Journal of South American Earth Sciences 172 (2026) 105949

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

Paleoenvironmental and paleoclimatic reconstruction of the Lagoa Grande das queimadas archaeological site, Piauí, Brazil

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ARTICLE INFO

Keywords:
Phytoliths
Microarchaeobotany
Human occupations landscape
Paleoecology
Northeast Brazil
Holocene

ABSTRACT

The area of this study is the Lagoa Grande das Queimadas archaeological site, located in the southwest of the state of Piauí, in the semi-arid region of Northeast Brazil, a region that is globally recognized for its archaeological and paleontological heritage. The use of biogenic silica (especially phytoliths) as proxies for paleoenvironmental reconstruction aimed to evaluate the paleoenvironment of ancient human occupations. The phytolith assemblages recovered from the sediment record of the Lagoa Grande das Queimadas archaeological site are predominantly composed of Poaceae morphotypes, mainlyBlocky, Bulliform flabellate, Acute bulbosus, and Elongate, with a reduced presence of woody dicotyledons (Spheroid ornate). Arecaceae phytoliths (Spheroid echinate) are also observed throughout the profile, increasing from the oldest to the most recent sample, along with fragments of sponge megascleres and microcharcoals. The results revealed that this region experienced climatic variations during the Greenlandian to Meghalayan, as demonstrated by the phytolith and aquatic bioindicator (sponge spicules and diatom frustules) records. The analyses indicate that between 12,908–12,478 and 4420–4233 cal yrs BP, the temperature and humidity increased progressively, followed by a transition from a more humid climate than at present to drier conditions starting from 4420–4233 cal yrs BP. The qualitative and quantitative results of the phytolith analyses, associated with other proxies studied at this site, contributed to constructing information about the archaeological site and its insertion into the landscape, in addition to understanding the mobility and subsistence models of past human groups during the Holocene in the interior regions of Northeast Brazil.

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https://doi.org/10.1016/j.jsames.2026.105949
Received 4 June 2025; Received in revised form 14 December 2025; Accepted 1 January 2026
Available online 7 January 2026

1. Introduction

Paleoenvironmental studies can provide support for the distinction and understanding of the impact of anthropogenic activities on natural climate variability along the Quaternary, especially during the Holocene. According to Cohen et al. (2013), the Holocene is marked by climatic variations that shaped the current characteristics of the global environmental context, and these variations can be inferred through geological, biological, and archaeological records.

Reconstruction of the environment of past human occupations is extremely important to archaeological research, for which phytoliths are extremely useful tools. Their abundance, durability, and diagnostic morphology are potential characteristics that have been broadly applied to paleoenvironmental and paleoecological reconstructions of the late Pleistocene to the Holocene (Greenlandian to Meghalayan Age) in various types of soils and sediments (Fredlund and Tieszen, 1997; Piperno and Becker, 1996; Alexandre et al., 1999; Coe et al., 2014, 2017, 2018; Paisani et al., 2016; Chueng et al., 2018, 2019; Dias et al., 2019; Seixas et al., 2019).

The state of Piauí, in northeast Brazil, is globally acknowledged for its archaeological and paleontological heritage, as the Serra da Capivara National Park with over a thousand archaeological sites, has been recognized by UNESCO (https://www.unesco.org/archives/multimedia/document-3544-por-2) as a World Heritage Site since 1991 (Pessis and Guidon, 2007; Kinoshita et al., 2014). The set of archaeological sites in the region includes more than 1200 sites, among which numerous paintings and carvings of the of the Northeast, Agreste, and Geometric Traditions have been recorded, associated with fires, lithic artifacts, ceramics, and animal and human bones dating to the late Pleistocene (~30,000–11,700 years BP) and Holocene. Certain sites corroborate the hypothesis of settlements prior to the Pleistocene-Holocene transition in the Americas (Boëda et al., 2014; Aimola et al., 2014).

With the chronology of human occupations in Piauí having been widely discussed, there is a consensus that the presence of human groups dates from the late Pleistocene (Guidon, 1994/1995; Martin, 1998; Parenti et al., 2003, 2021). The obtained dates, which are mostly from ceramic fragments, human bone remains, and charcoal structured in fires and in funerary context, indicate human occupations from the end of the Pleistocene to Greenlandian and Meghalayan. Human occupations in the Serra da Capivara mountains intensified between 13,000–8000 years BP, being recorded at 24 archaeological sites providing evidence of their territorial domain, which was previously concentrated in rock shelters (Lourdeau and Pagli, 2014; Lourdeau, 2019).

The Toca do Boqueirão da Pedra Furada site (BPF) and the Sítio do Meio site, which are located in the Serra da Capivara National Park are internationally recognized and have been studied in depth, due to their exceptional concentration of rock paintings, flaked lithic artifacts, and macro-remains of carbonized plants (Parenti, 2001; Chaves, 2000, 2002; Chaves and Reinhard, 2006; Boëda et al., 2013; Aimola et al., 2014; Mota and Scheel-Ybert, 2019, 2025). Parenti (2001) defined the lithic industries by chronostratigraphic phase: the Pedra Furada phase (ca. 50, 000–12,000 years BP), with a predominance of flakes, burins, cleavers, scrapers, hammers, and cores; and the Serra Talhada phase (ca. 10, 400–6150 years BP), with microflakes, hammers, planers, cleavers, burins, scrapers, choppers, cores, and retouch pieces. This last phase of human occupation also occurred at the Lagoa do Quari site (Parenti et al., 2003, 2021).

The Pleistocene-Holocene transition (13,000–8000 years BP), especially at the sites at the front of the *cuesta,* is marked by a lithic industry composed mostly of quartz and quartzite pebbles, followed by flint blocks or pebbles, chalcedony, and silicified sandstone (Lourdeau and Pagli, 2014; Lourdeau, 2019). At the Sítio Toca dos Coqueiros site (10, 640-235 years BP), four cleavers, fifteen flakes and two bifacial projectile points in hyaline quartz were found together with a human skeleton (Guidon et al., 1998), similarly to that recovered at the Lagoa Grande das Queimadas site. Projectile points occur occasionally and have been recorded by Guidon et al. (1998) at the Sítio Toca dos Coqueiros site, dated at ca. 10,000 years BP, and at the Lagoa Grande das Queimadas site, in the context of Holocene lithic industries. The sets of artifacts indicate typological variability, with dense operative chains (Parenti, 2001; Boëda et al., 2014, 2016; Lourdeau, 2019).

Although many rock shelters have been recorded in the Serra da Capivara, such as the Boqueirão da Pedra Furada site (Guidon and Pessis, 1993; Parenti, 2001; Guidon et al., 2002a,b; Parenti et al., 2003), there remains relatively little knowledge on humid areas (wetlands) filled with sediments from the late Pleistocene and Greenlandian with archaeological artifacts and megafauna fossils (Guérin et al., 1993; Parenti, 1996; Galindo et al., 1996; Guidon et al., 2009, 2018; Mützenberg et al., 2013).

The Serra das Confusões National Park, an adjacent area, contains many recognized archaeological sites, such as the Toca do Alto da Serra do Capim site (8000–3000 years BP) and the Toca do Enoque site (6220–3830 years BP) (Guidon and Luz, 2009; Faure et al., 2011), whereby the ages are related to funerary contexts.

The study area, Lagoa Grande das Queimadas (LGQ) (coordinates 9°12′40″ S 42°56′25"W), constitutes a record of human occupations dating from the Northgrippian/Meghalayan Ages (4420–4233 cal years BP), in an area adjacent to the archaeological area of the Serra da Capivara and Serra das Confusões National Parks.

Although there is a gap in the paleoecological and paleoenvironmental data from the study area, regional microarcheobotanical studies (i.e., pollen grains, phytoliths) in a geomorphologically similar area of wetlands in the northeastern semi-arid, such as the Serra da Capivara National Park, in Piauí, and Lagoa Uri de Cima or Pântano da Pingadeira, in Pernambuco, indicate climatic and paleoenvironmental variations from the end of the late Pleistocene (34,000 years BP) to the Meghalayian (4000 years BP) (Chaves, 2002; Galvão, 2019; Ramos, 2019; Moraes et al., 2020; Parenti et al., 2003, 2021; Freitas et al., 2022b).

Despite the archaeological significance of the region, in the municipality of Várzea Branca, where LGQ is located, there is little data on ancient human populations, their ways of life and technology; the paleoenvironment and regional paleoclimate for where these groups migrated to and/or temporarily settled during the late Pleistocene and Meghalayan, and the plant resources they consumed, managed, and possibly cultivated.

The main proxies used in this study are silica biomineralizations, especially phytoliths. Phytoliths are microscopic particles (between <60 and 100 μm) of biogenic opal, which are formed through the precipitation of amorphous silica from silicic acid solution [$Si(OH)_4$] between and inside the cells of living plants (Piperno, 1985). Due to the multiplicity and redundancy of phytolith production in plant organisms, it is difficult to assign taxonomic value to a single phytolith, so phytolith assemblages are used. However, it is possible to identify groups of typologies with taxonomic values in terms of vegetation type (Bremond et al., 2005a; Coe et al., 2014).

When analyzing a phytolith assemblage in soils/sediments, inferences can be made about the environment based on the calculation of phytolith indexes such as tree density (D/P), palm density (Pa/P), water stress (Bi%), climate (Ic%), and aridity (Iph%) (Coe et al., 2014, 2021), which contribute to making the proxy reliable for paleoenvironmental studies.

The analysis of phytoliths as plant micro-remains has become an increasingly popular tool in recent decades for archaeology, particularly in testing hypotheses related to plant domestication and the study of diet, especially in contexts where other plant remains (i.e., organic remains such as seeds, fruits, and pollen grains) are poorly preserved.

Several studies have been conducted with phytoliths extracted from sediments and archaeological artifacts, but the analysis of phytoliths recovered from archaeological soils is less common (Astudillo, 2018), especially in the study area. There are few studies on archaeological sites aimed at reconstructing paleoenvironmental conditions, especially in Brazil, with some examples being those of Caromano et al. (2013) at the Hatahara archaeological site in Central Amazonia; Watling et al. (2015, 2017) in geoglyphs in Acre; Watling (2016) and Watling et al. (2018) at the Teotonio site, upper Madeira River; Coe et al. (2017) at the Tarioba Sambaqui, Rio das Ostras, RJ; Machado et al. (2022) at the Casa de Pedra Sambaqui, SC; Chueng et al. (2018) at the Cabeças 4 Site, Serra Negra, MG; Ramos (2019) at the Lagoa Uri de Cima archaeological site in Pernambuco; and Galvão (2019) at Toca do Gongo III, Toca do Sítio do Meio, Toca da Janela da Barra do Antonião, and Toca do Gordo Garrincho, all in the Serra da Capivara National Park, Piauí.

This research is based on the hypothesis that LGQ sediments provide a record of climatic fluctuations during the Holocene, which correlate with human occupation patterns in northeastern Brazil. In this context,

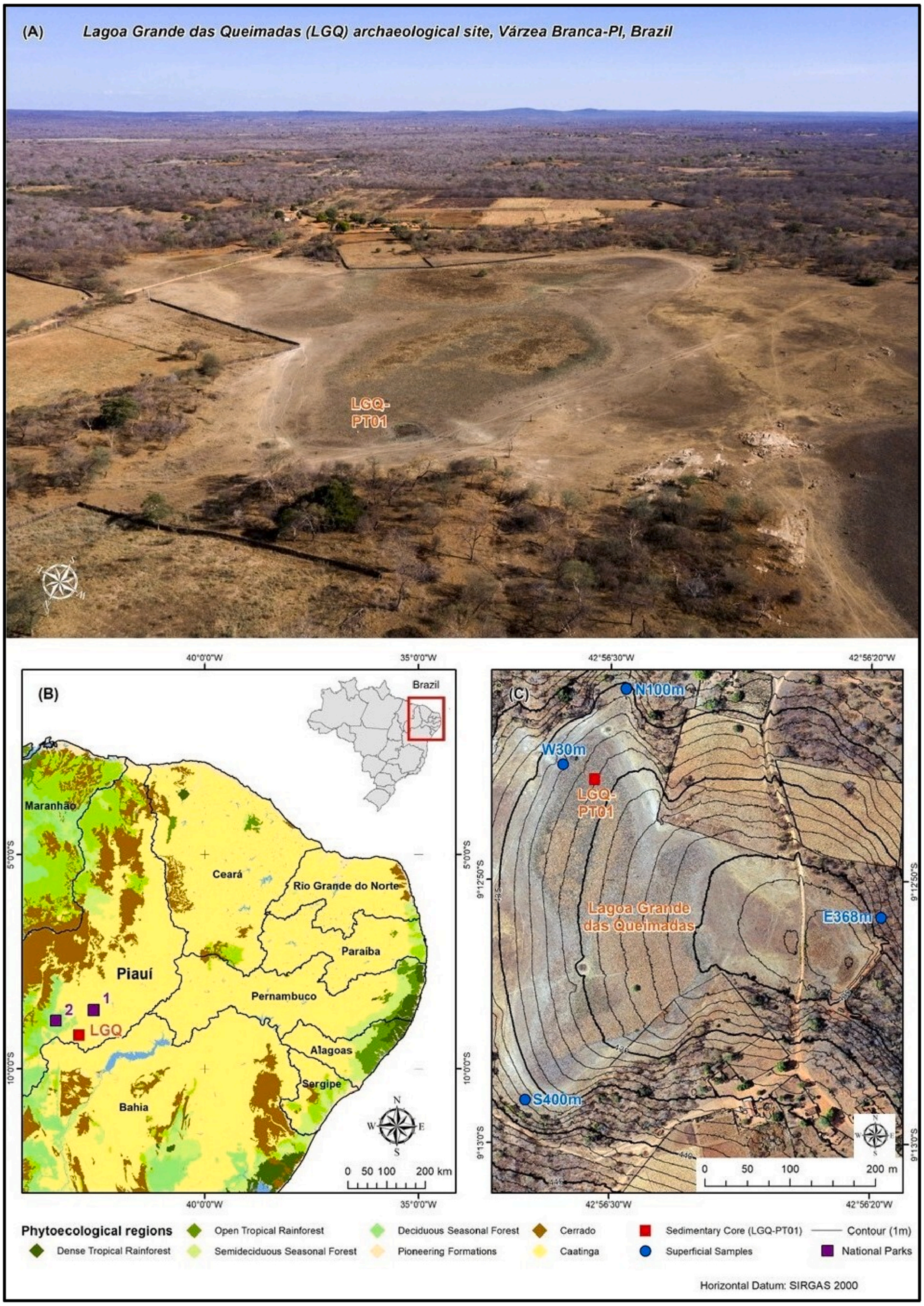

Fig. 1. Location maps of Lagoa Grande das Queimadas and sampling points. (A) Aerial view of the study area. (B) Map of phytoecological regions (modified by IBGE, 2021). The study area (red square) is located between (1) Serra da Capivara National Park and (2) Serra das Confusões National Park. (C) Satellite image of the study area and location of the LGQ-PT01 trench and surfaces sampled (Elaborated by Demetrio Mützemberg).

adopting a multiproxy approach can significantly contribute to the paleoenvironmental reconstruction of the region, enabling a better understanding of the environmental dynamics associated with past occupations.

The aim of this study is, therefore, to reconstruct the paleoenvironment and paleoclimate of ancient human occupations and establish a possible chronology for these changes during the Holocene' through analyses of biogenic silica and microcharcoal recovered from the archaeological record of Lagoa Grande das Queimadas. The phytolith data from Lagoa Grande das Queimadas will integrate the regional paleoclimatic and paleoenvironmental framework and shed light on wetland formation processes.

2. Study area

The state of Piauí has rich plant biodiversity due to its geographical location between the biomes of the Cerrado and the Caatinga, thus representing a large ecotone area. Remnants of a vegetational assemblage that occupied the area during the Pleistocene are still visible in this geographical area, particularly in relation to the distribution of dry and humid forests (Ab'Sáber, 1977). The regional climate is characterized as tropical semi-arid. The mean annual rainfall is defined in the Equatorial Continental Regime and is around 800 mm between December and March. The mean temperatures fluctuate between 34 and 20 °C (http://varzeabranca.pi.gov.br/; Instituto Brasileiro de Geografia e Estatística. IBGE, 1977).

The Lagoa Grande das Queimadas archaeological site (CNSA-IPHAN-PI-01847), where the geoarchaeological research is being conducted, is located in the São Raimundo Nonato microregion, in the municipality of Várzea Branca, in the southwest of the state of Piauí (Fig. 1). It is an open-air site situated between slopes, among temporary lagoons, settlements with fields, and cattle ranching areas (Guidon et al., 2007).

The municipality of Várzea Branca is situated between two biodiversity conservation areas, the Serra da Capivara National Park and the Serra das Confusões National Park. The Caatinga biome is characterized by a semi-arid climate (Fig. 1), with the regional vegetation consisting of low to medium-sized shrubby and tree-like Caatinga in shallow soils. As a result, hypoxerophilic caatinga characteristics prevail, this being small to medium-sized vegetation, adapted to shallow soils. The dominant species include *Mimosa hostilis*, *Mimosa sensitiva*, *Mimosa verrucosa*, *Senna sp.*, *Spondias tuberosa*, *Myracrodruon urundeuva*, *Anadenanthera colubrina*, and *Cnidoscolus quercifolius* around the lagoons (Emperaire, 1989; Lemos and Rodal, 2002). The region also has periods of transition to deciduous caatinga/cerrado (Aguiar and Gomes, 2004), as exemplified by *Bauhinia cheilantha*, which is a type of vegetation characteristic of the Piauí semi-arid (Ferraz et al., 1998).

Regional geology consists of two distinct domains: the crystalline rocks of the Precambrian basement and Cenozoic sediment cover. The basement rocks are represented by gneisses from the Sobradinho-Remanso Complex, schists, and various granites. The Cenozoic cover corresponds to unconsolidated sandy-clayey sediments and lateritic concretions belonging to the Detritus-Lateritic Deposits. The soils mostly originate from alteration of the gneisses, schist, and granite, and are shallow or thin, young, and stony in some areas, influenced by the underlying material. Among the regional soils, allic and dystrophic latosols of medium to clayey texture predominate. Also present are red-yellow podzolic soils, of medium to clayey texture, with stony and non-stony phases, as well as quartzose sands, which include essentially quartzose sandy soils that are deep, drained, devoid of primary minerals, and of low fertility (Aguiar and Gomes, 2004).

The humid, periodically flooded areas of the Brazilian Northeast semi-arid are classified as lagoons, water holes, or ponds, and are the product of the erosion of Precambrian metamorphic rocks. These basins have a semi-circular shape and are filled with fine, organic Quaternary sediments and some quartz pebbles. These lagoons receive an intermittent flow of water in times of drought, and a considerable volume of water in the wet season, serving as a water reservoir for the local population during drought periods (Parenti et al., 2003). The Lagoa Grande das Queimadas lagoon is a type R wetland, which are seasonal/intermittent saline/brackish/alkaline lakes and flats (Ramsar Secretariat, 2013) or seasonally inundated basins, according to Semeniuk and Semeniuk (2011) and Parenti et al. (2021).

3. Regional archaeological context

The area surrounding Lagoa Grande das Queimadas is one of the most important archaeological regions in the Americas, with over a thousand sites featuring rock paintings and engravings (Pessis and Guidon, 2007; Guidon et al., 2009), mostly on the consolidated sediments of the Parnaíba Sedimentary Basin and in the Serra da Capivara and Serra das Confusões National Parks (Fig. 1 and Table 1).

Detached blocks with rock paintings associated with the Northeast Tradition found in excavations, have been dated to about 10,500 years BP (Guidon and Arnaud, 1991). The antiquity of *Homo sapiens* in the Americas has also been discussed based on evidence of Pleistocene lithic industries in the Serra da Capivara, at the Boqueirão da Pedra Furada site, and at the Sítio do Meio site (Guidon and Delibrias, 1986; Parenti, 2001; Boëda et al., 2016; Lourdeau and Pagli, 2014; Lourdeau, 2019). The Holocene indigenous occupation is characterized by the presence of archaeological sites with flint lithic industries (Serra Talhada Phase) featuring a dominance of microliths, hammers, scrapers, planers, burins, and cores (Parenti, 2001). The oldest burial sites found in the Serra da Capivara date between 12,000 and 10,000 years BP (Lourdeau, 2019). Archaeological data indicate a change in material culture after the Middle Holocene, with the emergence of a new phase in the lithic industry (Agreste Phase) (Parenti, 2001) and of the Agreste Tradition of rock art (Pessis, 2003). There are many post-Middle Holocene archaeological sites containing vessels and ceramic fragments, sometimes associated with burial rituals inside these vessels (Cisneiros, 2006; Solari et al., 2018). The evidence so far points to a more recent occupation in the Serra das Confusões, with sites featuring rock art also being identified (Guidon and Luz, 2009) and human burials dated between 3750 ± 30 and 8590 ± 60 years BP (Solari et al., 2022).

Seasonally inundated basins or wetlands (i.e., Lagoa do Quari, Lagoa

Table 1
Some studies in archaeological sites in the Lagoa Grande das Queimadas region.

Archaeological region	Site	Period of occupation (yrs BP)	Study references
Parque Nacional da Serra da Capivara	Meio	29,000–6000	Guidon and Andreatta (1980, 1993); Aimola et al. (2014); Boëda et al. (2016)
	Toca da Tira-peia	~22,000	Lahaye et al. (2013)
	Boqueirão da Pedra Furada	19,500–6150	Aimola et al. (2014); Boëda et al. (2014)
	Toca do Garrincho	18,000–11,500	Peyre et al. (1998); Guidon et al. (2000); Santos et al. (2005)
	Toca dos Coqueiros	10,640-235	Guidon et al. (1998)
	Toca da Extrema II	4730–3100	Guidon et al. (2009)
	Toca do Gongo III	580–410	Solari et al. (2018a)
Serra das Confusões	Toca do Alto da Serra do Capim	8000–3000	Guidon et al. (2019); Solari et al. (2022)
	Toca do Enoque	5300–1880	Guidon and Luz (2009); Faure et al. (2011); Solari et al. (2020)

dos Porcos, Lagoa Uri de Cima, Lagoa da Pedra) contain numerous fossiliferous records of megafauna (cervids, giant sloths, toxodons) and flaked lithic artifacts dated from the Late Pleistocene (Guérin et al., 1993; Parenti, 1996; Galindo et al., 1996; Guidon et al., 2009, 2018; Mützenberg et al., 2013). Although there is still no emphatic direct evidence on the human interactions with Pleistocene megafauna, there is a unique record at the Sítio Toca da Janela da Barra do Antonião site (Bélo, 2012) indicating cut and fracture marks on *Paleolama*, *Hippidion*, *Eremotherium*, *Catonyx*, *Toxodon*, *Macrauchenia* and *Xenorhinotherium* bones. The paleontological and archaeological data from the Lagoa dos Porcos site record megafauna fossils dated from ca. 17,000 years BP and a discrete lithic industry containing six flint flakes, three granite artifacts, and a polished ax (Guidon et al., 2018). A similar situation occurred during the archaeological prospections and excavations at the Lagoa da Várzea Branca site, which has a record of Quaternary megafauna fossils and flaked lithic artifacts on the surface (scrapers, flakes, flat-convex). At the Lagoa Grande das Queimadas site, a few flaked lithic artifacts (scrapers, flakes, flat-convex, and projectile point) were recorded at a stratigraphic level of 80 cm and on surface level, without fossil records. The archaeological record indicates a chronology from the Meghalayan for local human occupations, in correlation with the materials recovered from sites 30 km away in the Serra da Capivara National Park. In the six stratigraphic layers investigated at the Lagoa Uri de Cima site (last 3000 years BP), various ceramic fragments, over 3000 flaked lithic artifacts, and megafauna bones from mammals were recovered, indicating zones of passage and probable temporary camps around these bodies of water (Faure and Guérin, 2013; Lourdeau & Pagli, 2013; Mützenberg et al., 2013).

Human artifacts have also been found in the lagoons south of the Parnaíba Sedimentary Basin, located mainly on crystalline rocks, such as Lagoa Grande das Queimadas. Paleoecological and paleoclimatic data from Lagoa do Quari, in the Serra da Capivara National Park area, recorded megafauna bones (e.g., *Eremotherium sp.*) at the Pleistocene-Holocene boundary, followed by a rich quartz and chert lithic industry, between 9944–9557 and 6308–6177 cal years BP. Pollen data indicate climatic fluctuations throughout the Holocene, with an open landscape and seasonal wet phases. (Chaves et al., 2002, 2008; Moraes et al., 2020; Parenti et al., 2003, 2021). Guidon et al. (2018) analyzed a depositional sequence from Lagoa dos Porcos, where bones of the extinct notoungulate mammal (*Piauhytherium capivarae*) associated with lithic artifacts were recovered and dated to the last 17,000 cal years BP (Guérin and Faure, 2014). The calcrete deposits from Lagoa Uri de Cima, Salgueiro (PE), corroborate the coexistence of human groups and paleofauna, with records of megafauna bones dated to 18,000 years BP (Macedo et al., 2017).

The study region hosts several archaeological and paleontological sites and was selected as having potential for archaeological, paleoclimatic, and paleoenvironmental research due to its preservation characteristics, such as sediment matrix granulation and low oxygen levels. The Lagoa Grande das Queimadas archaeological site (LGQ) is characterized as an open-air, pre-colonial site containing flaked lithic artifacts (Guidon et al., 2007), being part of a regional archaeological context of Holocene lithic industries documenting ancient human occupations at the site. Lagoa da Várzea Branca is adjacent to LGQ and houses a fossiliferous deposit of megafauna (i.e., maxilla of *Eremotherium sp.*), known to the local population due to wells dug in the area to obtain water during the dry season.

4. Materials and methods

4.1. Sampling

A total of 42 sediment samples from the archaeological record of Lagoa Grande das Queimadas were analyzed, including 38 subsurface samples and four surface samples (Fig. 1). The samples were collected from the LGQ-PT01 trench (Fig. 1) at 5 cm intervals between the depths of 205 cm (base of the profile) and 30 cm, and at 10 cm intervals from a depth of 30 cm to the top of the profile (Fig. 2; Table 2). The sampling followed the method described by Freitas et al. (2022a) applied to microarchaeobotanical studies. The LGQ-PT01 trench consists of olive sandy clays and carbonate pellets from the base (205 cm) to 135 cm, well-compacted gray clay between 135 and 100 cm, very dark gray clay with varying organic matter content between 100 and 20 cm, and dark gray organic soil at the top (Fig. 2). Its textural and color characteristics were described according to the Munsell Soil Color Chart. (2009) (Table 2).

The flaked lithic artifacts recovered from the surface and subsurface are primarily composed of quartz and quartzite, with smaller amounts of siltstone, flint, and chalcedony (Fig. 3). At a depth of 82 cm in LGQ-PT01, a milky quartzite scraper was recovered. The scraper has a soft percussion retouch (Fig. 3) as observed in Bodu et al. (1996).

4.2. Radiocarbon dating and age-depth modeling

Based on the initial microarchaeobotanical results, three 1 cm^3 samples from the sediment core LGQ-PT01 were dated using Accelerator Mass Spectrometry (AMS) radiocarbon dating collected at the depths of 80–85 cm, 145–150 cm, and 195–200 cm (Fig. 2). The samples were collected at depths of 80–85 cm, 145–150 cm, and 195–200 cm (Fig. 2), these being the deepest sample (195–200 cm), the sample that marks the appearance of aquatic indicators (145–150 cm), and the sample from the 80–85 cm stratigraphic level that coincides with the occurrence of a lithic artifact (scraper) (Fig. 3). Dating was carried out at the Swiss Federal Institute of Technology (ETH) and at the Laboratório de Radiocarbono da Universidade Federal Fluminense (Radiocarbon Laboratory of the Federal University of Fluminense) (LAC-UFF), Brazil. The ages were calibrated using the SHCal20 curve (Hogg et al., 2020), which is used in archaeological contexts in the Southern Hemisphere. The age model was constructed using OxCal. v4.4 (Bronk Ramsey, 2021). The calibrated ages and age–depth model were elaborated using LibreOffice Calc version 7.5.9.2.

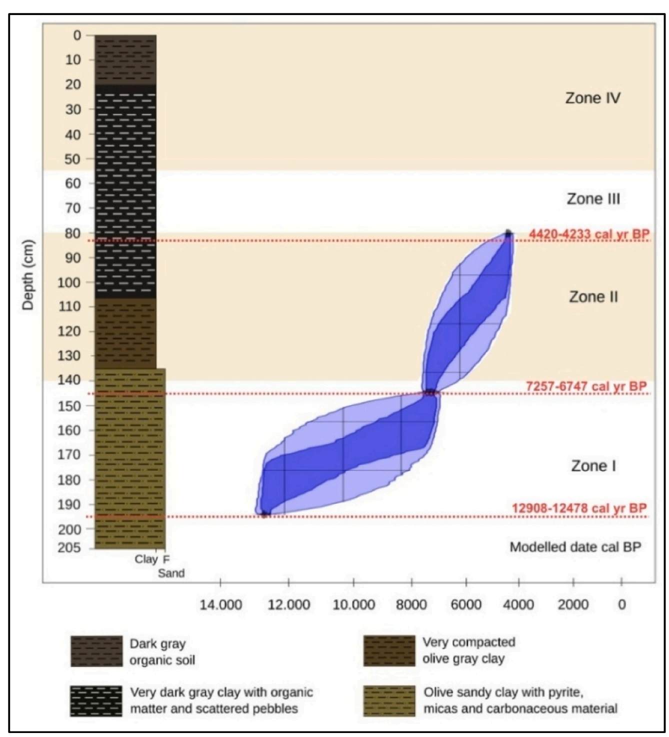

Fig. 2. Stratigraphic description and age–depth model from the LGQ-PT01 trench.

Table 2
Textural description of the LGQ-PT01 trench.

Depth (cm)	Description	Munsell color
0–20	Dark gray organic soil	5Y 4/1
20–100	Very dark gray clay with organic matter and scattered pebbles	5Y 3/1
100–135	Very compacted olive gray clay	5Y 4/2
135–205	Olive sandy clay with pyrite, micas and carbonaceous material (carbonate)	5Y 5/3

4.3. Biogenic silica and microcharcoal analysis

The extraction of biogenic silica was carried out at the Geosciences Laboratory (LABGEO) of the Department of Geography at the Faculdade de Formação de Professores da Universidade do Estado do Rio de Janeiro (UERJ-FFP). The initial preparation involved drying and passing 10 g of each sample through a 2-mm-mesh sieve, removing carbonates with hydrochloric acid, iron oxides with sodium citrate and dithionite, organic matter with nitric acid, bleaching with sodium hypochlorite, and the clay fraction through decantation with EDTA and sodium hexametaphosphate solution. A 25 μl aliquot of the precipitated material was taken and prepared on microscopy slides using Entellan® (permanent slides), where the content was determined, the main phytolith morphotypes described, and the particle condition assessed.

Microscopic analysis was conducted at the Laboratory of Environmental Dynamics (LABDIN) at UERJ-FFP. Identification and counting of at least 200 identifiable phytoliths were performed using an optical microscope, at 500 to 630x magnification to: a) estimate the relative frequency of different morphotypes according to the International Code for Phytolith Nomenclature (ICPN 2.0, Neumann et al., 2019); b) analyze the degree of alteration of phytoliths (identifiable/non-identifiable); and c) calculate the total phytolith stock present in 3 transects of the microscope slide for each sample (Coe et al., 2014, 2021).

From this count, tree cover density (D/P), palm density (Pa/P), and water stress (Bi%) indexes were calculated. The D/P index (Alexandre et al., 1997; Barboni et al., 2007; Bremond et al., 2005a) is calculated using the formula Spheroid ornate/(short-cells + Acute bulbosus + Bulliform.flabellate + Blocky). This index indicates the density of tree cover, which, in turn, enables us to infer whether the environment is more or less humid, since trees need require more moisture than grasses to survive. The Pa/P index (Coe, 2009; Coe et al., 2014) is the ratio between the percentage of phytoliths from Arecaceae (Spheroid echinate) divided by the sum of phytoliths produced only by Poaceae (short-cells + Acute bulbosus + Bulliform.flabellate + Blocky), and indicates the density of palm tree cover, which is generally associated with more humid environments. The Bi % index (Bremond et al., 2005b) is calculated by dividing the phytoliths produced by bulliform cells (Bulliform.flabellate + Blocky) by all the phytoliths produced only by Poaceae (short-cells + Acute bulbosus +Bulliform flabellate + Blocky). This index indicates the water stress suffered by vegetation, whether due to arid climate or fluctuations in the water table.

Other biogenic silica (fragments of sponge spicules and diatom frustules) were also observed on the same slides, but they have not yet been, only their presence/absence being recorded. The same procedure was adopted to record the presence of microcharcoal. These materials will be examined by specialists later as they may provide relevant environmental data.

4.4. Total organic carbon content (TOC) and grain size

The grain size and TOC analyses were carried out on 38 samples at 10 cm intervals for the first three samples from the top of the trench, and at 5 cm intervals to a depth of 200 cm. The TOC was quantified according to the *Manual de Métodos de Análise de Solo* (Manual of Soil Analysis Methods) (Teixeira et al., 2017), whereby the sediment sample is placed in an acidic environment and the TOC is determined through oxidation of the potassium dichromate, and the remaining dichromate is titrated with ferrous ion. The analyses were carried out using 270 mesh sieves for the coarse (sand) fraction, and the pipette method for the fine fractions (Teixeira et al., 2017). These analyses were performed at the Soil and Sediment Laboratory of the Federal University of Piauí by Marques et al. (2024). The morphological description and textural classification followed the *Manual de descrição e coleta de solo no campo* (Manual for Collection and Description of Soil in the Field) (Santos et al., 2005).

5. Results and discussion

5.1. Radiocarbon dating

Table 3 shows the results of the three AMS datings. The chronology of the sediment core indicates that the deposits accumulated during the Early and Late Holocene (Fig. 2). The base of the core (195–200 cm) was dated to 10,969–10,529 cal yrs BP; the 145–150 cm level to 5307–4787 cal yrs BP, and the 80–85 cm level to 4419–4234 cal yrs BP.

Fig. 3. Some lithic artifacts recovered from the Lagoa Grande das Queimadas archaeological site: A. Projectile point in clear quartz; B. Flake in milky quartz; C. Fragmented hammer in silicified sandstone; D. Scraper in silicified sandstone; and E. Lithic artifact (burin/scraper), made of quartzite with soft percussion retouching, recovered at a depth of 82 cm in LGQ-PT01. Scale: 5 cm.

Table 3
Radiocarbon determinations in conventional and calibrated ages.

Lab. code	Depth (cm)	Conventional ^{14}C ages (yrs BP)	Calibrated ^{14}C ages (cal yrs BP)
ETH-112621	80–85 cm	3934 ± 24 BP	4420–4233 (mean age 4330)
LACUFF-204141	145–150 cm	6150 ± 101 BP	7257–6747 (mean age 7010)
LACUFF-204142	195–200 cm	10,757 ± 107 BP	12,908–12,478 (mean age 12,693)

5.2. Phytoliths

The entire LGQ-PT01 sediment profile contains a large amount of phytoliths with high preservation rates and relative stability in the stock (between 260 and 204 phytoliths in 3 transects), without following the normal pattern of decreasing stock with increasing depth (Fig. 4 and Table 4).

Among the classified phytoliths, those produced by Poaceae are predominant, particularly Blocky, Bulliform flabellate, Acute bulbosus, and Elongate, with a reduced presence of woody dicotyledons (Spheroid ornate). Phytoliths from Arecaceae (Spheroid echinate) are also observed throughout the profile, increasing from the oldest sample to the most recent, although these were not observed in any of the modern samples. The presence of this morphotype in LGQ-PT01 may be related to the influence of ancient human occupations in the region, which may have managed these plants nearby for various uses (Figs. 4 and 5).

The presence of brown phytoliths was also observed throughout the profile (Fig. 5). The brown color suggests that they had undergone a combustion process, which could indicate natural paleo-fires and/or anthropogenic influence (Parr, 2006).

The tree cover density index (D/P) was consistently low (Fig. 4; Table 3), between 0.04 and 0.28, indicating open vegetation with a predominance of grasses, with variations that may reflect wet and dry periods. Similar values were found in previous studies in Rio Grande do Norte and other regions of Ceará (Dias et al., 2019; Aguiar, 2022). In the modern assemblages around the lagoon, the index ranged from 0 to 0.14, similar to the values at the top of the sediment profile.

The palm density index (Pa/P) of LGQ-PT01 was low (Fig. 4; Table 3), between 0.03 and 0.28, indicating open vegetation dominated by grasses and similar to the present, where shrubby-arboreal elements (or arboreal caatinga) such as Euphorbiaceae, Bignoniaceae, and Fabaceae, among others, occur, with few shrubby-herbaceous elements (Bromeliaceae and Cactaceae, among others). Similar results were found by Aguiar (2022) in the Serra de Uruburetama, Ceará. A slight trend of increasing Pa/P from the base to the top of the profile was observed, with variations in tree cover over time. It was not possible to calculate this index for the modern assemblage samples.

The Bi% index (water stress) of LGQ-PT01 shows moderate to high values (Fig. 4; Table 3), ranging between 68 % and 91 %, indicating an environment with high water stress, which is consistent with the semi-arid region and lagoon edges, which are heavily affected by variations in the groundwater table. Similar values were found by Aguiar (2022), in soil profiles on a dry slope in the Serra de Uruburetama, Ceará. Once again, it was not possible to calculate this index for the modern assemblage samples.

5.3. Sponge spicules and diatom frustules

The highest stocks of fragments of sponge spicules and diatom frustules were found between 145 cm and the top of the profile, indicating a flooding phase or lagoon stability. Below 150 cm, the stocks were absent (Figs. 4 and 5; Table 3). In the modern samples, there was a significant amount of sponge spicule fragments, surpassing the phytoliths, and significantly higher than in the surface samples of the sediment profile. However, diatom frustules were not found in the modern samples, as was the case in the surface samples of LGQ-PT01.

5.4. Microcharcoal

In the LGQ-PT01 sediment profile, microcharcoals were found in about 90 % of the samples, generally increasing from the base to the top, although the highest concentration was found near the base (180–185 cm) (Fig. 4; Table 3), indicating the absence of a lagoon. The presence of these microcharcoals suggests paleo-fires associated with a drier climate. Similar fragments were observed in the modern samples and

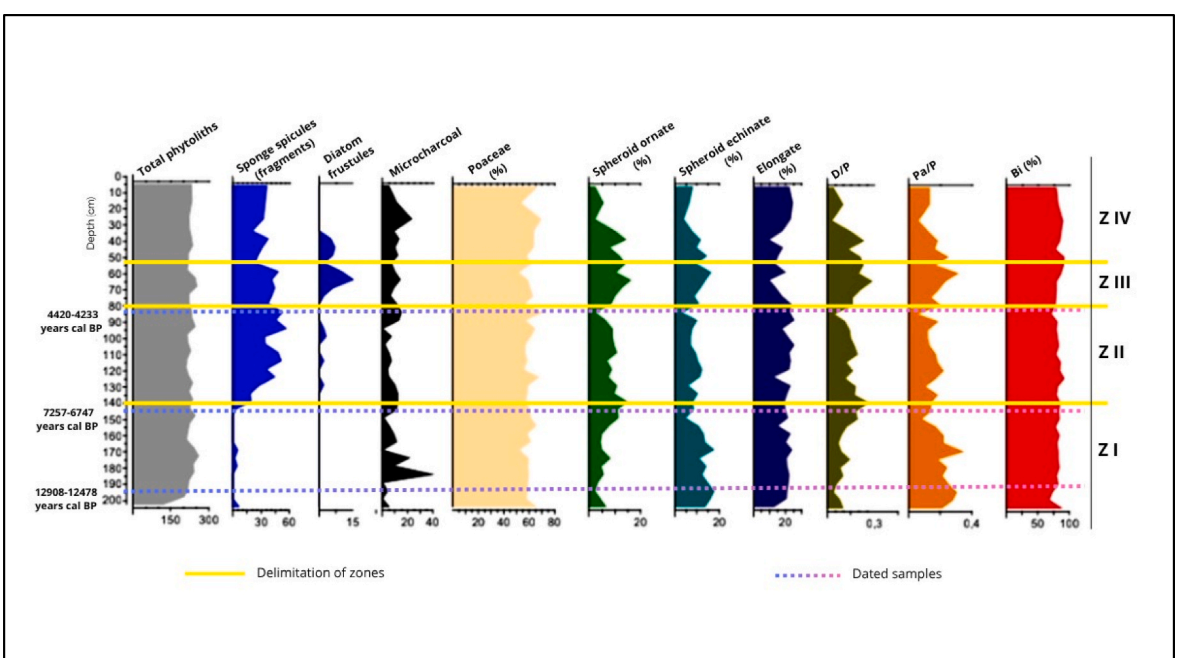

Fig. 4. Summary diagram of phytoliths and silica biomineralizations and phytolith indexes of tree density (D/P), palm tree cover density (Pa/P), and water stress (Bi%).

Table 4
Phytolith analyses and quantification of sponge spicules, diatom frustules, and microcharcoal from the sediment profile (LGQ-PT01).

Depth[a]	Phytoliths Total[b]	Blocky[c]	Bulliform flabellate[c]	Spheroid ornate[c]	Spheroid echinate[c]	Elongate[c]	Acute bulbosus[c]	Rondel[c]	Bilobate[c]	Classified[d]	Unclassified[d]	D/P[e]	Pa/P[f]	Bi%[g]	Sponge spicules Total[b]	Diatom frustules Total[b]	Microcharcoal Total[b]
5.0	233	31.7	20.8	2.5	8.4	22.3	12.9	1.5	0.0	86.7	13.3	0.04	0.13	79	36	0	5
15.0	234	28.2	16.2	5.6	6.8	24.8	7.7	1.9	0.0	91.0	9.0	0.10	0.13	82	34	0	11
25.0	223	35.2	26.8	2.3	4.2	23.5	7.0	0.9	0.0	95.5	4.5	0.03	0.06	89	32	0	23
32.5	226	35.3	19.9	10.4	8.0	17.9	8.5	0.0	0.0	88.9	11.1	0.16	0.13	87	20	0	9
37.5	232	37.4	16.8	14.5	11.7	10.3	9.3	0.0	0.0	92.2	7.8	0.23	0.18	85	37	5	13
42.5	238	29.3	19.4	8.1	9.9	18.5	14.9	0.0	0.0	93.3	6.7	0.13	0.16	77	31	7	10
47.5	221	37.0	16.0	12.0	14.5	15.5	5.0	0.0	0.0	90.5	9.5	0.21	0.25	91	26	6	12
52.5	220	38.4	17.2	14.3	9.9	13.8	5.4	1.0	0.0	92.3	7.7	0.23	0.16	90	23	2	7
57.5	217	26.7	18.9	10.7	16.5	20.4	6.8	0.0	0.0	94.9	5.1	0.20	0.31	87	48	10	10
62.5	247	26.9	19.7	16.6	13.9	10.3	9.4	1.3	1.8	90.3	9.7	0.28	0.23	79	41	15	14
67.5	254	30.4	17.9	12.9	11.6	14.3	10.7	2.2	0.0	88.2	11.8	0.21	0.19	79	44	6	9
72.5	224	27.5	21.5	10.0	9.0	18.0	13.0	1.0	0.0	89.3	10.7	0.16	0.14	78	41	2	6
77.5	222	24.8	18.4	8.7	11.2	23.8	10.7	1.9	0.5	92.8	7.2	0.16	0.20	77	37	0	11
82.5	233	29.7	20.7	2.7	3.6	23.0	9.5	10.8	0.0	95.3	4.7	0.04	0.05	71	52	0	15
87.5	234	26.6	19.2	6.5	10.3	25.7	7.5	4.2	0.0	91.5	8.5	0.11	0.18	80	45	0	13
92.5	247	27.7	23.7	9.4	8.0	17.9	7.1	6.3	0.0	90.7	9.3	0.14	0.12	79	56	2	0
97.5	217	29.7	20.3	9.4	7.4	21.8	11.4	0.0	0.0	93.1	6.9	0.15	0.12	81	33	3	7
102.5	218	27.2	20.3	9.9	7.4	25.7	9.4	0.0	0.0	92.7	7.3	0.17	0.13	83	34	0	2
107.5	229	25.0	19.5	11.0	9.5	22.5	12.5	0.0	0.0	87.3	12.7	0.19	0.17	78	48	0	5
112.5	216	27.0	24.0	7.0	10.5	23.5	8.0	0.0	0.0	92.6	7.4	0.12	0.18	86	51	2	7
117.5	211	25.9	21.9	9.0	12.4	22.4	8.5	0.0	0.0	95.3	4.7	0.16	0.22	85	35	0	4
122.5	220	35.3	26.4	7.5	11.4	12.9	5.5	1.0	0.0	91.4	8.6	0.11	0.17	91	44	0	5
127.5	238	30.3	17.9	10.9	6.0	23.4	10.4	1.0	0.0	84.5	15.5	0.18	0.10	81	28	2	10
132.5	223	26.6	19.8	9.7	10.6	21.3	10.1	1.9	0.0	92.8	7.2	0.17	0.18	79	18	0	12
137.5	237	27.5	21.3	15.0	8.2	19.3	8.7	0.0	0.0	0.0	208.0	0.26	0.14	85	19	0	12
142.5	225	29.8	20.7	11.1	8.7	19.7	9.6	0.5	0.0	92.4	7.6	0.18	0.14	83	2	0	11
147.5	246	28.1	24.0	11.5	5.1	21.7	9.7	0.0	0.0	88.2	11.8	0.19	0.08	84	0	0	1
152.5	226	27.2	23.8	7.9	10.9	15.3	14.9	0.0	0.0	89.4	10.6	0.12	0.17	77	0	0	5
157.5	219	28.9	20.4	5.0	12.9	23.4	9.5	0.0	0.0	91.8	8.2	0.09	0.22	84	0	0	9
162.5	213	28.0	21.5	4.5	13.5	20.5	12.0	0.0	0.0	93.9	6.1	0.07	0.22	80	0	0	11
167.5	243	26.4	16.9	5.0	17.9	24.4	5.0	0.0	4.5	82.7	17.3	0.09	0.34	82	5	0	0
172.5	260	26.4	22.9	8.4	11.0	20.7	9.7	0.0	0.9	87.3	12.7	0.14	0.18	82	2	0	21
177.5	239	31.0	19.2	4.9	14.3	21.2	9.4	0.0	0.0	84.9	15.1	0.08	0.24	84	4	0	8
182.5	241	26.5	20.4	5.7	12.3	22.3	10.9	0.0	1.9	87.6	12.4	0.10	0.21	79	0	0	39
187.5	223	25.0	23.5	3.5	15.0	22.0	11.0	0.0	0.0	89.7	10.3	0.06	0.25	82	0	0	0
192.5	218	22.2	19.7	2.5	17.7	21.2	16.7	0.0	0.0	90.8	9.2	0.04	0.30	72	0	0	4
197.5	204	21.4	18.2	4.7	16.1	20.8	18.8	0.0	0.0	94.1	5.9	0.08	0.28	68	0	0	0
202.5	122	36.3	21.6	6.9	13.7	12.7	8.8	0.0	0.0	83.6	17.2	0.10	0.21	87	6	0	5

[a] Cm.
[b] Unities.
[c] % of classified phytoliths.
[d] % of total.
[e] D/P= Spheroid ornate/(Bulliform flabellate + Blocky + Acute bulbosus + short cells).
[f] Pa/P= Spheroid echinate/(Bulliform flabellate + Blocky + Acute bulbosus + short cells).
[g] Bi% = [(Bulliform flabellate + Blocky)/(Bulliform flabellate + Blocky + Acute bulbosus + short cells)].

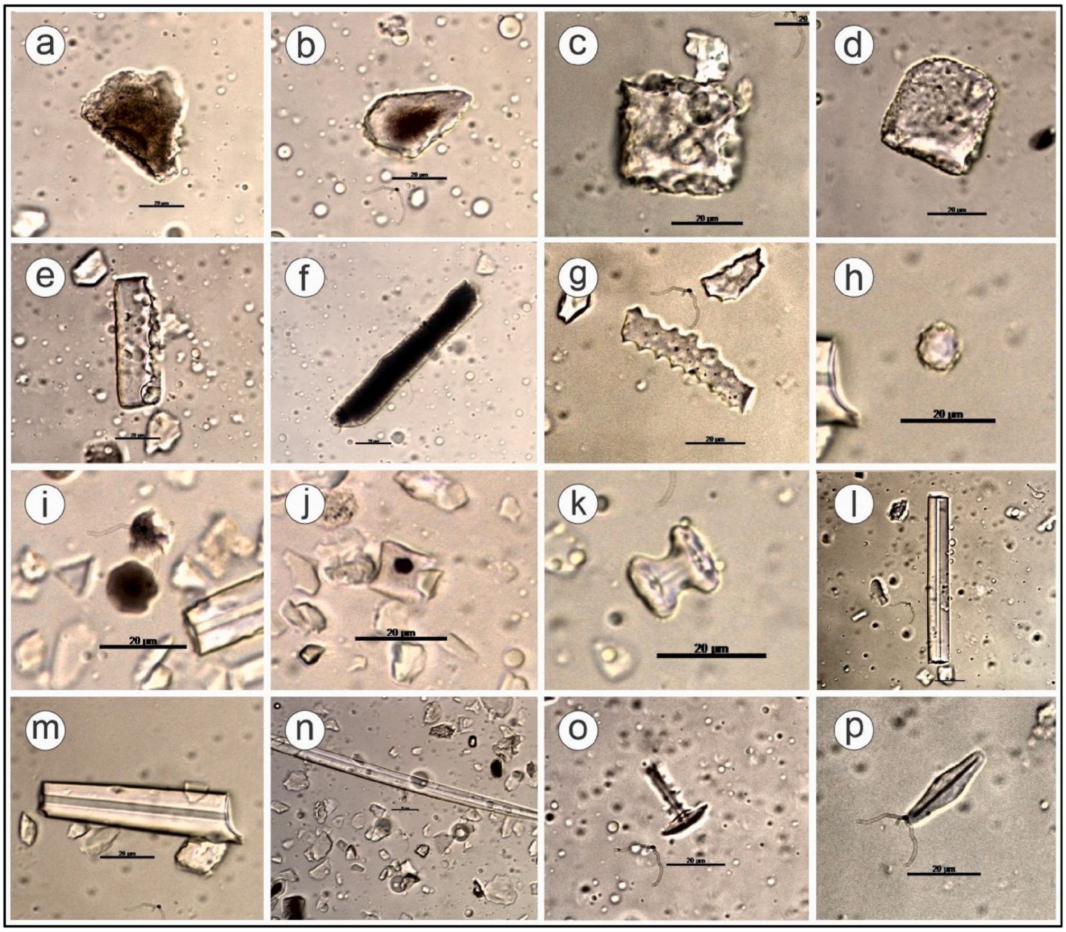

Fig. 5. Photomicrographs of the main phytolith morphotypes and other biogenic silica: a, b) Bulliform flabellate; c, d) Blocky; e, f, g) Elongate; h) Spheroid echinate; i) Spheroid ornate; j) Rondel; k) Bilobate; l, m, n) Fragments of Megasclere; o) Gemosclere; p) Diatom frustule.

may reflect natural fires or current human activity in this semi-arid region.

5.5. Environmental reconstruction

The environmental proxies used in this study enabled identification of the main characteristics related to the environmental conditions that shaped the evolution of the landscape during the Holocene at the Lagoa Grande das Queimadas site. The phytolith stock, D/P, Pa/P and Bi% phytolith indexes, together with diatom frustules, sponge spicules and microcharcoal, enabled the establishment of distinct zones. Zone boundaries were established considering the variations in terrestrial proxies (total of phytoliths and phytolith indexes) in correlation with the presence or absence of aquatic proxies, which enabled the identification of periods of increased or decreased humidity and the consequent changes in vegetation cover. The changes in grain size and TOC observed by Marques et al. (2024) for the same samples were also considered, indicating periods of more or less intense dynamics of sediment mobilization and/or deposition.

Thus, four phytolith zones were established (Fig. 4) in the sediment profile, corresponding to landscape evolution phases (Fig. 6) with different trends:

Zone I (ZI): 205-140 cm deep, between 12,908–12,478 cal yr BP and 7257–6747 cal yr BP (Figs. 4 and 6)

This zone is characterized by a higher phytolith stock than that of the uppermost sample (0–10 cm depth), which has only 233 phytoliths (Fig. 4). The grain size of this zone shows a higher sand content compared to the other zones, indicating a period of more intense dynamics, with concentrated rainfall, which is characteristic of a semi-arid climate, and a scarcity of aquatic indicators. Microcharcoal particles were observed in almost all the samples from this zone, with a peak of 39 particles recorded at a depth of 185-180 cm, the highest of the entire profile, suggesting a regional wildfire and possibly a greater amount of biomass in relation to other events recorded in the profile. The recurrence of this material at different levels of the profile indicates that wildfires occurred systematically, sometimes as peaks, during periods of greater intensity and frequency of wildfires, and other times as a smooth curve (Fig. 4). These variations have environmental significance, as they indicate periods of greater aridity.

The D/P ratio varied from 0.04 (similar to the uppermost layer of the profile) to 0.19 (at the upper zone boundary), indicating a trend of increasing tree cover from the base to the top of this zone. The Pa/P ratio varied significantly within this zone, ranging from 0.08 to 0.34, the highest of the profile, at 175-170 cm. The Bi% ratio fluctuated from 87 % at the base to 68 % (the lowest in the profile) (Fig. 4).

The results from this zone suggest a period of relative change in the vegetation, reflecting a more humid environment than at present, as indicated by the higher D/P and Pa/P values. Additionally, the record of aquatic bioindicators was almost zero, which indicates that the lagoon had yet to be formed, or was dry at that time.

The trends observed here have been found in other paleoenvironmental studies conducted in various areas of the Northeast, such as De Oliveira et al. (1999) in Bahia; Chaves (2000) in southeastern Piauí; Gouveia et al. (2005) in Piauí, Paraíba, and Ceará; Mota (2012) in Piauí; Tavares (2015) in Pernambuco; Zular et al. (2018) in Rio Grande do Norte; Medeiros (2019) in Pernambuco and Paraíba; Ramos (2019) in

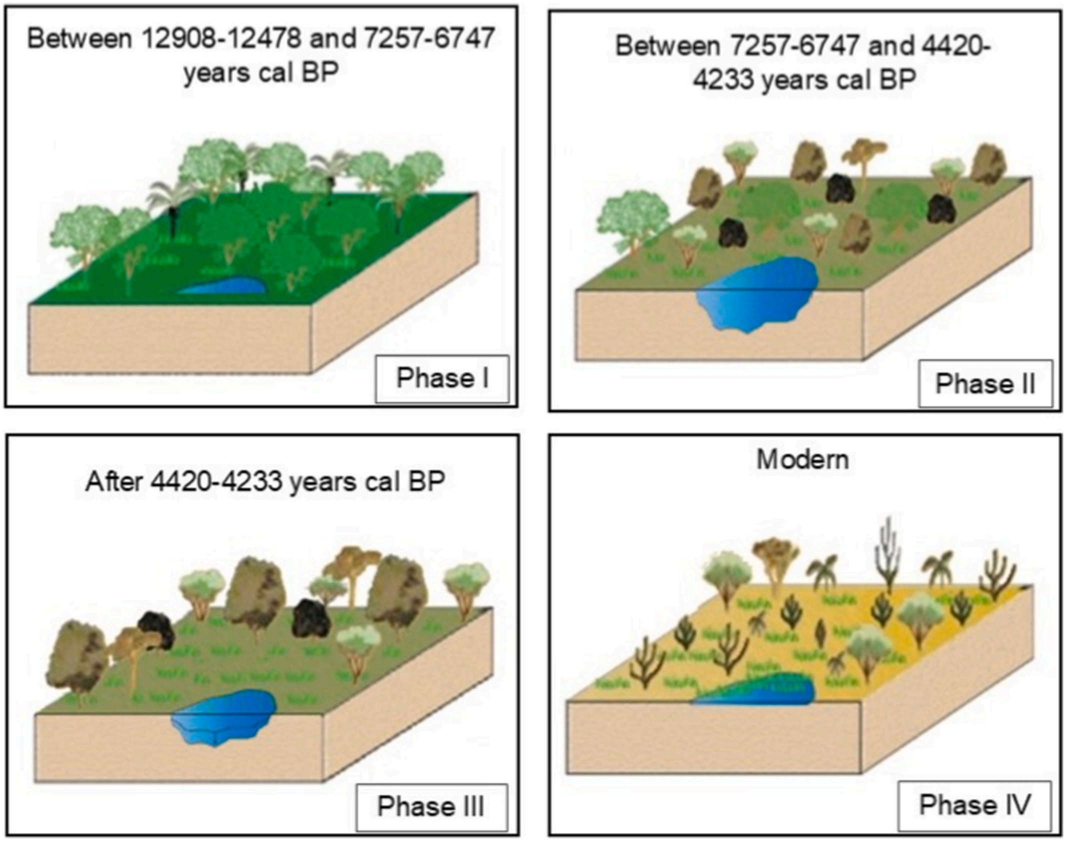

Fig. 6. Paleoenvironmental evolution of the Lagoa Grande das Queimadas archaeological site.

Pernambuco; Galvão (2019) in Piauí; and Machado et al. (2023) in western Bahia. All these authors estimate that temperature and humidity have been gradually increasing since the Pleistocene-Holocene transition at 11,700 years BP (De Oliveira et al., 1999; Behling et al., 2000; Ledru et al., 2006).

During the initial phase (Z I), higher values of the D/P and Pa/P indices reflect a more humid environment than today, with cooler, wetter conditions that favored the expansion of humid forests observed in the Northeast during the Pleistocene–Holocene transition (De Oliveira et al., 1999; Behling et al., 2000; Pessenda et al., 2010).

Zone II (ZII): 140 to 80 cm deep, between 7257–6747 cal yr BP and 4420–4233 cal yr BP (Figs. 4 and 6)

This zone is marked by an increase in clay-sized sediments, which indicates low-energy depositional conditions and coincides with the appearance of aquatic bioindicators, represented by diatom frustules and primarily sponge spicules. The abundance of spicules shows an increasing trend from the lower boundary of the zone, before peaking at a depth of 95-90 cm with 56 spicules, the highest amount in the profile. The phytolith stock was uniform, with similar values to the top of Zone I, with a peak of 247 phytoliths at 95-90 cm, which is the same sample that had the maximum number of fragments of sponge spicules (Fig. 4). The fact that only fragments of spicules were found may be indicative of reworking of the material, even under low depositional energy conditions, since these structures are quite fragile.

Microcharcoal particles are observed throughout the zone, except in the sample from 95 to 90 cm depth, which had no records of this indicator. The D/P ratio varied from 0.26 at the lower boundary of Zone II (140-135 cm depth) to 0.04 at the top of the zone. The Pa/P ratio varied from 0.22 to 0.05 (near the top of the zone). The Bi% ratio showed a trend of reduction from the base (85 %) to the top of the zone (71 %), with a peak of 91 % (one of the highest in the profile) at 125-120 cm deep (Fig. 4).

The results obtained from this zone suggest a phase of lagoon formation or expansion, indicated by the presence of aquatic indicators. Regarding terrestrial vegetation, there was no reduction in phytolith stock but rather a change in the type of plant cover, with a retreat of woody plants and an increase in herbaceous plants, which are better adapted to flooded areas.

The presence of aquatic proxies, the retraction of woody vegetation, and the expansion of herbaceous plants suggest a stage of Lagoon formation or expansion associated with the Early-Middle Holocene (9000–6000 years BP). This period, globally characterized by a warmer, wetter climate, favored the expansion of water bodies and open vegetation, (Ledru et al., 2006; Pessenda et al., 2010), in line with regional records, which indicate the advance of the Cerrado and Caatinga in northeastern Brazil during this period.

According to Chaves (2000), between 8700- and 7000-years BP, there was a reduction in aridity in southeastern Piauí. Tavares (2015) identified increased humidity and temperature during the same period.

Zone III (ZIII): 80-55 cm deep, after 4420–4233 cal yr BP (Figs. 4 and 6)

ZIII is characterized by a slight increase in the phytolith stock at its base and by a significant increase in diatom frustules, from zero at the top of ZII to 15 at a depth of 65-60 cm, while the fragments of sponge spicules and microcharcoal stocks remained stable compared to the previous zone (Fig. 4). The grain size remained similar to that of Zone II, with a predominance of the muddy fraction, especially clay.

The D/P ratio varied from 0.16 (base of the phase) to 0.28, the highest in the profile, at 65-60 cm deep, coinciding with the peak of diatom frustules, suggesting a wetter environment. The Pa/P ratio showed an increasing trend, ranging from 0.14 (at the base of the zone) to 0.31, the second highest in the profile (60-55 cm deep), also indicating increased humidity. The Bi% ratio recorded a variation from 77 % at the base of the zone, with a trend of increase, reaching 90 % at the top of the zone (the second highest in the profile), possibly indicating a response of the vegetation to changes in the lagoon's water level (Fig. 4).

These results indicate a brief period during which there was a small variation in terrestrial vegetation, indicating a trend of expansion associated with increased humidity and lagoon stability. The lacustrine stability recorded by diatoms in ZIII is consistent with the context of increased humidity identified in some sectors of the Northeast. At Around 4000 years BP, more humid conditions are recorded through the expansion of gallery forests and hydro-hygrophyte vegetation (Nascimento et al., 2009; Oliveira et al., 2015).

Zone IV (ZIV): 55-0 cm deep, after 4420–4233 cal yr BP (Figs. 4 and 6)

The uppermost zone of the profile is characterized by a slight increase in grain size (more sand and silt), stabilization of the phytolith stock, and a slight decrease in sponge spicules compared to the previous zone. The diatom frustule stock decreases upward, reaching zero in the most superficial samples (Fig. 4). Diatom frustules were also absent in the modern samples (MS) collected from the edge of the present lagoon. There is noticeable stability in the microcharcoal stock compared to Zones II and III, although a peak was observed at a depth of 30-20 cm (Fig. 4). This zone is also characterized by a significant reduction in the D/P, Pa/P, and Bi% ratios from the base to the top, whereby the D/P ratio varied from 0.23 to 0.04 in the most superficial sample (similar to those found in modern assemblages), the Pa/P ratio from 0.25 to 0.13, and the Bi% from 91 % to 79 % (Fig. 4).

The results from this zone indicate that, after 4419–4234 cal BP, there was a progressive decrease in humidity, with a possible opening of the vegetation and establishment of the Caatinga phytophysiognomies and the current semi-arid regime. (Fig. 4).

The results of this study follow the regional trend of the establishment of a semi-arid climate, coinciding with the end of the Holocene Climatic Optimum (Galvão, 2019). The drop in phytolith indices and the decline in diatom frustules in this zone reflect the reduction in humidity also recorded at other sites in the Northeast. From around 3000 years BP, there were changes in the hydrological cycle with the consequent impact of the atmospheric conditions in the intertropical convergence zone (ITCZ) in the Northeast of Brazil. This reflected a drier climate, similar to that of the present day (Cruz Junior et al., 2009), with the expansion of dry and semi-deciduous forest in some areas (Ledru et al., 2006), and an acceleration in the desertification process in the region from 1300 years BP.

5.6. Correlations with other regional paleoecological, paleoclimatic, and human occupation data

The phytoliths results indicate relative stability during the Holocene. According to Chueng (2020), although the Holocene has been more stable in comparison to the last 20,000 years BP, it has still been marked by a series of relatively abrupt events of smaller amplitude and duration. These include an increase in monsoon intensity beginning around 4000 years ago (Cruz et al., 2007; Bernal et al., 2016). This requires paleoclimatic records to provide higher resolution and greater chronological precision for interpretation.

The trends indicated by the phytolith indexes obtained in this study are similar to the paleoenvironmental patterns already recorded in different areas of northeastern Brazil. The studies by Dias et al. (2019) and Aguiar (2022), both in the Caatinga biome, confirm the consistency of the observed phytolith variations and reinforce that the plant dynamics identified in Lagoa Grande das Queimadas follow widely recognized environmental transformations in the region.

The TOC analysis, conducted by Marques et al. (2024), indicated low levels of organic matter in the samples near the base of the profile, which is probably related to the Younger Dryas period, when the cool, dry climate hindered vegetation growth. At the top of the profile, a relative increasing trend of TOC in the more superficial samples is observed. The result corroborates a condition already observed for soils in the semi-arid region of Brazil, as noted by Rego et al. (2013), whereby the sparse vegetation and tropical climate accelerate the mineralization of organic matter.

Thus, both the grain size and TOC analyses support the interpretation of phytolith deposition in lacustrine sedimentation and the incorporation of organic matter in such systems. These analyses corroborate evidence of climate change and lithological discontinuities in the LGQ-PT01 trench at the Lagoa das Queimadas archaeological site (Marques et al., 2024).

Others paleovegetational studies in northeastern Brazil indicate the expansion of humid forests and cooler climatic phases during the Pleistocene-Holocene transition (ca. 12,000–11,000 years BP), both in interior and coastal areas (De Oliveira et al., 1999; Behling et al., 2000; Pessenda et al., 2010). The Pleistocene-Holocene transition (between 12,000–11,000 years BP) coincided with an increase in rainfall influenced by the Younger Dryas, which marked a warming and climax of the forests and more humid microclimates in high-altitude areas of the interior and in coastal areas of the northeastern Brazil (Albuquerque and Lucena, 1991; De Oliveira et al., 1999; Cruz Junior et al., 2009).

The presence of microcharcoal in all the phytolith zones identified in the present study may be related to episodes of burning associated with the current semi-arid regime. Carcaillet et al. (2002) used radiocarbon dates from charcoal fragments in soil collected in areas between 5°N and 5°S in the northern Amazon basin as evidence of high concentrations of forest fires in the last two thousand years.

Establishment of the current semi-arid vegetation and climate pattern began around 5500 years BP, with the end of the Holocene Climatic Optimum (Galvão, 2019), with an increase in Caatinga species starting from 4500 years BP.

At around 4000 years BP, wetter conditions are recorded through the expansion of gallery forests and hydro-hygrophyte vegetation (Nascimento et al., 2009; Oliveira et al., 2015).

Lacustrine deposits are good indicators of paleoclimatic and paleoenvironmental changes as they record the stratigraphic or temporal sequence of such changes, in addition to sheltering numerous traces of past human occupations (Guidon et al., 2018). Despite the few lithic artifacts recorded in the subsurface at the Lagoa Grande das Queimadas site, it indicates Holocene human occupations around the water body, which can be understood as a zone of temporary habitation or passage for human hunter-gatherer groups. The lithic artifact (scraper) recovered from the layer at a depth of 85-80 cm in the LGQ-PT01 trench, whose organic sediments were dated at 4420–4233 cal yr BP, coincides with intense regional human occupations (Guidon et al., 2009; Guidon and Luz, 2009; Solari et al., 2018a; Solari et al., 2020).

Paleoclimatic and paleovegetational data coincide with the increase in the record of archaeological sites along the Holocene and, consequently, successive human occupations and their impacts in the Northeast region (Albuquerque and Lucena, 1991; Martin, 1998; Nascimento et al., 2009; Oliveira et al., 2015; Moraes et al., 2020; Freitas et al., 2022b).

6. Conclusion

The aim of this study was to contribute to the understanding of the paleoenvironmental and paleoclimatic context of ancient human occupations at the Lagoa Grande das Queimadas site during the Holocene in the interior areas of Northeast Brazil.

The trends observed in the four phytolith zones identified in this study are corroborated by regional data for the Holocene. The results revealed that the studied region underwent climatic fluctuations during the Holocene, as demonstrated by the phytolith and aquatic bioindicator (sponge spicules and diatom frustules) records in the lake sediments. These analyses indicate that between 12,908–12,478 and 4420–4233 cal yr BP, temperature and humidity progressively increased. From this period onward, a transition was observed from a more humid climate than at present to drier conditions, with the establishment of a semi-arid pattern and the Caatinga phytophysiognomy. When compared with previous studies, these results corroborate the trends observed in adjacent regions, suggesting regional climate change.

This is the first integrated study related to landscape reconstruction of past occupations at the Lagoa Grande das Queimadas Archaeological Site and the environmental changes that occurred during the Holocene. The qualitative and quantitative results of biogenic silica associated with other proxies studied at this site, contributed with information about the archaeological site and its integration into the landscape. In addition, the results can be compared with models of past human mobility and subsistence during the late Holocene in the interior areas of northeast Brazil, reinforcing the importance of an interdisciplinary approach in paleoenvironmental reconstruction.

This research enables reflection on this broader archaeological context and interpretation of how indigenous groups adapted to Quaternary climatic changes and their relationship with the environment.

CRediT authorship contribution statement

Roberta Maciel Pacheco Valente: Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Heloisa Helena Gomes Coe:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Karina Ferreira Chueng:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Aline Gonçalves de Freitas:** Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **David Oldack Barcelos Ferreira Machado:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Kita Chaves Damasio Macario:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Marcelo Alves Ribeiro:** Methodology, Investigation, Formal analysis, Conceptualization. **José Sebastián Carrión García:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The first author would like to thank the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) (88887.703642/2022), for granting the master's scholarship. This study was supported by the Fundaç ão de Amparo à Pesquisa do Estado do Piauí and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (FAPEPI/CNPq) (PPP, n. 007/2018 PPP, n. 007/2018, 5414.UNI253.59746.15052018 and PDCTR-PI, n. 006/2021, 301392/2022-6), through the regional development grant awarded to Aline Freitas, and the Instituto do Patrimônio Histórico e Artístico Nacional (IPHAN) (01402.000266/2023–97), which authorized the archaeological prospecting and excavation. Thanks also to the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ) for the Junior Post-doctoral Fellowship grant as part of the Programa de Apoio à Fixação de Jovens Doutores no Brasil (151018/2023-5 – Project 400724/2023-5). We would also like to thank José Carrión for performing one of the radiocarbon dating, Eduardo Salgado for the art-graph of the silica biomineralization diagrams, and the reviewers for their substantial contributions to the article.

Data availability

Data will be made available on request.

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