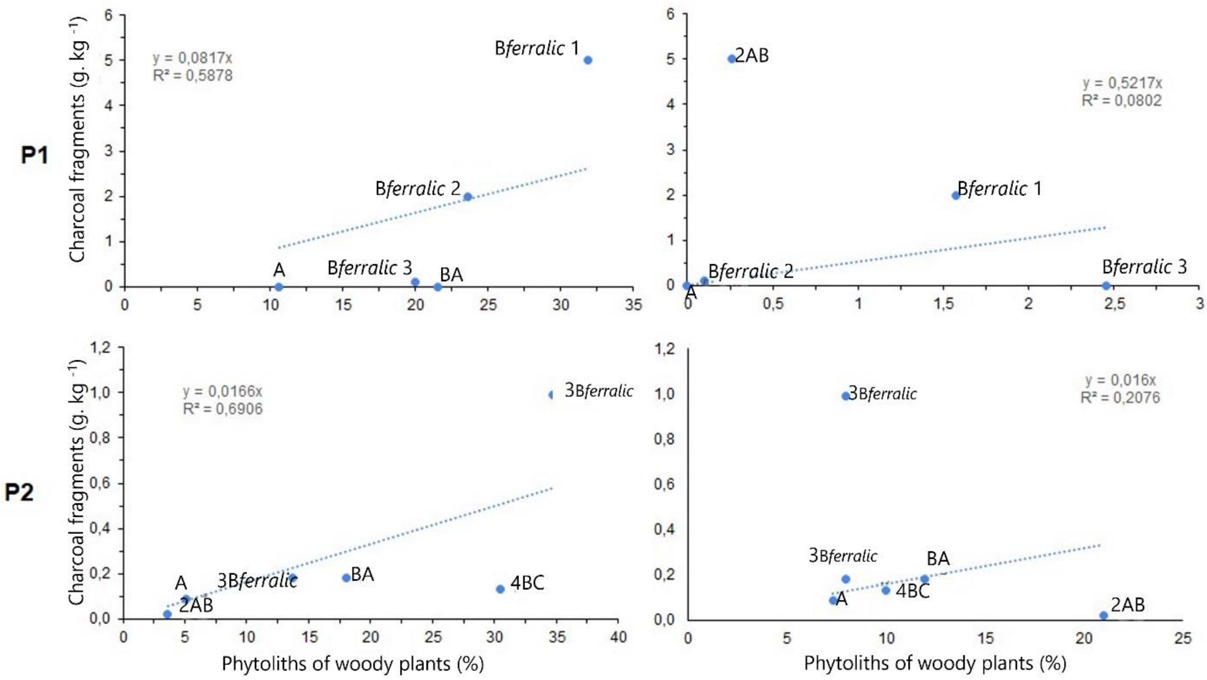

Figure 9. Positive Coefficient of Determination (R^2) between charcoal fragments and woody plant phytoliths and burned phytoliths from P1 and P2, in anomalous features, Loanda (PR).

4. Discussion

The studied anomalous feature displays deep and pedogenetically evolved soil profiles in the upstream sector, where the samples were collected. Considering that soil functions as a reservoir of environmental records (JANZEN, 2016), it was observed that the studied soils exhibited a range of indicators capable of preserving memories, both in their undisturbed state (P1) and in the presence of edaphic and geomorphic disturbances (P2). P1 is an autochthonous soil, developed in situ, from the underlying sandstone, and P2 is an allochthonous soil, developed from a pre-latosolized colluvial material, transported from upstream by means of processes related to the evolution of the erosive feature (creep, subsidence, etc.). In P2, the A horizon presents attributes (color, texture, pH and SOM) similar to the other surrounding soils, a common condition in allochthonous soils and paleosols (RETALLACK, 2001). In the underlying horizons, pedogenesis, including bioturbation, was effective in obliterating the macromorphological features of the parent material such as stratigraphy and color, making the profile more homogeneous. As a result, the macromorphological properties of P2 do not evidence signs of colluvial processes. However, geochemical and granulometric characteristics still preserve the irregular ordering of constituents, which reveals its colluvial nature. Two discontinuities were identified in this soil, which was described at a dissected point, in the upstream sector of the anomalous feature studied. Considering the described attributes, both profiles were classified as Latossolo Vermelho Eutrófico according to the Brazilian Soil Classification System (EMBRAPA, 2018), without reference to the colluvial origin of P2. This reference is made when we use WRB/FAO (2015), which classifies this soil as Haplic Ferralsol (Colluvic). The classification of the soils already presents the first information regarding the environmental history of the studied feature, evidencing the occurrence of instabilities in the slopes and their morphogenetic evolution throughout the Holocene. The ^{14}C ages of the SOM delimit the time frame of this analysis, which is limited to about 7,760 years Cal. BP.

Considering the autochthonous nature of the P1 soil and a profile thickness (>700 cm) it is possible that its history is older than the Holocene. The soil attributes of P2, on the other hand, indicate two phases of environmental instability: the first occurred at the end of the Lower Holocene, around 5700 cal years BP, when the parent material of the 3B ferralic horizon was deposited; the second occurred around 1900 cal. BP, the time of deposition of the material that constitutes the 2AB horizon, which presents a sandier texture than the rest of the profile. This texture suggests the presence of an original material poor in clay or that a lateral transformation system of illuviation would be settling in this profile (OLIVEIRA; SANTOS; CALEGARI, 2020). Eluvial horizons, such as 2AB, are frequent in the northwest region in steeper/dissected sectors of the slopes (CALEGARI, 2000; NAKASHIMA, 1999; OLIVEIRA; SANTOS; CALEGARI, 2020). Both interpretations can be corroborated by the lack of phytoliths (sterile phytolith assemblage) in this horizon.

Phytoliths are important markers of paleoenvironmental events, but their preservation in soil/sediments can be affected by several factors (MADELLA et al, 2013). Coarser textured material, as observed in the studied profiles, is not an ideal storage condition for phytoliths (FISHKIS; INGWERSEN; STRECK, 2009) and can compromise their preservation within the soil. This occurs because the low clay and organic matter content, as observed in the 2AB horizon, compromises the soil structuring (KÄMPF; CURI, 2012), which could trap the phytoliths inside, and protect it from the elution processes in the profile (LI et al., 2020), common in the soils of the Northwestern region of Paraná (OLIVEIRA et al., 2020). Samples without identifiable phytoliths (sterile) are often associated with the eluviation process in the profile (PIPERNO, 1985), because phytoliths, which have size > 5μm, can migrate along with silt and clay to the underlying horizon, as observed in this profile, between the 2AB and BA horizons and at the base of the 3B ferralic. In this sense, the samples that presented phytoliths are, in general, concordant with those with higher total carbon (TC) contents, which reinforces the interpretation of colluvion. According to this interpretation, the horizons that preserve phytoliths would be former buried surface horizons, already highly weathered and homogenized. It is important to note, however, that this interpretation should be considered in conjunction with other evidence, such as the geochemical and granulometric characteristics of the soil, to obtain a more complete picture of the environmental history of the study area.

Profile P1 has typical attributes of the Ferralsols of the Caiuá region, with the exception of eutrophication, which occurs in a smaller proportion in this soil class in the region, according to EMBRAPA (1984). This characteristic can indicate the cycling of nutrients, such as Ca, that are contributed by the natural vegetation (SSF) in the superficial horizon of the soils (VITAL et al., 2004). Furthermore, the paleogully area has never been completely deforested, since at least the 1940s (GOULART; SANTOS, 2014), which suggests that the profile developed in situ, without signs of colluvion or reworking. It is the soil that best preserves the biotic memories of the evolution of vegetation and climate throughout the formation of this feature. The regularity in the vertical distribution of the attributes of this soil proves its autochthonousness.

The profile presents an isotopic signal of $\delta^{13}C$ (~-24‰), typical of vegetation composed predominantly of C_3 plants (~79%), indicating the presence of a forest vegetation. Subtle variations in the isotopic values indicate that there was never a significant vegetation change in this period, as the isotopic variations are always <3‰. A small gap in vegetation is inferred by the samples between 20 and 30 cm, when the values show isotopic enrichment of ~2‰ relative to the over and under samples, which suggests higher contribution of C_4 plants (~38%) in the soil organic matter composition.

The interpretation about the vegetation along the profile is reinforced by the presence, quantity, diversity and distribution of phytoliths, which were detected up to 300 cm depth. Furthermore, the isotopic data analysis suggests that the vegetation between 720 and 300 cm depth was similar to the present one, being predominantly composed of C_3 plants, indicating a forested vegetation, but more woody than in the upper part of the profile. From 300 cm to the top of the profile, the combination of the isotopic and phytolith results allows us to distinguish three environmental moments.

Zone Ia presents a forest vegetation, which developed under warmer and more humid climatic conditions than today, favoring pedogenesis (KÄMPF; CURI, 2012). From Zone Ib on, the forest vegetation persists, but under a significantly colder and drier climate than in the previous period. In this zone it is common to find charcoal fragments, indicative of fires, which has been observed in studies in the Pleistocene/Holocene transition in the South and Southeast regions of Brazil (CALEGARI et al., 2013c; DE OLIVEIRA et al., 2005; GOUVEIA et al., 2002; PESSENDA et al., 2005; SOUZA et al., 2019). The high correlation between woody plant phytoliths and charcoal fragments in this profile reinforces the hypothesis that fires occurred and that the vegetation was predominantly forest for this period.

Zone II characterizes a transitional phase, with more open vegetation. The charcoals found in this zone give evidence of a period with fire incidence (PESSENDA et al., 2005). The presence of charcoal fragments, burned phytoliths and phytoliths of woody plants indicates vegetation with greater forest cover in this phase. A vegetation with more woody plants is a necessary condition for charcoal formation. However, it is important to note that the distribution of charcoal fragments can be influenced by several factors. For example, coal particles can be displaced by gravity or by water and soil mass flows, which can result in accumulation in lower areas of the landscape. In addition, studies suggest that most of the charcoal in soils located in a top position, as in the case of P1, reflects the burning of vegetation at the sampling site or in nearby areas (HORN; UNDERWOOD, 2014). Studies conducted in South and Southeast regions of Brazil, and especially in the State of São Paulo, have reported the presence of charcoal lines at depths between 60 and 100 cm, dated between 4,000 and 3,000 years Cal. BP. (CALEGARI, 2008; GOUVEIA et al., 1999; SOUZA et al., 2019). These deposits are considered important indicators of vegetation and climate dynamics in the late Holocene.

Although Zone II is characterized by a wetter phase than the adjacent zones, the uneven distribution of moisture may have allowed fires to occur in the area. This irregularity in moisture is reflected in the FS index, which marks water stress in grasses. The isotopic and phytolithic data indicate an opening in the vegetation, which was coming from a phase with occurrence of water stress. The lower tree cover of the soil is a factor that favors the formation of surface runoff and linear erosive processes (BIGARELLA; MAZUCHOWSKI, 1985; JUSTUS, 1985) The sandy nature of the soils formed from Caiuá sandstone, combined with an irregular distribution of moisture, may have intensified these processes. This environmental instability may have contributed to the formation of Zone II, characterized by greater openness of vegetation and incidence of fires, which can be compared to the current conditions of Cerradão in the Central region of Brazil. Coutinho (1990) points out that the drier climate and higher temperatures favor the occurrence of natural fires of the vegetation cover, which propitiates the maintenance of the current Cerrado flora and fauna. This instability initiated in Zone II is consolidated in Zone III.

In phytolith zone IIIa (60-20 cm), the assemblage indicates a subtle reduction of tree cover, with a greater contribution of herbaceous plants. The phytolith indices suggest a drier and cooler climate than the present and that of Zone IIIa. The ^{14}C age of the beginning of this zone, coincides with a drier phase recorded by different proxies, both in the Northwest region (STEVAUX, 1994; STEVAUX; SOUZA FILHO; JABUR, 1997), and in the South and Southeast regions (CALEGARI et al., 2013a; DE OLIVEIRA et al., 2005; PESSENDA et al., 2005;

SOUZA et al., 2019). The transition between the Middle and Upper Holocene was also indicated as a drier period by Souza et al. (2019) in a SSF fragment in southwestern São Paulo. In this region, the forest underwent a more significant opening in this period, which has been interpreted as the period when Cerradão has installed.

Zone IIIb is characterized as the driest and coldest of the profile and accords with a probable resumption of incision of the studied paleogully (anomalous feature), whose beginning seems to have been in the Pleistocene by Goulart (2020). The isotopes and phytolith assemblage indicate this drier phase. Previous studies with phytoliths in the central region of São Paulo state indicate a dry phase at the end of the Middle Holocene, when Cerrado vegetation would have been established, preceding the formation of the current SSF (SOUZA et al., 2019). The interpretation of the data suggests that the current SSF would have started its formation around 400 cal years BP. In a broader analysis it is found that the period of Zone IIIb coincides with the Bond Cycle 1, a 1500-year event that has been recorded as a cooler and wetter period in the North Atlantic (BOND et al., 1997, 2001), with correspondences of Bond Cycles 1, 2 and 3 in Antarctica (GANOPOLSKI; RAHMSTORF, 2001). In Brazil, however, these cycles are still poorly documented.

P2, of colluvial origin, provides relevant information for reconstructing the paleoenvironmental conditions of the study area. It is important to emphasize the low frequency of phytoliths and phytoliths of grasses of the subfamily Chloridoideae and Pooideae, besides the absence of a diagnostic phytolith morphotype of woody angiosperms, such as SPHEROID ORNATE, in Zone II. These morphotypes are relatively small (<50μm) and may have been affected by taphonomic processes that led to their destruction or redistribution (by eluviation process) in the profile, as discussed in other studies (CORDOVA; SCOTT, 2010; RUNGE, 1999). Based on the isotopic data, it was found that the predominant vegetation during the Lower Holocene was composed of C^3 plants. Although the sterile samples in phytoliths limited the accuracy of the isotopic data, the recovered assemblages allowed us to infer the presence of a forest vegetation in Zone I, which corresponds to the period prior to about 7,700 y cal. BP (Lower Holocene).

The conditions observed in this zone agree with the current literature, which indicates humid climatic conditions in the northwestern region of Paraná in the Middle Holocene (STEVAUX, 1994). On the other hand, studies in Cerrado and SSF areas show that the Southeast and Center-West regions experienced drier conditions in the Middle Holocene, promoting vegetation change (PESSENDA et al., 1996). In other regions, this change would have occurred around 3,500 - 3,000 ^{14}C years BP in Botucatu, Anhembi, and Pirassununga (SCHEEL-YBERT et al., 2003); after 4,000 14C years BP in Jaguariúna (GOUVEIA et al., 1999); after ~3,000 ^{14}C years BP in Piracicaba and Londrina (PESSENDA et al., 1996); after 2800 cal. years BP in Assis (KAMMER, 2018); around 3,000 years cal. BP in Gaia/Alvilândia (SOUZA et al., 2019) and about 4,610 - 4,010 ^{14}C years BP in Mato Grosso do Sul (STEVAUX, 1994).

Zone II, which presented a greater number of samples with phytoliths, indicates a more expressive arboreal cover and occurrence of hidric stress (FS) and charcoal fragments, mainly in Zone IIa. However, the interpretation of subzones II is hampered due to the signs of colluvion and evidence of translocation in this part of the profile, which makes it impossible to discuss these subzones in this paper. In Zone III, the environmental condition is like Zone IIIb of P1, but with a shorter development time. It is noteworthy in this zone the large amount of taphonomized phytoliths, suggesting more aggressive environmental and edaphic conditions for the integrity of the assemblage incorporated to the soil, which makes it difficult to discuss the environmental significance of these samples.

In light of the foregoing, considering the regional denudation rates and the anomalous features of Loanda, it is possible to infer that the drier conditions of Zone III, of both profiles, early in the Middle to Upper Holocene transition, created an environment that, although not dry enough to promote an exchange of vegetation, caused its opening. The evidence of periods of hidric stress suggests that there was a greater concentration of rainfall at times. Additionally, the sandy nature of the soils derived from the Caiuá sandstone, deep and highly weathered, as suggested by the morphological, physical and geochemical attributes of these soils, together with a little dissected relief, establish a favorable scenario for the development of erosive processes, which may have acted in the expansion of the paleogully under study. In the literature, concentrated rains on uncovered soils are considered as triggering factors for the development of large gullies in a few hours or days in the Northwest Paraná (BIGARELLA, MAZUCHOWSKI, 1985: MAACK, 2002).

The formation of large gullies is reported as a mechanism of morphogenetic evolution in Northwestern Paraná since the late Pleistocene. Bigarella and Mazuchowski (1985) emphasize that these processes are a response to the climatic instabilities imposed during this period, especially in the region where the sandstone of Caiuá Group occurs. According to these authors, after the Last Glacial Maximum, humid conditions would have installed themselves in the region, promoting a general dissection of the landscape and drier phases conditioned extensive solifluxion processes, generating rudaceous paleopavements, sediment deposition in floodplains and formation of floodplain terraces. Based on the data obtained at Loanda, it is suggested that the process that would have intensified the evolution of the G3 paleogully was related to the wet period, which began about 1000 years Cal. BP and lasted until the stabilization of conditions similar to today's, approximately 400 years Cal. BP. and lasted until the stabilization of conditions similar to today, approximately 400 years Cal. BP. This process would have promoted the advance of the forest over the slopes of the feature, which led to the stabilization of the slopes and maintenance of the forest until the present day, when the use and occupation in the surroundings of the feature would be triggering a new phase of instability by accelerated erosion.

5. Conclusion

Analysis of the isotopic composition of the SOM and phytolith assemblage in the Loanda G3 paleogully area indicated predominance of C_3 plants in the last ~7,700 cal years BP and that the vegetation has always been forested, with opening phases associated with drier periods in the Middle Holocene and cooler periods in the Upper Holocene.

The changes in moisture and the opening of the vegetation, along with the sandy nature of the soil about 2,200 cal years BP, contributed to the intensification of erosional processes that formed the anomalous feature, as well as the others, preserved in the landscape. The present SSF was established in the last ~400 cal years BP.

Regarding the paleogully G3 at Loanda, we conclude that its enlargement is related to an environment with more open vegetation and drier climate than the present one during the Middle to Upper Holocene transition. The increase of humidity in the upper Holocene (post ~1,500 cal. years BP) may have favored the intensification of the erosive process and its subsequent stabilization due to the advance of the forest over the slopes of the feature, already with kilometer dimensions, preserved in the landscape until the present days. However, the morphogenetic instability at the edge of the feature affected the pedogenetic development of P2, which presents an ancient colluvial phase (Middle Holocene), changing the distribution of the proxies in the profile, especially the phytoliths, compromising the paleoenvironmental interpretation.

Supplemental Materials: Supplemental Information IS-1 and IS-2 described in the article are available online at: https://github.com/revbrgeomorfologia/n_vocoroca/blob/main/RBG-2328-Informacoes-Suplementares.xlsx

Author Contributions: M. R Calegari: Design, methodology, formal analysis, resources, writing (initial - review - editing), supervision, funding acquisition; L. Marcolin: Design, methodology, data acquisition, writing (initial); P. Camargo: methodology writing (review); L. J. C. Santos: Conception, formal analysis, writing (review), project administration, and funding acquisition. All authors have read and agreed to the published version of the manuscript." Authorship should be limited to those who have substantially contributed to the work reported. Fill in only after acceptance for publication.

Funding: This research used financial resources from research coordinated by L. J. C Santos, Project funded by the National Council for Scientific and Technological Development (CNPq - Process 445654/2014/7 and CAPES 88881370828/2019-01; M. R. Calegari FINEP project - Innovation and Research - MCTI/FINEP/CT-INFRA - PROINFRA - 02/2014 - FINEP Agreement - Ref. 150/16 (Agreement 01180080 00) and CNPq - Process 312494/2020-3. This work was also supported by the Coordination for the Improvement of Higher Education Personnel - Brazil (CAPES) - Funding Code 001.

Conflict of Interest: The authors declare no conflict of interest. The funders had no interference in the development of the study; in the collection, analysis or interpretation of the data; in the writing of the manuscript, or in the decision to publish the results.

Acknowledgments: The authors of this research would like to thank the Graduate Program and Geography of UFPR and UNIOESTE (Marechal Cândido Rondon campus), CAPES, CNPq for the financial support through doctoral scholarship of the first author and aid to research projects (CNPq- Process 312494/2020-3). To the Soil Fertility and Environmental Dynamics

Laboratory (LEDA) of UNIOESTE (Marechal Cândido Rondon campus) for the chemical analyses and phytolith extraction, respectively. To the Stable Isotopes Laboratory (CENA/USP) for the carbon isotope analysis.

References

1. ALEXANDRE, A.; MEUNIER, J. D.. Plant impact on the biogeochemical cycle of silicon and related weathering process. **Geochimica et Cosmochimica Acta**, vol. 61, p. 677–682, 1997.
2. BENVENUTO, M. L.; HONAINE, M. F.; OSTERRIETH, M. L.; MOREL, E. Differentiation of globular phytoliths in Arecaceae and other monocotyledons: morphological description for paleobotanical application. **Turkish Journal of Botany**, vol. 39, p. 341–353, 2015.
3. BIGARELLA, J. J.; MAZUCHOWSKI, J. Z. Visão Integrada da Problemática da Erosão. Simpósio Nacional de Controle da Erosão. **Anais**...Curitiba: 1985
4. BOND, G.; KROMER, B.; BEER, J.; MUSCHELER, R; EVANS, M N.; SHOWERS, W; HOFFMANN, S; LOTTI-BOND, R; HAJDAS, I; BONANI, G. Persistent Solar Influence on North Atlantic Climate During the Holocene. Science, vol. 294, no. 554. A Pervasive Millennial-Scale Cycle in North Atlantic Holocene and Glacial Climates. **Science**, v. 278, n. 5341, p. 1257–1266, 14 nov. 1997.
5. BOND, G.; SHOWERS, W.; CHESEBY, M.; LOTTI, R.; ALMASI, P.; DEMENOCAL, P.; PRIORE, P.; CULLEN, H.; HAJDAS, I; BONANI, G. Persistent Solar Influence on North Atlantic Climate During the Holocene. **Science**, v. 294, n. 5549, p. 2130–2136, 7 dez. 2001.
6. CALEGARI, M. R. **Distribuição da Cobertura Pedológica e o Relevo no Alto Vale do Ribeirão Água do São Francisco - Nova Esperança - PR**. Dissertação de Mestrado em GEografia. Universidade Federal de Santa Catarina, 2000.
7. CALEGARI, M. R. **Ocorrência e significado paleoambiental do Horizonte A húmico em Latossolos**. Piracicaba: Doutorado em Agronomia. Escola Superior de Agricultura Luiz de Queiros - USP. 2008.
8. CALEGARI, M.R.; MADELLA, M.; VIDAL-TORRADO, P.; PESSENDA, L.C.R.; MARQUES, F.A. Combining phytoliths and $\delta^{13}C$ matter in Holocene palaeoenvironmental studies of tropical soils. **Quaternary International**, v. 287, p. 56–62, 2013a.
9. CALEGARI, M. R.; MADELLA, M.; VIDAL-TORRADO, P.; OTERO, X. L.; MACIAS, F.; OSTERRIETH, M.. Opal phytolith extraction in oxisols. **Quaternary International**, v. 287, p. 56–62, 2013b.
10. CALEGARI, M. R.; VIDAL-TORRADO, P. Memórias bióticas de solos selecionados da XIII Reunião Brasileira de Classificação e Correlação de Solos: condições ambientais e pedogênese. In: SILVA, M. B. E et al. (Eds.). . **Guia de Campo da XIII Reunião Brasileira de Classificação e Correlação de Solos: RCC do Maranhão**. 1. ed. Brasília, DF: EMBRAPA, 2020. p. 546–565.
11. CAMPOS, A. C. DE; LABOURIAU, L. G. Corpos Silicosos de Gramineas dos Cerrados II. **Pesquisa Agropecuaria Brasileira.**, v. 4, p. 143–151, 1969.
12. CARNELLI, A. L.; MADELLA, M.; THEURILLAT, J. P. Biogenic silica production in selected alpine plant species and plant communities. **Annals of Botany**, v. 87,n. 4, p. 425–434, 2001.
13. CECCHET, F. A. **Conjunto de Fitólitos dos Estratos Inferiores da Floresta Ombrófila Densa: Subsídios Para Reconstrução Paleoambiental.** Marechal Cândido Rondon: Trabalho de Conclusão de Curso. Colegiado de Geografia, 2012.
14. CHEN, I.; LI, K.; TSANG, C. Silicified bulliform cells of Poaceae: morphological characteristics that distinguish subfamilies. **Botanical Studies**, vol. 61, n. 1. 2020.
15. CORDOVA, C. E.; SCOTT, L. The potential of Poaceae, Cyperaceae, and Restionaceae phytoliths to reflect past environmental conditions in South Africa. In: RUNGE, J. (Ed.).. **Palaeoecology of Africa**. 1. ed. London: CRC Press,. v. 30 p. 107–135. 2020.
16. COUTINHO, L. M. Fire in the Ecology of the Brazilian Cerrado. In: J.G., G. (Ed.). . **Fire in the Tropical Biota. Ecological Studies (Analysis and Synthesis)**. Springer, Berlin, Heidelberg, 1990. p. 82–105.
17. De OLIVEIRA, P. E.; BEHLING, H.; LEDRU, M--P.; BARBERI, M.; BUSH, M.; SALGADO-LABOURIAU, M. L.; GARCIA, M. J.; MEDEANIC, S.; BARTH, O. M.; BARROS, M. A.; SCHEEL-YBERT, R. Paleovegetação e Paleoclimas do Quaternário do Brasil. In: SOUZA, C. R. D. G.; SUGUIO, K.; LIVEIRA, ANTONIO MANOEL DOS SANTOS DE OLIVEIRA, P. E. (Eds.). **QUATERNÁRIO DO BRASIL**. 1. ed. Ribeirão Preto: Holos Editora, 2005. p. 52–74.

18. DIESTER-HAAS, L.; SCHRADE, H.J.; THIEDE, J. Sedimentological and paleoclimatological investigations of two pelagic ooze cores off Cape Barbas, North-West Africa. **Meteor Forsch-Ergebnisse.C**., vol. 16, p. 19–66, 1973. .
19. EMBRAPA. SERVIÇO NACIONAL DE LEVANTAMENTO E CONSERVAÇÃO DE SOLOS. Levantamento de Reconhecimento dos Solos do Estado do Paraná**.** Rio de Janeiro: **Boletim de Pesquisa 27 -** TomoI, 1984.
20. EMBRAPA. **Sistema Brasileiro de Classificação de Solos**. 5.ed., rev ed. Brasília, DF: EMBRAPA, 2018.
21. FARQUHAR, G.D.; EHLERINGER, J.R.; HUBICK, K.T. Carbon isotope discrimination and photosynthesis. **Annual Review of Plant Physiology and Plant Molecular Biology**, v. 40, p. 503-537, 1989.
22. FELIPE, P. L. de L.. **Coleção de referência de fitólitos de Eudicotiledoneae da Floresta Ombrófila Densa: Subsídios para estudos paleoambientais em regiões tropicais**. Trabalho de Conclusão de Curso - Colegiado de Geografia. Universidade Estadual do Oeste do Paraná, 2012.
23. FERNANDES, L. A.; COIMBRA, A. M. REVISÃO ESTRATIGRÁFICA DA PARTE ORIENTAL DA BACIA BAURU (NEOCRETACEO). **Revista Brasileira de Geociências**, v. 34, n. 4, p. 717–728, 2000.
24. FISHKIS, O.; INGWERSEN, J.; STRECK, T. Phytolith transport in sandy sediment: Experiments and modeling. **Geoderma**, v. 151, n. 3–4, p. 168–178, 2009.
25. GOLOVATI, D. **Mudanças paleoambientais ocorridas durante o Holoceno nos municípios de Campo Mourão e Cianorte-PR**. Dissertação de Mestrado em Geografia. Universidade Estadual de Maringá, 2015.
26. GANOPOLSKI, Andrey; RAHMSTORF, Stefan. Rapid changes of glacial climate simulated in a coupled climate model. **Nature**, vol. 409, n. 6817, p. 153–158, 2001.
27. GOULART, A. Á. **Taxas de Denudação e Ferramentas Morfométricas Aplicadas na Análise da Evolução de longo Termo do Relevo do Sul da Bacia Sedimentar Bauru**. Tese de Doutorado em Geografia.. Universidade Federal do Paraná, 124p. 2020.
28. GOULART, A. Á.; SANTOS, L. J. C. Evolução Temporal e Espacial das Paleovoçorocas Presentes no Município de Loanda/PR. **Revista Geo**, v. 5, n. 21, p. 81–86, 2014.
29. GOUVEIA, S. E M.; PESSENDA, L. C R.; BOULET, R.; ARAVENA, R.; SCHEEL-YBERT, R. Isótopos do carbono dos carvões e da matéria orgânica do solo em estudos de mudança de vegetação e clima no quaternário e da taxa de formação de solos do estado de São Paulo. **Anais da Academia Brasileira de Ciencias**, v. 71, n. 4, p. 968–980, 1999.
30. GOUVEIA, S.E.M; PESSENDA, L.C.R; ARAVENA, R; BOULET, R; SCHEEL-YBERT, R; BENDASSOLI, J.A; RIBEIRO, A.S; FREITAS, H.A. Carbon isotopes in charcoal and soils in studies of paleovegetation na climate changes during the late Pleistocene and the Holecene in the southeast and centerwest regions of Brazil. **Global and Planetary Change**, v. 33, n. 1/2, p. 95–106, 2002.
31. GRIMM, E.C. CONISS: A Fortran 77 program for stratigraphically constrained cluster analisys by the method of the incremental sum of squares. **Pergamon Journals**, vol. 13, p. 13–35, 1987. .
32. GUERREIRO, R. L.; STEVAUX, J. C; PAROLIN, M.; ASSINE, M. L. Late Pleistocene and Holocene paleoenvironments in ponds and alluvial sediments of Upper Paraná River, Brazil. **Revista Brasileira de Paleontologia**, vol. 16, no. 1, p. 39–46, 30. 2013.
33. HORN, S. P.; UNDERWOOD, C. A. Methods for the Study of Soil Charcoal as an Indicator of Fire and Forest History in the Appalachian Region, U.S.A. (T. A. Waldrop, Ed.)Proceedings, Wildland Fire in the Appalachians: Discussions among Managers and Scientists. **Anais**...Asheville, NC: U.S.: Department of Agriculture Forest Service, Southern Research Station., 2014.
34. HUISMAN, S. N.; RACZKA, M. F.; MCMICHAEL, C. N.H. Palm phytoliths of mid-elevation Andean forests. **Frontiers in Ecology and Evolution,** vol. 6, 2018.
35. ICPT - International Committee for Phytolith Taxonomy; NEUMANN, K.; STRÖMBERG, C. A E; BALL, T.; ALBERT, R. M.; VRYDAGHS, L.; CUMMINGS, L, S.. International Code for Phytolith Nomenclature (ICPN) 2.0. **Annals of Botany**, vol. 124, no. 2, p. 189–199, 24. 2019.
36. ITCG. INSTITUTO DE TERRAS, C. E G. DO E. DO P. **Mapa Fitogeográfico**. Disponível em: <http://www.iat.pr.gov.br/modules/faq/category>. Acesso em: 29 set. 2021.
37. IUSS WORKING GROUP WRB. **Base referencial mundial del recurso suelo 2014, Actualización 2015. Sistema internacional de clasificación de suelos para la nomenclatura de suelos y la creación de leyendas de mapas de suelos**. ROMA: FAO, 2015.

38. JANZEN, H. H. The Soil Remembers. **Soil Science Society of America Journal**, v. 80, n. 6, p. 1429–1432, 2016.
39. JUSTUS, J. Erosão acelerada em solos arenosos: tipos e estágios de evolução, identificados sobre imagens de radar em escala 1:250.000. In. Visão integrada da problemática da erosão. **Anais Simpósio Nacional de Controle de Erosão**, 1985.
40. KAMMER, A. P. **Reconstituição paleoambiental da vegetação da Estação Ecológica de Assis-SP – A trajetória evolutiva do Cerrado no Holoceno**. Trabalho de Conclusão de Curso - Departamento de Geografia. Universidade Estadual do Oeste do Paraná- Unioeste, 58p. 2018.
41. KÄMPF, N.; CURI, N. Formação e evolução do solo (pedogênese). In: KER, J. C. et al. (Eds.). **Pedologia: Fundamentos**. 1. ed. Viçosa/MG: Sociedade Brasileira de Ciência do Solo, 2012. p. 207–302.
42. LANA, M. do C.; FRANDOLOSO, J. F.; FEY, R.; RICHART, A.; FONTANIVA, S.. **Análise química de solo e de tecido vegetal: metodologias analíticas**. 2nd ed. Cascavel, PR: EDUNIOESTE, 2016.
43. LI, Z.; DE TOMBEUR, F.; LINDEN, C. V.; CORNELIS, J.-T.; DELVAUX, B. Soil microaggregates store phytoliths in a sandy loam. **Geoderma**, vol. 360, p. 114037, 2020.
44. LIMA, E S.; FELFILI, J. M.; MARIMON, B. S.; CARIOT, A.. Diversidade, estrutura e distribuição espacial de palmeiras em um cerrado sensu stricto no Brasil Central - DF. **Revista Brasileira de Botanica**, vol. 26, no. 3, p. 361–370, 2003.
45. LISTO, D. G.D.; BALDER, R. F. T. M.; CORRÊA, A. C. C. B.; RAMOS, D. A. M. C.; CALEGARI, M. R.. Weathering pits as a geochronometer of environmental changes in the State of Pernambuco, Northeastern Brazil. **Quaternary International**, 2022.
46. MACEDO, R. S. **Pedogênese e indicadores pedoarqueológicos em Terra Preta de Índio no município de Iranduba - AM**. Tese de Doutorado em Ciências. Escola Superior de Agricultura "Luiz de Queiroz"/USP, 2013.
47. MADELLA, M.; POWERS-JONES, A.; JONES, M. K. A Simple Method of Extraction of Opal Phytoliths from Sediments Using a Non-Toxic Heavy Liquid. **Journal of Archaeological Science**, v. 25, p. 801–803, 1998.
48. MADELLA, M.; LANCELOTTI, C.; OSTERRIETH, M. L. Comprehensive perspectives on phytolith studies in Quaternary Research. **Quaternary International**, vol. 287, p. 1–2, 2013.
49. MEHRA, O.P.; JACKSON, M.L. Iron Oxide Removal from Soils and Clays by a **Dithionite**-Citrate System Buffered with Sodium Bicarbonate. **Clays and Clay Minerals**, vol. 7, no. 1, p. 317–327, 1960.
50. MOZER, J. H. C**oleção de Referência de Fitólitos e Reconstituição Paleoambiental da Floresta Ombrófila Densa Altomontana no Parque Estadual Carlos Botelho - SP**.Dissertação de Mestrado em Geografia. Universidade Estadual do Oeste do Paraná- Campus Marechal Cândido Rondon, 205p. 2021.
51. NAKASHIMA, P. **Sistemas pedológicos da região noroeste do Estado do Paraná: distribuição e subsídios para o controle da erosão**. Tese de Doutorado em Geografia. Universidade de São Paulo, 1999.
52. NITSCHE, P. R.; CARAMORI, P. H.; RICCE, W. da S.; PINTO, L. F. D. **Atlas climático do estado do Paranpa**. Londrina, PR: IAPAR, 2019.
53. NEUMANN, K.; FAHMY, A.; LESPEZ, L.; BALLOUCHE, A.; HUYSECOM, E.. The Early Holocene palaeoenvironment of Ounjougou (Mali): Phytoliths in a multiproxy context. **Palaeogeography, Palaeoclimatology, Palaeoecology**, vol. 276, no. 1–4, p. 87–106, 2009.
54. OLIVEIRA, J. G.; SANTOS, L. J. C.; CALEGARI, M. R. Relação Solo-Relevo em Sistema Pedológico Argissolo-Neossolo Quartzarênico na Região Noroeste do Estado do Paraná: Caso de Amaporã. **Revista Brasileira de Geomorfologia**, v. 21, n. 3, 1 jul. 2020.
55. OLIVEIRA, M.. **A morfometria das enigmáticas feições erosivas no relevo do Noroeste do Paraná.** Dissertação de Mestrado em Geografia. Universidade Federal do Paraná, 2021.
56. PARR, J. F. Effect of fire on phytolith coloration. **Geoarchaeology**, vol. 21, no. 2, p. 171–185, Feb. 2006.
57. PESSENDA, L. C.R.; ARAVENA, R.; MELFI, A. J.; TELLES, E. C.C.; BOULET, R.; VALENCIA, E. P.E.; TOMAZELLO, M. The use of carbon isotopes (^{13}C,^{14}C) in soil to evaluate vegetation changes during the holocene in Central Brazil. **Radiocarbon**, vol. 38, no. 2, p. 191–201, 1996a
58. PESSENDA, L.C.R.; LISI, C.S.; GOUVEIA, S. E. M. **O Laboratório C-14 do CENA e estudos de reconstrução paleoambiental (vegetação e clima) no Brasil**. 1. ed. Piracicaba: CENA/USP, 1998.

59. PESSENDA, L. C.R.; GOUVEIA, S. E.M.; ARAVENA, RAMON; GOMES, B. M.; BOULET, RENE; RIBEIRO, A. S.. ^{14}C dating and stable carbon isotopes of soil organic matter in forest-savanna boundary areas in the southern Brazilian Amazon region. **Radiocarbon**, v. 40, n. 2, p. 1013–1022, 1998b.
60. PESSENDA, L. C.R.; GOUVEIA, S. E.M.; FREITAS, H. A.; RIBEIRO, A. S.; ARAVENA, R.; BENDASSOLLI, J. A.; LEDRU,M-P.; SIEFEDDINE, A F.; SCHEEL-YBERT, R. Isótopos do Carbono e suas Aplicações em estudos paleoambientais. In: GOUVEIA, C. R. D. S. et al. (Eds.). **Quaternário do Brasil**. 1. ed. Ribeirão Preto. p. 75–92. 2005
61. PIPERNO, D. **Phytoliths : a comprehensive guide for archaeologists and paleoecologists**. AltaMira Press, 238p. 2006.
62. PIPERNO, D. R. Phytolith taphonomy and distributions in archeological sediments from Panama. **Journal of Archaeological Science**, v. 12, n. 4, p. 247–267, 1985.
63. RAITZ, E. **Coleção de referência de silicofitólitos da flora do Sudoeste do Paraná: subsídios para estudos paleoambientais**. 2012. Universidade Estadual do Oeste do Paraná- Campus Francisco Beltrão, 2012. Available at: http://tede.unioeste.br/handle/tede/1211.
64. RAMÍREZ, A. I. A.; RASBOLD, G. G.; PAROLIN, M.; STEVAUX, J. C. Phytoliths and seeds in fluvial island paleoenviroment reconstruction (interaction with pollen analysis). **Journal of South American Earth Sciences,** vol. 89, p. 30–38, Jan. 2019.
65. 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**, vol. 99, 1 Apr. 2020
66. RETALLACK, G. J. **Soils of the Past: An Introduction to paleopedology**. 2ª Ed. ed. [s.l.] Blackwell Science, 2001.
67. RUNGE, F. The opal phytolith inventory of soils in central Africa - Quantities, shapes, classification, and spectra. **Review of Palaeobotany and Palynology**, v. 107, n. 1–2, p. 23–53, 1999.
68. SANTOS, L. J. C.; OKA-FIORI, C.; NALDY, E. C.; FIORI, A. P. SILVEIRA, C. T DA; SILVA, J. M. F.; ROSS, J. L. S. Mapeamento Geomorfológico do Estado do Paraná. **Revista Brasileira de Geomorfologia**, v. 7, n. 2, p. 3–12, 2006.
69. SANTOS, J. C. A. **Paleogeografia e paleoambientes do Baixo Curso do rio Ivaí – Pr. 2013**. Dissertação De Mestrado em Geografia. Universidade Estadual de Maringá, 83p.2013.
70. SANTOS, R. D.; SANTOS, H. G.; KER, J. C.; ANJOS, L. H. C.; SHIMIZU, S. H. **Manual de descrição e coleta de solo no campo**. 7a (Revisa. Viçosa: SBCS, 2015.
71. SCHEEL-YBERT, R.; GOUVEIA, S. E. M.; PESSENDA, L. C. R.; ARAVENA, R.; COUTINHO, L. M. BOULET, R. Holocene palaeoenvironmental evolution in the São Paulo State (Brazil) based on anthracology and soil δ13C analysis. **The Holocene**, v. 13, n. 1, p. 73–81, 2003.
72. SILVA NETO, E. C.; CALEGARI, M. R.; PEREIRA, M. G.; MARANHÃO, D. D. C.; SCHIAVO, J. A.; FONTANA, A.; FERNANDES, J. C. F, Phytoliths as indicators of pedogenesis and paleoenvironmental changes in Spodosols of the state of Rio de Janeiro, Brazil. **Science of The Total Environment**, v. 636, p. 1070–1080, set. 2018.
73. SOUZA, E.; CALEGARI, M. R.; VIDAL TORRADO, P.; MADELLA, M.; MACEDO, R. S. Análise Fitolitica Aplicada na Reconstituição Paleoambiental na ESEC Caetetus – Gália (SP). **Perspectiva Geográfica**, v. 14, n. 20, p. 96–106, 2019.
74. STEVAUX, J. The upper Paraná river (Brazil): Geomorphology, sedimentology and paleoclimatology. **Quaternary International**, v. 21, p. 143–161, jan. 1994.
75. STEVAUX, J. C.; SOUZA FILHO, E. E.; JABUR, I. História Quaternária do Rio Paraná em sue alto curso. In: VAZZOLER, A. E. A.; AOSTINHO, A. A.; HANH, N. S. (Eds.). **A Planície de inundação do alto Rio Paraná**. Maringá: UEM,. p. 47–72. 1997.
76. STEVAUX, J. C. Climatic events during the Late Pleistocene and Holocene in the Upper Parana River: Correlation with NE Argentina and South-Central Brazil. **Quaternary International**, vol. 72, no. 1, p. 73–85,. 2000
77. STRÖMBERG, C. A. E.; DUNN, R. E.; CRIFÒ, C.; HARRIS, E. B. Phytoliths in Paleoecology: Analytical Considerations, Current Use, and Future Directions. In: CROFT, D. A.; SU, D. F.; SIMPSON, S. W. (Eds.).

Methods in Paleoecology: Reconstructing Cenozoic Terrestrial Environments and Ecological Communities. Springer, 2018. p. 235–287.

78. STEVAUX, J. C. Climatic events during the Late Pleistocene and Holocene in the Upper Parana River: Correlation with NE Argentina and South-Central Brazil. **Quaternary International**, vol. 72, no. 1, p. 73–85, Oct. 2000
79. STUIVER, M.; POLACH, H. Discussion: Reporting of ^{14}C Data. **Radiocarbon**, vol. 19, p. 355–363, 1997.
80. TEIXEIRA, P. C.; DONAGEMMA, G. K.; FONTANA, A.; TEIXEIRA, W, G.. **Manual de métodos de análise de solo**. 3. ed. rev. Brasília, DF:, 2017.
81. TWISS, P. C. Predicted world distribution of C_3 and C_4 grass phytoliths.In. Rapp, G.Mulholland, S C .**Phytolith Systematics: Emerging Issues.,** 1992. p. 113–128.
82. TWISS, P. C.; DORT JR., W.; SORENSON, C. J. Grass-opal phytoliths as climatic indicators of the Great Plains Pleistocene. In: JOHNSON, W. C. (ed.). **Quaternary environments of Kansas,** vol 5. Guidebook Series, Kansas Geological Survey. 1st ed. Kansas: Geologic Survey, 1987. p. 179–188.
83. VITAL, A. R. T.; GUERRINI, I. A.; FRANKEN, W. K.; FONSECA, R. C. B. Produção de serapilheira e ciclagem de nutrientes de uma floresta estacional semidecidual em zona ripária. **Revista Árvore**, v. 28, n. 6, p. 793–800, dez. 2004.