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Research Article

Depositional processes and the formation of the paleontological and archeological record at the Lagoa dos Porcos site, Southeastern Piaui

Os processos deposicionais e a formação do registro paleontológico e arqueológico do sítio Lagoa dos Porcos, Sudeste do Piauí

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Abstract: This article addresses the processes involved in the formation of Quaternary sedimentary deposits at the Lagoa dos Porcos site, with emphasis on stratigraphic analysis, with the aim of providing new contributions on the depositional processes involved in the formation of the paleontological and archaeological record of this shallow lake, located in the Serra da Capivara Archaeological Area, in the semi-arid region of Piauí. The research method used a combination of granulometric analysis, verification of morphological properties, radiocarbon dating (AMS) and optically stimulated luminescence (OSL) in samples of sediments and carbonate nodules from stratigraphic profile 4. The data obtained indicate that the lake holds information reflecting at least four periods of deposition related to the Pleistocene, the Pleistocene/Holocene transition, and the early and recent Holocene. Regarding the source area of the paleofauna bones and archaeological material, it is proposed that they came from the surrounding areas, such as the pediment ramps and ancient terraces.

Keywords: Quaternary sedimentary deposits; Porcos shallow lake; Paleontological and archaeological record; Pleistocene; Holocene.

Resumo: O presente artigo aborda os processos atuantes na constituição dos depósitos sedimentares quaternários do sítio Lagoa dos Porcos, com ênfase na análise da estratigrafia, com o objetivo de trazer novas contribuições sobre os processos deposicionais atuantes na formação do registro paleontológico e arqueológico desta Lagoa, situada na Área Arqueológica Serra da Capivara, no semiárido piauiense. O método empregado na pesquisa utilizou a combinação de análise granulométrica, verificação das propriedades morfológicas, datações por Radiocarbono (AMS) e Luminescência Opticamente Estimulada (LOE) em amostras de sedimentos e nódulos carbonáticos do perfil estratigráfico 4. Os dados obtidos indicam que a paleolagoa guarda informações que refletem pelo menos quatro momentos de deposição relacionados ao Pleistoceno, a transição Pleistoceno/Holoceno e ao Holoceno antigo e recente. Quanto a área fonte dos ossos da paleofauna e material arqueológico, propõe-se que teriam sido provenientes das porções de entorno, como as rampas de pedimento e os antigos terraços.

Palavras-chave: Depósitos sedimentares quaternários; Lagoa dos Porcos; Registro paleontológico e arqueológico; Pleistoceno; Holoceno.

1. Introduction

Lake and river environments and their surroundings have long been favored sites of human occupation due to their aquatic, faunal, and plant resources. Shallow lakes are important representatives of such sedimentation environments, which, in addition to providing paleoenvironmental information, in many cases also present records of paleofauna and past human occupation, allowing the study of the interaction of human groups with the physical landscape, as is the case of the Lagoa dos Porcos archaeological and paleontological site, located in the Serra da Capivara Archaeological Area, in the semi-arid region of southeastern Piauí.

The shallow lakes of the Brazilian semi-arid region are currently temporary and depend directly on the rainfall that supplies the surface and subsurface water systems; therefore, the presence of water in these environments depends on annual precipitation. According to Guerra (1993), the natural tendency of these temporary water bodies is to fill up with sediments, becoming entirely silted. Thus, Lagoa dos Porcos is an ephemeral lake exhibiting a shallow seasonal water cover typical of the semi-arid environment.

Research conducted in the Serra da Capivara Archaeological area has permitted the identification and assessment of key characteristics of the region's shallow lakes. In the study area, these water bodies predominantly exhibit elongated or rounded shapes, covering areas of less than 1 km², and possess sedimentary fills with thicknesses ranging from 1 to 2.5 meters. Their occurrence in the landscape usually coincides with structural alignments and is typically found in clusters, primarily situated on the flat surfaces of pediments (Guidon et al., 2012).

Shallow lakes-like features are prevalent in regions where the Archean metamorphic complexes of the São Francisco Province are exposed, particularly within the weathered dissected pediments morphological unit located on the southern and southeastern peripheries of the Serra da Capivara National Park. The slope of the terrain on pediment ramps significantly influences water impoundment, as evidenced by a high density of shallow lakes in areas with average slopes of less than 0.5°. In contrast, regions with gradients ranging from 0.5° to 1° exhibit a low density of lakes, while sectors with slopes exceeding 1° are characterized by a paucity of such features (Laborda and Mendes, 2012 apud Felice; Guidon; Mendes, 2014).

Research conducted by Parenti et al. (2003, 2021), Guidon et al. (2012, 2018), and Mendes (2016) has established the stratigraphic characteristics of shallow lakes in the crystalline basement regions of Southeast Piauí, which typically consist of a bottom sandy or gravelly layer containing fossilized paleofauna, an intermediate sand layer, and a top silt-clay layer often marked by desiccation cracks. Tundisi and Tundisi (2008) highlight that lacustrine environments are characterized by low hydrodynamics, promoting the deposition of fine-grained sediments like silt and clay that would otherwise remain suspended in more turbulent conditions. Recent geomorphological studies have increasingly leveraged lake sediments to reconstruct erosion and sedimentation histories through sedimentological, geochemical, geochronological, and biological analyses (Zhao et al., 2024). As closed sediment storage systems, shallow lakes accumulate debris from surface denudation processes, ultimately evolving into self-contained morphological units with readily identifiable sediment source areas, thus providing advantageous characteristics for paleoenvironmental and archaeological reconstructions.

Regarding studies on site formation processes in shallow lakes, the work of Scheifler et al. (2024) in the archaeological area of Laguna Chica in the Central Pampean Dunefields of Argentina provides basilar information. Chronologies obtained by Radiocarbon and Optically Stimulated Luminescence suggest human occupations during the middle Holocene (~8,050-6,535 cal. yr BP) and at the beginning and end of the late Holocene (~3,350-2,870 and ~1,640-1,535 cal. yr BP). Human occupations occurred under drier conditions, with aeolian sediments accumulated under an arid/semi-arid regime within an aeolian-lacustrine interaction environment. Although the physiographic context of Laguna Chica differs from that of Lagoa dos Porcos, the study constitutes a benchmark for understanding the different dynamics and processes involved in forming sites in shallow lacustrine environments.

In Brazil, especially in the Northeast region, studies on the locations where fossilized bones of paleofauna and lithic remains are found have been carried out mainly from a paleoenvironmental or paleontological point of view. The presence of lithic artifacts and bones of paleofauna in sedimentary deposits has been recorded, in addition to Lagoa dos Porcos, in the sites Lagoa da Pedra (Parenti, 1996), Lagoa São Vitor, Lagoa Uri de Cima (Mutzenberg et al., 2013; Felice et al., 2013; Macedo, 2016; Souza, 2018) and Lagoa do Quari (Parenti et al., 2021). However, few

studies still aim at the formation of the paleontological and archaeological records, mainly due to the complexity of shallow lacustrine environments.

At the archaeological and paleontological site Lagoa da Pedra, located in the district of Conceição das Creoulas, state of Pernambuco, excavations revealed a filling of coarse allochthonous sediments at the base and finer at the top. Fossilized bones of paleofauna and lithic artifacts were found in the sedimentary deposit, which, according to Parenti (1996), were deposited together. Analyses performed on the lithic materials demonstrated typological diversity and unifacial tools, suggesting an association with the lower Holocene (Parenti, 1996). Unfortunately, the lack of dating of the sedimentary deposit prevents further inferences about the formation of these records.

The Lagoa Uri de Cima site, located in the municipality of Salgueiro, state of Pernambuco, presents sedimentary filling formed by six levels (vertisol, 1A, 1B, 1B-2, 2, and 3) with deposition chronologies between 3,500 ± 360 years BP to 34,600 ± 690 years BP (Mutzenberg et al., 2013). Research carried out by Felice et al. (2013) and Macedo (2016) allowed the elaboration of proposals for the formation of the records evidenced in the gravel layer cemented by carbonate concretion with a deposition age of 34,600 ± 690 years BP (LOE). The radiocarbon ages (AMS) for the carbonation process range from 8,220-7,820 cal years BP (Beta-347149) and 4,050-3,960 cal years BP (Beta-347144), therefore being a calcinomorphic cementation related to the middle and upper Holocene (Felice et al., 2013; Mutzenberg et al., 2013; Macedo, 2016). The gravel level was studied through detailed micro excavations in the laboratory due to the degree of compaction and hardness that prevented excavations in the field.

Tiny paleofauna bones were found within the cemented gravel layer during the micro-excavations carried out in the laboratory. Larger ones were extremely rare. Taphonomic analyses revealed that the bone fragments had suffered abrasion and indicated that bones and quartz clast had been mixed, had the same inclinations and orientations, and were subjected to the same depositional event. Regarding the archaeological content associated with the gravel layer, out of a universe of approximately 4,000 quartz pebbles, only six chipped pebbles could be attributed to possible anthropogenic remains. In order to state with complete certainty the occurrence of lithic pieces associated with the deposition of the gravel layer, more in-depth traceological analyses would be necessary, as well as the excavation and analyses of more samples from the concretionary level. If this presence is confirmed, the lithic deposition events would have been the same ones that dragged the surrounding paleofauna's bones and other clasts to the lake's rocky bottom (Macedo, 2016).

In the context of the Lagoa Uri de Cima site, Souza (2018) performed an intra-site spatial analysis of the lithic material evidenced in stratigraphic layers 1B (coarse clastic sedimentation) and 1B-2 (pelitic sedimentation). According to the author, this site is characterized by the high proportion of instruments and flint (allochthonous) as the most common raw material. The data demonstrated that chipping activities were carried out outside the central depression, and only fortuitous chippings were conducted inside. Therefore, the site can be characterized more as an area of use than lithic manufacture. The lake connects to the drainage network from an outlet to the north. This linkage, despite sporadic, helps understand the dispersion of smaller lithic materials, which may have been carried out of the lacustrine environment during torrential events of higher magnitude.

The Lagoa do Quari site, located in the municipality of São Raimundo Nonato, state of Piauí, was also excavated. Its area was divided into five sectors (A, B, C, D, and E) to control field activities, with sector D presenting the highest density of paleontological and archaeological remains, but without stratigraphic association. The sedimentary layers of this sector were described, from base to top, as follows: layer 1 – solid medium- and coarse-grained sand; layer 2 – gravel formed by poorly sorted pebbles supported by clasts with a sandy-clayey-silty matrix, with the presence of complete and fragmented paleofauna bones; layer 3 – solid silty sand and poorly sorted quartz with lithic artifacts; layer 4 – silty clay with sparse quartz granules and the presence of lithic artifacts (Parenti et al., 2021). Unfortunately, as in the case of Lagoa da Pedra, no dating of the sedimentary layers was carried out for this site either, which hinders the reconstruction of the environmental circumstances behind the depositional events.

According to Parenti et al. (2021), the fossilized bones of the paleofauna present conservation states ranging from complete and well-preserved bones to many rolled and weathered bone fragments. Regarding lithic artifacts, these were made from autochthonous raw materials such as quartz, quartzite, and gneiss and allochthonous materials such as flint and chalcedony. The authors explains the distribution of lithics in Layer 4 as a taphonomic problem resulting from the formation of dissection cracks on the lake's surface.

This article aims to reconstruct the depositional processes involved in the formation of the Quaternary sedimentary deposits at the Lagoa dos Porcos site through stratigraphical analysis. The objective is to establish the depositional processes that contributed to the formation the shallow lake's paleontological and archaeological record. Additionally, the data and findings from this study will serve as a reference for future research in similar areas of lacustrine accumulation in Brazil's semi-arid region, where the stratigraphic and paleoenvironmental record of such landforms is still largely underexplored.

2. Study Area

The study area is located in the semi-arid region of southeastern Piauí, approximately 30 km from the Serra da Capivara National Park. Paleoenvironmental research carried out in the region allows us to propose, in summary, that a colder and drier climate with pulsatile episodes of high precipitation possibly marked the paleoclimate during the Last Glacial Maximum. The late Pleistocene presented a period of aridity with episodic oscillations in humidity. At the same time, the Pleistocene/Holocene transition was marked by rapid climate change with signs of increased humidity and precipitation. Although drier than the previous period, the early Holocene was still predominantly humid, with the middle Holocene marked by wetter conditions than the current ones. The end of the middle Holocene and entry into the upper Holocene is characterized by a transition to more severe semi-arid conditions that prevail until the present with recurrent long drought episodes (Santos, 2007; Mutzenberg, 2010; Galvão, 2019).

Archaeological excavations and interdisciplinary research conducted across various sites and remains within the distinct geomorphological domains of the region have led to the identification of at least three distinct periods of human occupation. These periods are characterized by the presence of Pleistocene hunter-gatherer groups, hunter-gatherer populations from the Pleistocene/Holocene transition, and Holocene hunter-gatherer and pottery-producing communities (Parenti, 2001; Guidon, 2014; Maranca & Martin, 2014; Lourdeau, 2019). Documentation of these occupations is evidenced by 1,242 sites, which include shelters beneath sandstone and karst rock formations, karst caves, lithic workshops, pottery villages, and shallow lakes. Notable archaeological and paleontological findings are concentrated at Lagoa dos Porcos, which is the primary focus of this article.

Lagoa dos Porcos is an open-air archaeological and paleontological site where lithic remains and paleofauna fossilized bones have been found. The site is located at the Lagoa dos Porcos village in the municipality of São Lourenço do Piauí, under the geographic coordinates 9°9'10.94"S and 42°38'59.08"W, at an altitude of 389 m (Figure 1).

Figure 1. Aerial view of the Lagoa dos Porcos site in the rainy season after the excavation campaign. **Source:** Fumdham collection.

The Lagoa dos Porcos archaeological site is located in the São Francisco Geological Province, specifically in the area where the Archean geological unit known as the Sobradinho-Remanso Complex outcrops. This complex comprises migmatized gneisses associated with granitoid with subordinate granulites, migmatitic, tonalitic-trondhjemitic, and granodioritic orthogneisses, with amphibolitic mafic enclaves and remains of supracrustal rocks (CPRM, 2009).

The Lagoa dos Porcos area lies close to a Proterozoic shear zone (CPRM, 2009). Therefore, this currently temporary lake's genesis, morphology, and evolution were influenced by the occurrence of areas of structural weakness (fractures and joints). The site is located on rocky outcrops, resulting in residual reliefs with rocky surfaces and gneiss boulders. Its genesis is probably linked to the formation of a weathering pit. Intercalated depositions of lake terraces occur in its surroundings (Figure 2).

The sediments that fill the lake are topped by a dark-colored vertisol rich in organic matter. Here, dissection cracks common to this type of soil characteristic of the semi-arid environment can be observed, and their occurrence is related to the lake's microenvironment.

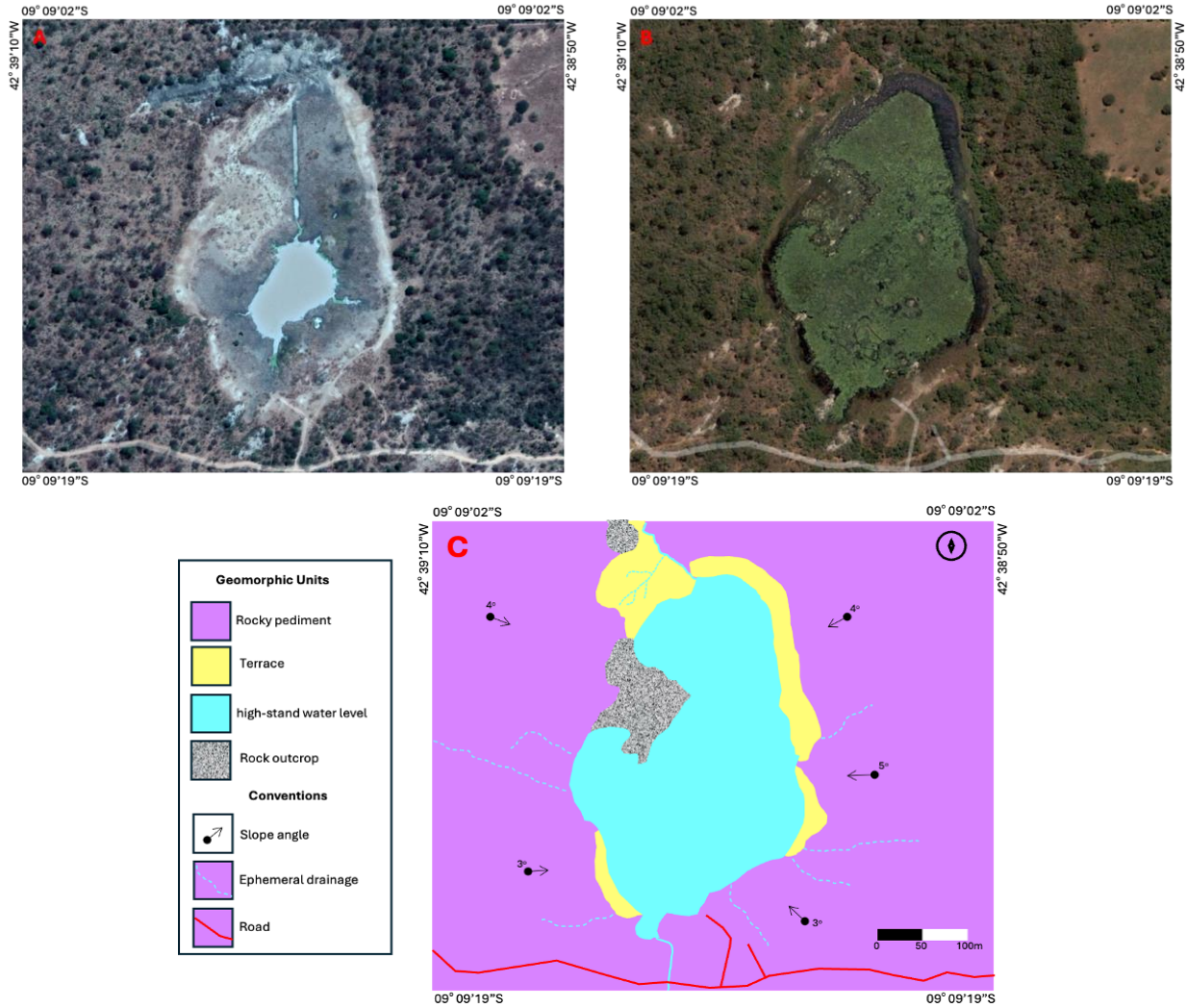

Figure 2. A: Lagoa dos Porcos during the dry season, following excavation, June of 2018; B: Lagoa dos Porcos at the high-stand water level, with the surface covered in water hyacinths at the end of the rainy season, May of 2004; C: Geomorphic units of the Lagoa dos Porcos and surroundings. Images from Google Earth Pro. **Source:** the authors.

Regarding hydrography, the main watercourses that drain the municipality of São Lourenço do Piauí are the São Lourenço, Pedregulho, Seco, Cavaleiro and Canário creeks (CPRM, 2004). Lagoa dos Porcos is located along the intermittent drainage of the Canário Creek, part of the Piauí River watershed. The headwaters of the Canário Creek are at 413 m, while its confluence with the higher-order drainage is at 387 m. The section of the channel that intersects the lake in a south-north direction has an elevation ranging from 391 to 389 m. To the north, along the same drainage, there is another lake adapted to the structural weakness zones that subordinate the course of the Canário Creek (Figure 3).

Figure 3. Location of the Lagoa dos Porcos site in the drainage network. **Source:** adapted from Google Earth Pro and National Water-resources Authority (ANA).

At this site, archaeological remains characterized by lithics were evidenced. According to Guidon et al. (2018), lithics appear on the soil surface, concentrated in the northeast portion (Figure 4), and within the sedimentary deposit, specifically at the base of layer 5 of sandy clay matrix, approximately 2 m deep, where few lithics were collected together with paleofauna bones (Figure 5).

Figure 4. Identification of the lithic remains on the surface of the Lagoa dos Porcos site. **Source:** Fumdham collection.

The archaeological remains collected on the soil surface and within the sedimentary deposit (base of layer 5) total 455 lithic pieces, corresponding to 36 tools, 250 cores, 147 flakes with cortex, and 22 flakes without cortex, made of flint, quartz, quartzite, granite, gneiss, and silicified sandstone. At the base of the deepest layer (layer 5), 11 lithics (tools, flakes, and cores in flint, granite, and gneiss) were associated with the paleofauna´s bones in areas 1 and 2 of the lake´s depocenter (Figure 5). The sediments covering these paleontological and archaeological remains were dated using the Optically Stimulated Luminescence (OSL) technique and provided an age of 17,000 BP (Guidon et al., 2018).

The raw materials used to make the lithic artifacts come from the Archean metamorphic complexes of the São Francisco Province. In the lower parts of the relief, granites, gneisses, schists, metamorphic limestones, quartz veins, and quartzite outcrops (Barros et al., 2012). Flint is also recorded in the São Lourenço Creek bed, just 11 km from Lagoa dos Porcos.

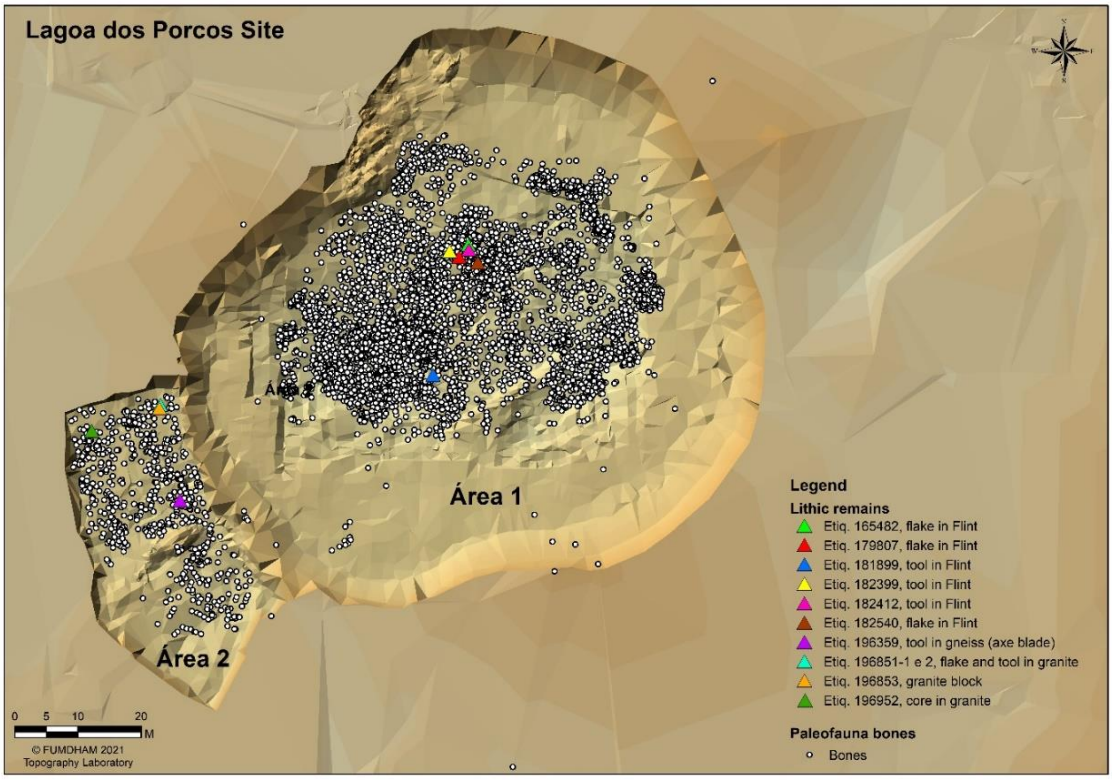

Figure 5. Location of the 11 lithic remains associated with the paleofauna bones in the deepest layer in excavation areas 1 and 2 of Lagoa dos Porcos. **Source:** modified from Fumdham collection.

Regarding other research carried out in the area, the study on climate change by Mendes (2016) stands out, where the author raises the hypothesis that Lagoa dos Porcos probably went through two distinct moments of evolution, possibly marked by a fluvial and a lacustrine phase. The fluvial phase was characterized by greater hydrodynamic energy, which allowed the deposition of coarse sediments and large bone fragments of the paleofauna. This phase was likely related to a moment of higher precipitation, and the place where Lagoa dos Porcos lies today was occupied by the bed of a perennial river. The author also points out that the roundness, wear, and abrasion of most of the bones, in addition to the parallelism of the larger axis of the long bones, would attest to river transport under conditions of permanent flow (Mendes, 2016). On the other hand, the lacustrine phase, proposed by Mendes (2016), would have been marked by the deposition of clay resulting from the decrease in precipitation and, consequently, lower environmental hydrodynamics.

During the excavations carried out by Fundação Museu do Homem Americano (Fumdham) in Lagoa dos Porcos, paleofauna bones were found amidst a coarse gravel bed composed of pebbles, cobbles, blocks, and boulders (Figures 6 and 7), which demonstrates the occurrence of a high-energy environment during deposition (Guidon et al., 2018).


Figures 6 and 7. Concentration of paleofauna bones amidst pebbles, cobbles, blocks, and boulders. **Source:** Fumdham collection.

According to Guidon et al. (2012), Guérin and Faure (2013, 2014) and Mayer, Kerber and Ribeiro (2013), the fossils from Lagoa dos Porcos present different states of integrity, sometimes composed of well-preserved complete elements, where in some cases anatomical association was observed, as well as fragments and incomplete elements with and without signs of abrasion, rounding and weathering. The paleontological remains characterized by bones paleofauna total approximately 10,600 fossils. Their arrangement in the deposit was mostly concentrated, with a few dispersed specimens.

The taxonomic analysis carried out according to the degree of identification possibility allowed a classification with varying degrees of precision; in some cases, it was possible to verify genus and family, and in others, only order or class. Among the identified taxa are Cervidae undetermined, Pampatherium humboldti, Eremotherium rusconi, Mylodonopsis ibseni, Hippidion sp., Equus sp., Glyptodontidae undetermined, Panochthus greslebini, Haplomastodon waringi, Macrauchenia patachonica, Notiomastodon platensis, Smilodon populator, Toxodon platensis, Piauhytherium capivarae, Paleolama niedae and Paleolama major (Table 1) (Guidon et al. 2012; Guérin and Faure 2013, 2014; Mayer, Kerber and Ribeiro, 2013 and Fumdham database).

Table 1. List of taxa, identified anatomical parts and state of conservation of the analyzed specimens

Taxa	Anatomical parts	State of conservation
Cervidae (undetermined)	Astragalus, horns, tooth, phalanx, femur, jaw, metacarpals, tibias, vertebrae	Complete and fragmented
Pampatherium humboldti	Plates	Complete and fragmented
Eremotherium rusconi	Skulls, jaws, teeth, humeri, radii, ulnae, femurs, tibiae, talus, calcanei, tarsi and phalanges.	Complete and fragmented
Mylodonopsis ibseni	Tibiae	Complete and fragmented
Hippidion sp.	Teeth and mandible	Fragmented
Equus sp.	Teeth	Complete and fragmented
Glyptodontidae (undetermined)	Plates	Fragmented

Panochthus greslebini	Astragalus, calcaneus, cuboid, phalanges, tibia, femur, metatarsals, sesamoids and plates	Complete and fragmented
Haplomastodon waringi	Astragalus, teeth, phalanges, femurs, vertebrae, metatarsus, metapodial, unciform, patella, humerus and tusk	Complete, incomplete and fragmented
Macrauchenia patachonica	Teeth, phalanges, radius-ulna, tibia-fibula and humerus	Complete and incomplete
Notiomastodon platensis	Teeth and femur	Complete, incomplete and fragmented
Smilodon populator	Skull and phalanx	Complete and fragmented
Toxodon platensis	Skull, Skull and mandible, ulna, teeth, femurs and metapodium	Complete, incomplete and fragmented
Piauhytherium capivarae	Skulls, ulna, teeth, femurs, fibulas, mandibles, metacarpals, radius, tibia, tibia-fibula and humeri	Complete, incomplete and fragmented
Paleolama sp.	Astragalus, ulna, teeth, scapula, phalanges, femurs, metapodial, metatarsal, pelvis, radius-ulna, radius and tibia	Complete, incomplete and fragmented
Paleolama major	Teeth, calcaneus, metatarsus and phalanges	Complete and fragmented

Source: Guidon et al. (2012), Guérin and Faure (2013, 2014), Mayer, Kerber and Ribeiro (2013) and Fumdham database.

Chronological data for two teeth from the families Gomphotheriidae and Toxodontidae, recovered from the Lagoa dos Porcos site, were obtained through Electron Paramagnetic Resonance (EPR) analysis. This technique yielded ages of 26,000 ± 400 years and 22,000 ± 300 years, respectively. These findings substantiate the late Pleistocene chronology associated with the lake's fossil record. As noted by Kinoshita et al. (2014, p. 1), these dates coincide with a period characterized by a significant increase in precipitation in Northeast Brazil, suggesting a potential link between this environmental shift and the deposition of these remains. Furthermore, in addition to the fossilized paleofauna, evidence of extant fauna, including species of Chelonia and birds from the Vulturidae family, has also been documented in Lagoa dos Porcos (Guidon et al., 2012).

During the excavation campaigns at the Lagoa dos Porcos site, important specimens were found for archaeological and paleontological research in the region, reinforcing the presence of environments distinct from today's. In some circumstances, the fact that lithic pieces were found in the same layer of bones of the paleofauna attests to the site's relevance for discussions that address the coexistence between human groups and the paleofauna. The fossils evidenced present different states of conservation and fossilization, reinforcing the environmental characteristics synchronous with the action of taphonomic and depositional processes, which allowed the preservation of this assemblage.

Lagoa dos Porcos is a shallow, ephemeral lake located in the semi-arid region of southeastern Piauí state. The lake is elliptical in shape and approximately 390 m long and 240 m across. The fossil deposits are concentrated in potholes carved by erosion on the gneiss bedrock of the lake bottom. The lake lies on a low-relief rocky pediment surface, cut by the ephemeral drainage of the Riacho Canário, less than 400 m south of its confluence with a higher-order channel. Its connection with the current river system is restricted to episodes of torrential rains from December to March. The nearest intermittent higher-order drainage is the Piauí River, approximately 13 km to the north. The lake's sediment fill is approximately 2,5 m thick and dates back at least to the last 17 ka (Guidon et al., 2018). Evidence of fluvial deposition occurs as remnants of fluvial-lacustrine terraces in its surroundings. The gray

lacustrine deposits range from clayey to sandy clayey in texture, progressing to a vertisol at the top of the sequence. The stratigraphic level where the megafaunal bones and human artifacts overlap occurs at a depth of c. 2 m from the surface.

Although the taphonomy of the lake's fossil assemblage is not the focus of this contribution, the arrangement of the bones amidst the sediment indicates an environment of complex evolution, incorporating low-energy periods, with the presence of potholes carved on the sandy-clayey saprolite, possibly resulting in attractive waterhole environments for the mega-fauna in periods of severe drought. At other times, the lake was connected to the drainage network under a semi-arid high-energy regime characterized by torrential runoff, whose floods resulted in the deposition of terraces, whose remainders are disconnected from the contemporary drainage. Lacustrine periods, marked by high water levels, led to the sedimentation of fines, the parent material for the vertisols that cap the stratigraphic sequence. Furthermore, some translocation and concentration of carbonates by capillarity, forming nodules (Figures 15 and 16), occurred during drier phases.

The fossil assemblage allows the inference of some types of taphonomic environments typical of shallow lakes (Fillios et al., 2010), one of which is characteristic of waterholes, probably associated with moments of harsher droughts of the late Pleistocene, where the gneiss saprolite of the lake, dotted with potholes, trapped megafauna specimens, resulting in some of the well-preserved fossils recovered from the lake (Guidon et al., 2012; Guérin e Faure, 2013, 2014; Mayer, Kerber e Ribeiro, 2013), without signs of geochemical wear or mechanical abrasion (Figure 8).

Figure 8. Skull and mandible of Toxodontidae *Piauhytherium capivarae* well-preserved. **Source:** Guérin and Faure (2013, p.161 and 164).

The taphonomic environment of waterholes in ephemeral drainages studied in other semi-arid contexts, such as the margins of the Kalahari Desert in Zimbabwe by Conybeare and Haynes (1984), indicates that in the case of shallow lakes connected to the drainage network, the occurrence of well-preserved skeletons and accumulations of fragmented bones transported by the current may coexist, indicating reworking of the muddy deposits of the waterholes in the phases in which the flow is reestablished within the channel. This mixing of fossil material in various degrees of preservation is the case of Lagoa dos Porcos, where although fragmentation and accumulation of bones with abrasion characteristics predominate, well-preserved specimens are also occasionally found, with no apparent signs of weathering in subaerial conditions or friction suffered when submerged in the transporting.

Wiest et al. (2016) also propose that the waterhole environment, with a continuous decrease in the volume of available water during a prolonged dry period, is responsible for the large concentration of animals under water stress, seeking to quench their thirst, which would result in taxonomic diversity and a large concentration of skeletons. This scenario is consistent with the variety of species found in Lagoa dos Porcos. However, the disarticulated state of the bones and their spatial concentration in potholes at the bottom of the shallow lake, or trapped upstream of rocky sills transverse to the flow's direction, indicates the subsequent reworking and substantial loss of fragments from the original thanotocenosis.

The taphonomic environment of Lagoa dos Porcos is mainly characterized by gravitational flows, where the fragments arranged in the surroundings of the lacustrine depression were dragged by surface runoff. This high-energy, short-distance transport resulted in a bed of bioclasts and coarse minerogenic gravel supported by a clayey-sandy matrix encompassing fragmented bones with worn joints (Figures 9 and 10).


Figures 9 and 10. Bioclasts gravel including bone fragments of paleofauna and minerogenic clasts. **Source**: Fumdham.

Working with a thanatocenosis in a semi-arid Upper Pleistocene drainage in the southwestern United States, Wiest et al. (2016) found that most of the fossils' surfaces contained evidence of subaerial alteration with the presence of stains caused by supergene mineralization. Likewise, the bones showed evidence of fracturing by fluvial transport, with fractures parallel and transverse to the bone structure, demonstrating the various impacts the specimens suffered in a high-energy environment. According to the authors, transverse fractures are evidence of post-burial remobilization, while those parallel to the bone structure may also result from sediment compaction.

In Lagoa dos Porcos, the bones occur in concentrations filling paleo-depressions on the lake bottom (potholes), demonstrating wear and lack of articulation, which indicates transport from the surroundings of the shallow lake, including the river-lacustrine terraces that border it, and burial by both diffuse surface and gravitational flows. However, the existence of fossils in good preservation also suggests the reworking of waterhole deposits in the episodes when the lake was reconnected to the Riacho Canário drainage network. The transportation of these fragments as bedload under torrential conditions would explain the ubiquitous occurrence of fragmented material trapped upstream of rocky sills transverse to the flow direction (Figures 11 and 12).


Figures 11 and 12. Fragments of femur without articular ends and radius with wear on the end. **Source**: Fumdham.

The description above suggests a complex system that evolved as a seasonally closed basin receiving high-energy surface flows, alternating periods of high water with the sedimentation of clays, and drier phases with precipitation of carbonate nodules (Figures 15 and 16) probably associated with capillarity rise in the vadose zone in more recent upper Holocene times. Nonetheless, the sediments lack the presence of a duricrust or calcinomorphic cementation, as found in other shallow lakes in the region (Mutzenberg et al., 2013). Furthermore, the relative paucity of iron remobilization, creating nodules or crusts, is reflected in the absence of cement consolidating the lake deposits.

3. Methodology

The methodology employed in this research used a varied set of analytical techniques. Following fieldwork and excavation routines, the sediments' physical characteristics were investigated by means of grain size and morphological analysis. Geochronology was determined through Radiocarbon dating (AMS) and Optically

Stimulated Luminescence (OSL), while environmental aspects were evaluated using Carbon Isotopes (δ13C). The analyses were performed on sediment samples from stratigraphic profile 4, which has six layers and is 2.5 m thick, corresponding to the complete stratigraphic profile of the Lake, with its base resting on saprolite (Figure 13 and Table 2).

Figure 13. Collection of sediment samples in stratigraphic profile 4, at the Lagoa dos Porcos site. **Source:** Fumdham collection.

Table 2. List of samples collected in stratigraphic profile 4 and the analyses performed.

Site Lagoa dos Porcos	Layer	Depth in relation to the surface (cm)	Analysis
Stratigraphic profile #4	1	35	Grain size
	2	85	Grain size, OSL and Radiocarbon dating, $\delta^{13}C$
	3	125	Grain size
	4	160	Grain size, OSL and Radiocarbon dating, $\delta^{13}C$
	5	190	Grain size
	6	220	Grain size

Source: the authors.

3.1 Field work

Field activities were carried out during the dry season. The initial work involved conducting a topographic survey of the shallow lake area, covering approximately 390 meters in length and 240 meters in width. A Leica Total station was used in the topographic survey to locate the remains of archaeological and paleontological materials. Following this, the identification, mapping, and collection of lithic artifacts on the surface were undertaken.

Before beginning extensive surface excavations, a large longitudinal trench was opened. As the trench advanced toward the depocenter, fossilized paleofaunal bones were revealed. Initial test pits measuring approximately 2 x 2 meters were excavated in the depocenter area and expanded as bones were discovered in the deeper layers above the altered bedrock at the lake base. This process resulted in two large excavation areas, designated as area 1 and area 2 (Figure 14).

Some lithic artifacts from the surface were found as intrusive elements in the uppermost sediment layer, having been displaced into this recent stratum through dissection cracks from the overlying vertisol. However, no archaeological or paleontological materials were found in the subsequent layers until reaching the top of the saprolite, where the paleofaunal bones were deposited. Some lithic artifacts with rounded edges were also recovered from this deeper layer (Guidon et al., 2018).

Given the lake's size and the absence of archaeological or paleontological materials in most sedimentary deposits, manual and mechanical excavation techniques were employed for sediment removal. A small Bobcat tractor with an adapted blade was used to scrape and mechanically excavate sediment in layers just over five centimeters thick in areas without archaeological or paleontological remains.

From layer 4, which precedes the layer with the paleontological and archaeological remains, the excavation was carried out manually, maintaining a stripping thickness of approximately 5 cm, in order to guarantee the integrity of the remains and their *in situ* positions.

Three test pits were also manually excavated in the lake's margin, one in the western portion and two in the eastern portion, and also a toposequence with three test pits in the southwest portion of the lake (Figure 14). No archaeological or paleontological remains were found in these soundings.

The sediment filling was moist, making sieving impractical. However, all excavated sediments were systematically examined and sorted during the excavation process. As the weathered bedrock was reached and paleofaunal bones were uncovered at a depth of approximately two meters, groundwater began to seep into some areas. Small drainage trenches were excavated to direct the water, which was pumped out.

All identified lithic and paleontological remains were georeferenced, systematically collected, and sent to the Fundação Museu do Homem Americano laboratories, where curation and analysis were conducted. Upon the completion of fieldwork in 2012, the excavated area of the lake became a reservoir for rainwater, which the local community can use, particularly during the long dry season.

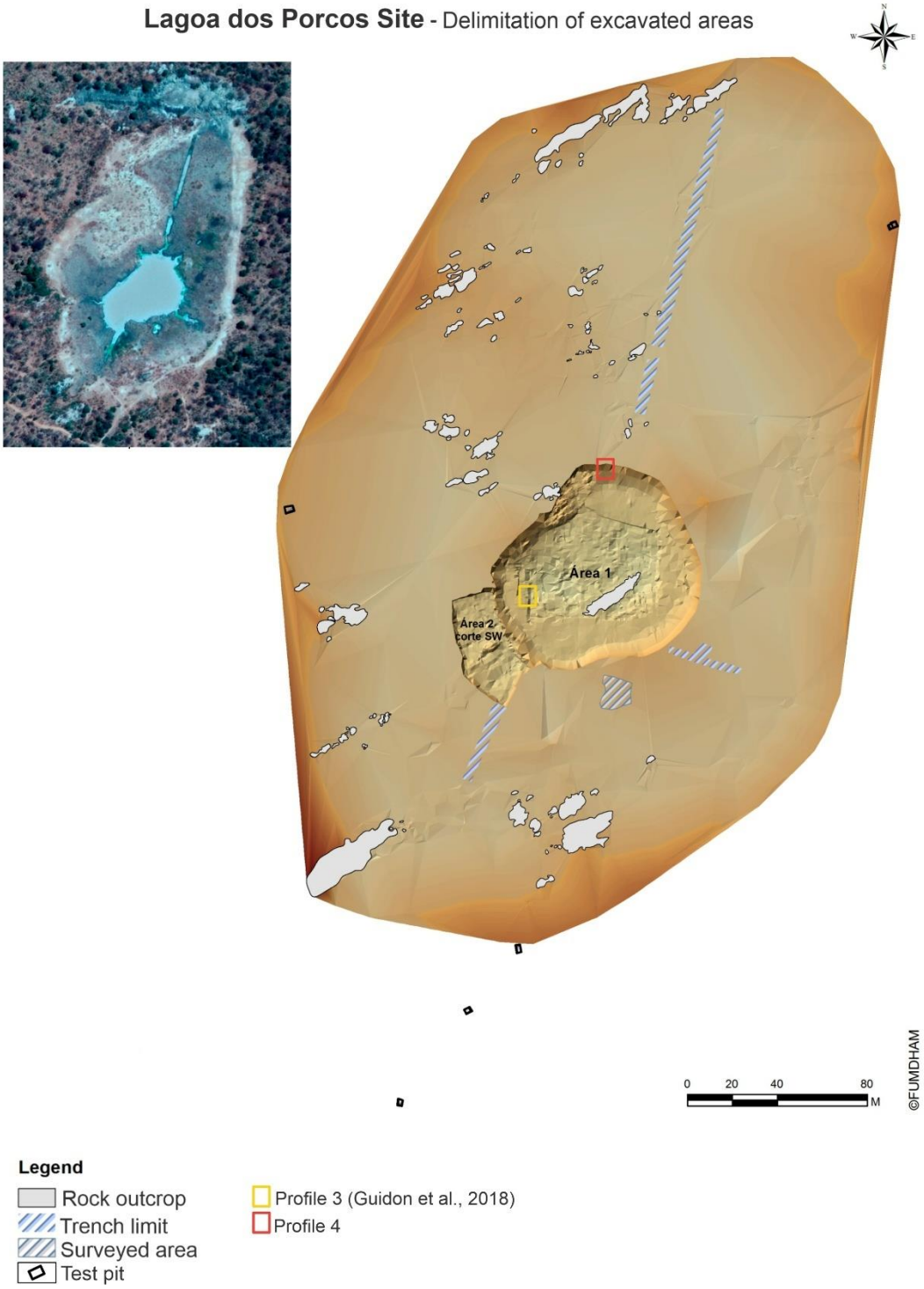

Figure 14. Delimitation of the Lagoa dos Porcos with the location of the test pits, surveyed area, trenches and excavated areas 1 and 2 in the lake's depocenter. **Source:** adapted from Guidon et al. (2018).

3.2. Grain size analysis

In order to understand the environment, genesis and evolution of sedimentation, and the hydrodynamic regimes that acted in the formation of the research site, the granulometric characterization of the sediments of the six layers that make up the stratigraphic profile was carried out by the sieving method at the Fumdham Sedimentology Laboratory. The fine sediments were evacuated by washing in running water, and their percentage was calculated by subtracting the final dry weight from the initial one. The data obtained in the dry sieving process

result in specific values for each granulometric fraction. These were subjected to treatment following the statistical parameters of Folk and Ward (1957) to calculate the degrees of sorting, asymmetry, and kurtosis and to prepare the Pejrup (1988) and Shepard (1954) diagrams for the classification of the hydrodynamics and texture of the matrix using the SysGran 4.0 program.

According to Suguio (1973), the degree of sorting is linked to the type of sediment transport and its maturity, while the degree of asymmetry provides indications about the nature of the flow, which can be positive (unidirectional) or negative (bidirectional), while kurtosis reflects the degree of flattening of the granulometric distribution. The sediment samples collected in the layers of the stratigraphic profile were also analyzed according to the morphological properties of compaction, texture, and color, the latter based on the Munsell code. Together with the granulometry, these analyses allowed the characterization of the sediments that make up the Quaternary deposits in question.

3.3. Optically Stimulated Luminescence (OSL)

To define the chronology of the deposition episodes, sediment samples from layer 2, collected at a depth of 85 cm, and layer 4, collected at 160 cm from the surface, were dated. The technique used was Optically Stimulated Luminescence (OSL) performed by Datação, Comércio & Prestação de Serviços LTDA, applying the SAR (single aliquot regenerative-dose) protocol with 15 aliquots per dated sample. The mineral analyzed was quartz.

3.4. Radiocarbon (AMS) and carbon isotopes ($\delta^{13}C$)

The identification of climatic and vegetation indicators was performed by means of radiocarbon dating (AMS) and carbon isotope analyses ($\delta^{13}C$) performed by the Beta Analytic Laboratory, on carbonate elements (Figures 15 and 16) present in the sedimentary deposit, specifically nodules from layers 2 and 4. The dates obtained from these carbonate elements allow us to know the periods in which the carbonation processes occurred, primarily related to environmental and climatic changes.

The isotope analyses of these same carbonate elements also allowed us to verify the carbon isotopes of the soil organic matter ($\delta^{13}C$), which in turn provide information about the climate and environment.

Calibrated radiocarbon ages were provided in two sigma by Beta Analytic Laboratory using the BetaCal4.20: HPD method and the SHCAL20 calibration curve (Bronk Ramsey, C. 2009; Hogg et al. 2020).

Figures 15 and 16. Separating carbonate nodules in the clayey sediment matrix. **Source:** Negreiros (2022).

The results obtained with this analysis, crossed with the results of the granulometric distribution and Optically Stimulated Luminescence (OSL), provided data for the interpretations regarding the paleoenvironmental and environmental dynamics of the archaeological and paleontological site Lagoa dos Porcos, presented below.

4. Results and discussion

4.1. Grain size characterization

This analysis showed that in stratigraphic profile 4, the granulometric fractions vary between granules, very coarse sand, coarse sand, medium sand, fine sand, very fine sand, and silt/clay, as shown in Figure 17.

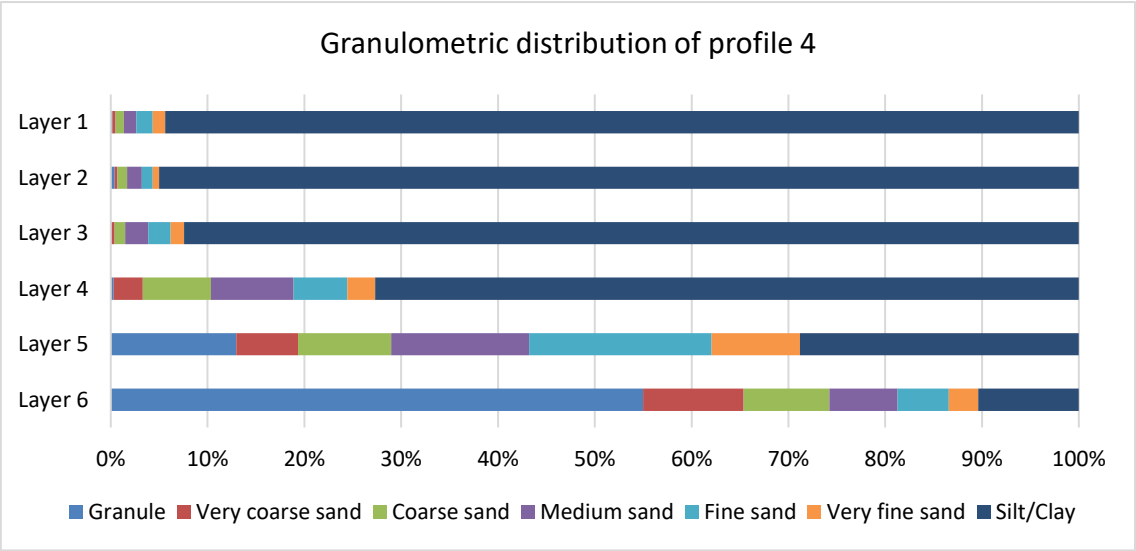

Figure 17. Granulometric distribution of stratigraphic profile 4 of the Lagoa dos Porcos site. **Source:** the authors.

The predominant class is clay/silt, present in all layers as well as sand, while granules appear more expressively only in layers 5 and 6, in the latter in a higher percentage. The distribution of the classes shows that for layers 1, 2, 3, and 4, sedimentation/deposition occurred in a lower energy environment, therefore, more slowly, while for layers 5 and 6, the greater quantity of granules demonstrates a more accentuated hydrodynamics.

In layers 1, 2, 3, and 4, a predominance of the clay and silt fraction is evident. Mendes (2016) posits that the observed increase in clay content may be attributed to a reduction in circulation and turbulence of water flow within the drainage system. This phenomenon could be associated with a decrease in precipitation and a subsequent high-stand water level following a flood event. Similarly, at the Lagoa Uri de Cima site in the central semi-arid region of Pernambuco, which shares comparable geomorphological and depositional characteristics (Mutzenberg et al., 2013), the formation of a pelitic layer rich in clay could also stem from a high-stand water period. This scenario would facilitate the sedimentation of fine particles in a low-energy environment, despite the overarching semi-arid conditions prevalent in the region.

The granulometric analysis provided data on the following variables: classification, selection, asymmetry, and kurtosis according to the parameters of Shepard (1954) and Folk and Ward (1957). In general, the clay or mudstone classification predominates for the sediment matrix (Table 3).

Table 3. Statistical parameters: classification, sorting, asymmetry, and kurtosis of the sediment matrix of stratigraphic profile 4, Lagoa dos Porcos site.

Layer	Classification	Sorting	Asymetry	Kurtosis
1	Clay (mudstone)	Very well sorted	Very positive	Very platykurtic
2	Clay (mudstone)	Extremely poorly sorted	Very positive	Very platykurtic
3	Clay (mudstone)	Very well sorted	Very positive	Very platykurtic
4	Clay (mudstone)	Extremely poorly sorted	Very positive	Very platykurtic
5	Sandy clay	Extremely poorly sorted	Very positive	Very platykurtic
6	Clayey sand	Extremely poorly sorted	Very positive	Very platykurtic

Source: the authors.

The result of the statistical parameters of the sample matrix relative to the hydrodynamics indicates low energy acting on the deposition of sediments, according to the Pejrup diagram (1988) (Figure 18). Regarding sorting, the sediments of layers 1 and 3 are very well sorted, while layers 2, 4, 5, and 6 are extremely poorly sorted. Regarding the kurtosis data, the result for all layers is very platykurtic, indicating short movement of the sediments. The asymmetry resulted in positive values for all samples analyzed, confirming a unidirectional flow. The presence of granules and larger quantities of sand in layers 5 and 6 demonstrates stronger hydrodynamics for depositing these two deeper layers.

In contrast, the overlapping layers 4, 3, 2, and 1 were formed in a lower energy environment. Through the analysis of the granulometric classes, it is possible to verify a coherence between the energy of the environment and the deposition of the sediments, demonstrated by the gradual increase of the granulometric fractions towards the base of the profile, where for layers 1, 2 and 3 the hydrodynamics were lower. In turn, layer 4 presents a transition to the two underlying layers. This difference is further demonstrated by the presence in layers 5 and 6 of clasts constituted by fragments of gneiss, paleofauna bones, lithic pieces, and occasional quartzite boulders deposited in layer 5 and in the transition to the saprolite of layer 6. Therefore, it is observed that the minerogenic sediments and bioclasts found in layers 6 and 5 were subjected to a high competence torrential transport. In contrast, the formation of layers 4, 3, 2, and 1 is mainly associated with surface runoff.

The deposit is generally reasonably compacted, and the layers, according to the Shepard diagram (1954), present textures ranging from clay or mudstone (layers 1, 2, 3, and 4) to sandy clay (layer 5) and clayey sand (layer 6). According to the Munsell code, the moistened sediment colors vary between very dark gray (5Y 2.5/1), dark gray (2.5Y 3/1), and greenish-gray (5Y 4/2) (Figure 18).

Hardened carbonate nodules were found in the Lagoa dos Porcos sedimentary fill in layers 2, 3, 4, and 5. The nodules occur most frequently in layer 2, are reasonably frequent in layer 4, and sporadic in layers 3 and 5 (Figure 18). Morphologically, these carbonate concretions present predominantly rounded shapes, followed by elongated and irregular ones, with dimensions varying between 1 and 2 cm. The presence of nodules allowed the dating of the carbonation periods by radiocarbon.

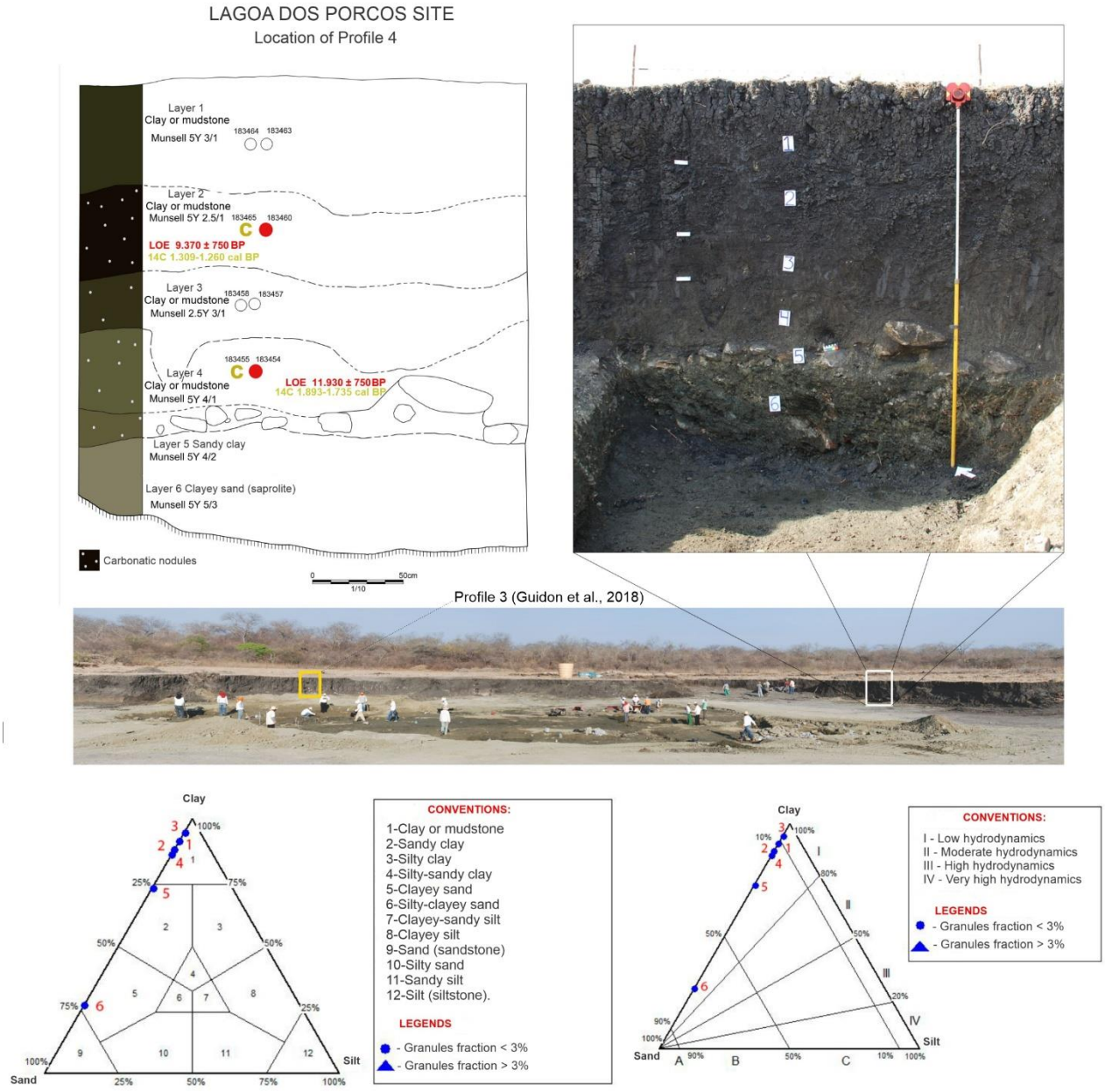

Figure 18. Synthesis of sediment analysis of profile 4, Lagoa dos Porcos site. **Source:** the authors.

4.2. Geochronological characterization

The samples from layers 2 and 4, with depths of 85 cm and 160 cm from the surface, respectively, were subjected to Optically Stimulated Luminescence (OSL) dating, resulting in ages of 9,370 ± 750 years BP and 11,930 ± 750 years BP (Figure 18 and Table 4).

Table 4. Correlation of sedimentological, geochronological and vegetation data obtained for stratigraphic profile 4.

	Sample	Depth (cm)	OSL Age (sediments)	Radiocarbon age (carbonate nodules)	$\delta^{13}C$ Vegetation (carbonate nodules)
Profile 4	**Layer 2**	85	9,370 ± 750 BP	1,309 - 1,260 cal BP (Beta-632446)	-9,2 (C4)
	Layer 4	160	11,930 ± 750 BP	1,893 - 1,735 cal BP (Beta-632447)	-11,8 (C4)

Source: the authors.

Layer 2, dated at 9,370 ± 750 years BP (Figure 18 and Table 4), lower Holocene, corresponds to an extremely poorly sorted clayey sediment with very positive asymmetry and very platykurtic kurtosis. In turn, layer 4, dated at 11,930 ± 750 years BP (Figure 18 and Table 4), was deposited in the Pleistocene/Holocene transition and, like layer 2, refers to an extremely poorly sorted clayey sediment with very positive asymmetry and very platykurtic kurtosis.

Regarding depositional processes, the ages of 11,930 ± 750 years and 9,370 ± 750 years BP obtained for the Lagoa dos Porcos site demonstrate different depositional moments with an interval of approximately 2,560 years between the dated layers, related to the Pleistocene/Holocene transition and the lower Holocene, respectively.

The ages of 1,950 ± 60 years BP (OSL) from layer 1, 7,430 ± 40 years BP (Radiocarbon) from layer 3, and 17,000 ± 500 years BP (OSL) from layer 5 obtained by Guidon et al. (2018) for the Lagoa dos Porcos site (profile 3), added to the new chronologies obtained in this research (profile 4), demonstrate chronostratigraphic coherence regarding the depositional sequence analyzed and reinforce that the lake's accommodation space was filled from the Last Glacial Maximum (LGM) to the upper Holocene.

Also, the stratigraphical characteristics of Lagoa dos Porcos are similar to those of other shallow lakes studied in the region. It is possible to correlate the occurrence of carbonate nodules and concretions in the sedimentary deposit with similar evidence from the Rasa, Arroz, Alegre, Adamastor, and Sobrado lakes studied by Mendes (2016) and also in Lagoa do Quari studied by Parenti et al. (2021). In Lagoa dos Porcos, specifically in stratigraphic profile 4, hardened carbonate nodules evolved to form a calcrete layer.

The nodular calcretes present in stratigraphic profile 4 made it possible to use the radiocarbon technique to verify the chronology of the carbonation process. Ages of 1,309-1,260 years cal BP (Beta-632446) were obtained for layer 2 and 1,893-1,735 years cal BP (Beta-632447) for layer 4 (Figure 18 and Table 4). Thus, calcrete formation at this site is related to the recent Holocene, reflecting the current semi-arid climate established in the region.

In the Lagoa dos Porcos stratigraphic section, the presence of carbonate nodules demonstrates the formation of a type of calcrete related firstly to the precipitation of calcium carbonate in the host sediment and secondly to the circulation of both groundwater and rainwater, which generates a combination of downward movements due to percolation hindered by the presence of clay and upward movements due to capillarity (Alonso-Zarza, 2003). The association of the different factors that generated the nodular calcrete is a consequence of the seasonality of the semi-arid environment, which alternates between periods of saturation of the environment by water and high evapotranspiration. The carbonation analyzed occurred *pari passu* with the pedogenetic processes that led to the evolution of a vertisol at the top layer of the shallow lake.

The deepest layers of profile 4 are formed of coarser sediments, with pebbles, blocks, cobbles, and boulders, indicating transport and deposition under torrential conditions. Subsequently, fine sediments in moments of attenuated hydrodynamics were deposited by decantation in still or slow-moving waters influenced by surface runoff. In turn, the formation of nodular calcrete marks the occurrence of a pedogenetic process under a semi-arid climate similar to the current one.

4.3. Vegetation characterization

The analysis of carbonate nodules also allowed data to be obtained to characterize the vegetation of Lagoa dos Porcos. The values obtained from carbon isotope analyses ($\delta^{13}C$) were -9,2‰ for layer 2 and -11,8‰ for layer 4 (Table 4). These results indicate the presence of plants with a C4 photosynthetic cycle, characterized by grasses reflecting an open vegetation environment and a hot climate, related to the recent Holocene, reflecting the current semi-arid climate established in the region.

4.4. The formation of the paleontological and archeological records

Regarding the formation of the paleontological and archaeological records for Lagoa dos Porcos, using the information on the paleofauna from Guidon et al. (2012), Guérin and Faure (2013, 2014), and Mayer, Kerber, and Ribeiro (2013), the archaeological data from Guidon et al. (2018), coupled with taphonomic information from other semi-arid shallow lake and fluvio-lacustrine environments (Conybeare e Haynes, 1984; Fillios et al., 2010; Wiest et al.,2016), and data obtained from the present research, an interpretative proposal in the form of a summary was put forward.

The fossilized bones of the paleofauna occur in the deepest layers (layer 5) in contact with the saprolite developed on the gneiss (layer 6). These would have been deposited in periods prior to 17,000 years ago, according to Guidon et al. (2018). The bones also appear in the same layer, where some pebbles, cobbles, blocks, boulders, and lithic pieces were found (Figures 6, 7 and 19 to 21). The sedimentological context shows that high-energy torrents transported those materials. The occasional quartzite boulders, as well as the larger clasts, floating within a finer matrix, also demonstrate the occurrence of gravitational flows similar to those associated with the Quaternary colluvial deposition already widely recognized elsewhere in the semi-arid Northeast (Carvalho et al., 2024; Fonsêca et al., 2020; Mutzenberg et al., 2013).

Figure 19. Paleofauna fossilized bones and coarse sediment (gravel) within the same depositional layer. **Source:** Fumdham collection.

Figure 20. Lithic remain (red square) in the same layer as the paleofauna bones. **Source:** Guidon et al, (2018).

Figure 21. Rounded Boulder at the base of layer 5. **Source:** Felice (2010).

The clasts and bones of the paleofauna appear in concentrations forming clusters (Figures 22 and 23) in different areas at the base of layer 5, and in the transition to the top of the saprolite, where the the presence of bones is discontinuous, thus indicating restricted deposition. This fact demonstrates a modulation of the hydrodynamics controlled by the topographies of the bottom and margin of the Lake. It is also related to the presence of outcrops of more resistant gneisses, which would not have allowed uniform deposition, acting as obstacles, sometimes directing and intensifying the competence of the transport flow, sometimes reducing its energy and favoring deposition over shallow pools or gentle depressions of the Lake's paleo-topography. The base of the Lake could

have been stepped initially, which accounts for the unevenness that trapped the sediments, but the intensification of saprolitization changed this morphology.

Figure 22. Clusters of paleofauna bones. **Source:** Fumdham collection.

Figure 23. Clusters of paleofauna bones. **Source:** Fumdham collection.

As for the source area of the bones, pebbles, blocks, boulders, and archaeological material, it is proposed that they came from the immediate surroundings, characterized by the surfaces of the pediment ramps and the remnants of ancient terraces (Figure 2).

Information from previous studies (Guidon et al. 2012; Guérin and Faure 2013, 2014 and Mayer, Kerber, and Ribeiro, 2013) associated to the taphonomical characterization of shallow-lakes allows us to propose that bones of animals that died in different periods were transported together, probably from the sectors of the pediment surfaces and terraces where the skeletonized animals would have been exposed to the elements for a certain period. In these same areas, animals that died in later periods or were still alive would have been dragged into the Lake during exceptional torrential rain events, thus generating taphonomic differentiations of integrity, fragmentation, abrasion, and articulation.

The history of the formation of the paleontological record can be summarized as follows: the weathering paleo-depression has acted as aggradation and driving area for the deposition of paleofauna bones and clasts, while the shallow pools within the larger paleo-depression served, in turn, as traps for the concentrated deposition of bones. Subsequently, the accommodation space of the shallow lake was filled by gravitation flows and siltation, leading to the inhumation of the paleofauna.

Regarding the formation of the archaeological record, most of the lithic pieces associated with paleofauna and other clasts showed rounding in the chipping scars and neocortex formation (Figure 24 and 25), demonstrating both antiquity and evidence of transport and abrasion.

Figures 24 and 25. Lithic remains found in the same depositional layer as the paleofauna. **Source:** Fumdham collection.

Probably the ancient archaeological sites on the terraces and banks of the Lake would be the places of origin of these lithic pieces deposited in the deeper layers, where the bones of the paleofauna are also found. According to Guidon et al. (2018), these paleontological and archaeological remains were buried by the same sediments from layer 5, dated at 17,000 years BP. In this way, the Pleistocene sites around the Lake would have been established before 17,000 years, reinforcing the antiquity of human occupation in the region (Guidon and Delibrias, 1986; Parenti, 2001; Felice, 2002; Melo, 2007; Lahaye at al. 2013; Aimola et al. 2014; Boeda et al. 2014a; Boeda et al. 2014b; Boeda et al. 2016; Lourdeau, 2019).

Analyzing the stratigraphic sequence starting from the base of the profile towards the surface, layer 4 superimposed on the deposit with clasts, paleontological and archaeological materials presents a deposition chronology of 11,930 ± 750 years BP, followed by layer 3 without verified chronology, which was buried by layer 2 sediments dated to 9,370 ± 750 years BP. This ca. 9,000-year-old layer, in turn, was covered by a dated deposit during research by Guidon et al. (2018) in 1,950 years BP. This most recent deposition layer coincides with the presence of lithic materials on its surface and within its first 15 cm. These archaeological remains were also associated on the surface and subsurface with pebbles and stones, mostly of quartz and, less frequently, flint.

The presence of these materials at the top of the stratigraphic profile demonstrates that they were displaced, from the surrounding area, by colluvium in association with rainfall events that increase the dynamics of gravitational flows under semi-arid pene-contemporary conditions, having been carried with the other clasts from the ancient terraces to the surface of Lagoa dos Porcos, and later incorporated into the top of layer 1. The desiccation cracks formed in the vertisol probably contributed to this. Therefore, it is possible to propose that, for the studied area, the Holocene sites with chronologies later than 9,000 years ago would have been established on the terraces and adjacent rocky ramps when events occurring after 1,950 years BP would have displaced the materials to the surface of the Lake.

Human occupations surrounding the Lagoa dos Porcos environment were directly related to the existence of water resources and the presence of fauna and flora suitable for human subsistence, as well as paleofauna animals. From the middle Holocene onwards, with the recrudescence of semi-aridity, the Lake was most likely used as a refuge by human groups on a seasonal basis during the short periods when the rains supplied it.

Material input into the Lake, combined with erosion processes, have destroyed or altered the characteristics of the ancient terraces, with only a few depositional levels remaining around the lake. Human activities since the historical occupation of the area, including the construction of houses, the opening of roads and paths, planting of crops, grazing, and livestock farming, have intensified the impacts and disturbed the possible remaining prehistoric sites.

5. Final remarks

The data obtained from this research served as a reference for preparing an initial proposal on the chronologies of deposition, paleoenvironmental events, and the formation of the paleontological and archaeological record of Lagoa dos Porcos.

Figure 26 below summarizes the main data obtained in this research, together with the existing data, emphasizing the chronologies available for the formation of the deposits and for the paleontological and archaeological record.

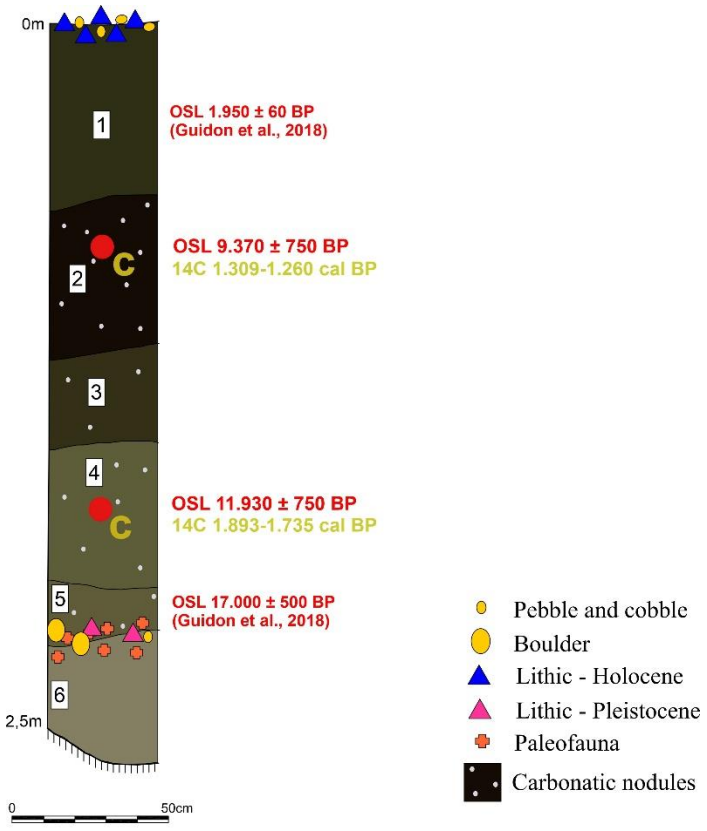

Figure 26. Composite stratigraphic profile for Lagoa dos Porcos. **Source:** the authors.

In order to interpret the geomorphic and stratigraphic findings of this research, it is crucial to bear in mind that Quaternary sedimentation in the lowland tropics is recognized as time-dependent (Thomas and Thorp, 1995; Thomas and Murray, 2001; Thomas, 2008). Although depositional landforms provide, at best, incomplete, truncated environmental data, they still convey valuable information about the operation of surface processes under a given set of climatic triggers. As recognized by the literature on the Quaternary geomorphology of Northeast Brazil, the latter responds to large-scale atmospheric circulation forcings, often linked to climatic

teleconnections with events initiated elsewhere on the planet operating either cyclically or stochastically in various timescales (Bezerra et al., 2008; Gurgel et al., 2013; Fonsêca et al., 2020; Lima et al., 2021; Listo et al., 2023; Fonsêca et al., 2024).

The chronostratigraphy of the Lagoa dos Porcos site shows that the onset of the paleontological and archaeological record relates to torrential events that occurred around 17,000 years ago. Subsequently, the shallow lake holds information reflecting at least three deposition periods. One period related to the Pleistocene/Holocene transition occurred around 11,000 years ago, and another dated around 9,000 years ago, probably related to the Climatic Optimum. The conditions of the sedimentation environment related to these two chronologies reflect periods of input of fine sediments from the surrounding area under conditions of moderate water availability. Human occupation could have occurred during these periods in the area surrounding the Lagoa dos Porcos.

The latest information available on the chronology of deposition of the shallow lake reflects the third period established at a recent age of approximately 1,900 years for the input of sediments, which indicates an environment with moderate to low water availability. On the surface of this deposition, the clasts and lithic pieces that appear would have been carried into the lake, indicating that gravitational flows and surface runoff were the primary agents, with these materials coming from the surrounding area and from ancient sites established on the terraces and on the banks of the Lake itself. Carbonate precipitation chronologies of 1,309-1,260 years cal BP and 1,893-1,735 years cal BP demonstrate the continuous carbonation process during prevailing semi-arid conditions similar to the present.

The absence of well-defined depositional chronologies for the sedimentary fillings at the Lagoa do Quari site, also situated in the proximity of the Serra da Capivara National Park, precludes a comprehensive comparison and analysis of depositional chronological data from these very similar physiographic contexts. However, comparisons can be drawn with the Lagoa Uri de Cima site, located approximately 300 km to the east in Pernambuco. At this site, sandy sediments deposited through gravitational flows during torrential conditions have covered paleontological remains, including vertebrate bones and some lithic artifacts. These sediments have been OSL dated to approximately 18,600 ± 2,300 years BP, making them roughly contemporaneous with the 17,000-year BP layer that overlays the paleontological and archaeological contexts at Lagoa dos Porcos. In light of this information, it becomes feasible to establish regional, chronological comparisons with paleoenvironmental and climatic implications, utilizing data from at least two other shallow lakes (Mendes, 2016) as well as various depositional landforms (Mutzenberg, 2010; Galvão, 2019), for which analogous chronologies have been documented.

Surveys were conducted at Lagoa Rasa and Lagoa Dona Catarina, located approximately 6 and 4 km from Lagoa dos Porcos, respectively. Nonetheless, no archaeological or paleontological remains were identified. The exposed stratigraphic profiles were 2.3 and 1.4 meters thick. The sandy layers at the base of the profiles were OSL-dated, rendering depositional ages of 17,300 ± 1,600 years BP for Lagoa Rasa and 17,900 ± 2,400 years BP for Lagoa Dona Catarina. These ages coincide with Lagoa dos Porcos' basal layer and are attributed to the increased frequency of torrential episodes during the HS1 climatic event (Mendes, 2016).

In the Boqueirão da Pedra Furada valley region, Mutzenberg (2010) reported an age of 11,700 ± 1,700 years BP for layer 7 of vertical section DBPF01 (2.9 m depth) and 11,300 ± 1,300 years BP for layer 4 of vertical section DBPF03 (2.8 m depth). These depositional events were interpreted as outcomes of intense rainfall associated with climatic events at the onset of the Pleistocene/Holocene transition. Complementarily, Galvão (2019) investigated colluvial sediments from the archaeological sites Toca do Gongo III, Toca da Janela da Barra do Antonião, and Toca do Gordo do Garrincho, yielding results that aligned closely with those of Mutzenberg (2010) and the present study. The depositional chronologies established for these sites are as follows: Toca do Gongo III, with an age of 11,770 ± 2,740 years BP at a depth of 160 to 170 cm; Toca da Janela da Barra do Antonião, with an age of 11,700 ± 1,400 years BP at a depth of 30 to 40 cm. The authors linked these ages to the Younger Dryas period, characterized by conditions that facilitated the generation of mud and debris flows due to increased precipitation. In contrast, for the Toca do Gordo do Garrincho, an age of 9,500 ± 1,780 years BP was determined at a depth of 120 to 130 cm, which is associated with the Lower Holocene Climatic Optimum.

From the depositional chronologies listed for the different geomorphological environments of the Serra da Capivara region, the importance of the depositional events that occurred 17,000, 11,000, and 9,000 years BP becomes evident, as they were recorded in the stratigraphic sequences of the archaeological and paleontological sites, in environments as diverse as shallow lakes, colluvial deposits in sandstone and karst shelters and alluvial fans confined in canyons and gorges of the drainage network of the cuesta front.

The refinement of the findings and the search for new data on the formation of Quaternary deposits and on the formation of the paleontological and archaeological record are still necessary, as they may generate more information on the paleoenvironmental contexts and human occupation, increasing knowledge about these contexts for the southeast of Piauí, and on the long term interaction between human groups and the semi-arid environment of the Northeast of Brazil.

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