Virtual micromorphology: The application of micro-CT scanning for the identification of termite mounds in archaeological sediments

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ARTICLE INFO

Keywords:
Microarchaeology
X-ray micro-computed tomography
Lagoa Santa
Lapa do Santo
Earth ovens
Geoarchaeology

ABSTRACT

X-ray micro-computed tomography (micro-CT) scans were conducted on impregnated sediment blocks from the early Holocene rockshelter site of Lapa do Santo, East-Central Brazil. The analysis was designed to investigate the presence of termite mound fragments in the archaeological sediments and test the value of complementary techniques in micromorphological studies. Soil feeding termites have been common in the tropical soils of Central Brazil since the Paleogene/Neogene and exist in high concentrations in the surroundings of Lapa do Santo. The micro-CT scans revealed a distinctive spongy microstructure inside some of the clay aggregates in the sediments that are not visible in thin section, matching the spongy microstructure inside termite mound fragments. The microstructure consists of a mix of clay and organic material (feces, saliva and other body fluids) produced by termites to cement the mounds’ matrix. The cements are undistinguishable from the matrix under the microscope, but clearly visible in the micro-CT scans given the low attenuation coefficient of organo-mineral matter. The termite mound fragments appear dispersed within the ashy matrix (made of intact and reworked combustion features), suggesting their possible use in earth ovens. The combination of combustion features and reworked earth ovens attests to the complex input of anthropogenic sediments in the formation of Lapa do Santo. This study demonstrates that micro-CT can potentially disclose materials not visible in thin section and can be utilized as a complementary technique to micromorphology.

1. Introduction

Archaeological science is constantly incorporating new techniques to increase the resolution of data. X-ray micro-computed tomography (micro-CT) has been recently proposed as a high-tech, complementary technique to overcome some limitations of thin section analyses in petrographic and micromorphological studies, (Baker et al., 2012; Bendle et al., 2015; Edwards et al., 2017; Gualda and Rivers, 2006; Ngn-Tillard et al., 2016; Ngn-Tillard and Huisman, 2017; Ward and Maksimenko, 2019). Micro-CT is a common method in paleoanthropology, frequently used to scan human bones (Scherf, 2013; Weber and Bookstein, 2011) and to study the internal structure of diminutive anatomical features such as dentition (e.g., Le Cabec et al., 2013; Skinner et al., 2008), trabecular bone (e.g., Scherf et al., 2015; Skinner et al., 2015), bony labyrinth (e.g., Gunz et al., 2012), and the ossicles of the middle ear (e.g., Stoessel et al., 2016).

Micro-CT can complement the geoarchaeological investigation of archaeological deposits expanding traditional micromorphological analyses in different ways by (Adderley et al., 2001; Huisman et al., 2014; Ngn-Tillard and Huisman, 2017; Ward and Maksimenko, 2019): 1) enabling observation of the micromorphology of archaeological sediments in three dimensions; and 2) providing information on the thickness, density and elemental composition of sediment components—in terms of micro porosity and atomic number. However, micro-CT scanning is still an expensive technique when the equipment is not available to use in scientific collaboration, and there is still little literature on the geoarchaeological interpretation of results (i.e., for site formation processes analyses, identification of activity areas, site taphonomy, among others).

Despite the recent use of micro-CT scanning in geoarchaeology, the technique has long proven its value in the earth sciences (see reviews in Carlson, 2006 and Gudde and Boone, 2013). Micro-CT has been commonly used for the three-dimensional visualization of sedimentary components, in studies dealing with: the texture and porosity of sediments and rocks (Baker et al., 2012; Bendle et al., 2015; Carlson et al., 2000; Gualda and Rivers, 2006; Ketcham, 2005; Kilfeather and van der
Meer, 2008; Landis et al., 2000; Tarplee et al., 2011; Voltolini et al., 2011); three-dimensional petrography (Van Geet et al., 2001); soil studies (see review in Taina et al., 2008); conservation of buildings (Cnudde et al., 2004; Rozenbaum, 2011); analyses of archaeological artifacts (lithics, ceramics, bone, ostrich eggshells, antler and wood objects) (Abel et al., 2011; Bello et al., 2013; Bugani et al., 2009; Haneca et al., 2012; Kahl and Ramminger, 2012; Mcbride and Mercer, 2012; Mizuno et al., 2010; Ngan-Tillard et al., 2016; Yanget al., 2018); plant remains in the archaeological context (Coubray et al., 2005); and midden composition (Adderley et al., 2001; Huisman et al., 2014; Ward and Maksimenko, 2019).

In this study, we conducted the micro-CT scanning of impregnated blocks of sediment from the archaeological site of Lapa do Santo (Minas Gerais, East-Central Brazil) (Fig. 1) to investigate the presence of an intriguing component initially identified through micromorphological analyses – termite mound fragments described in the early Holocene levels (Villagran et al., 2017). Termite mounds are ubiquitous features in central Brazil and have existed in the area for millions of years (Sarcinelli et al., 2009; Schaefer, 2001). Particularly in the surroundings of Lapa do Santo, almost 300 termite mounds were mapped during the field season of 2014 (Villagran et al., 2017).

Inner galleries with smooth, curved walls are the most diagnostic features of termite mound fragments compared to blocky aggregates of local oxisol (Fig. 2A and B). In a study on the characterization of termite mounds from Minas Gerais built by termites of the genus Cornitermes, Sarcinelli et al. (2009) describe slight differences in microstructure and composition between the termite mounds and the oxisol. The walls of termite mound fragments have massive microstructures made of microaggregates welded with yellowish, striated cements made of the termites’ body fluids. When weathering takes place, the microaggregates are loosened and the microstructure becomes similar to the oxisol.

Termites build their mounds by ingesting and transporting soil material in their gut or mandibles, mixing it with excrements, saliva and other body fluids (Brauman, 2000; Cosarinsky and Roces, 2007; Jungerius et al., 1999; Lee and Wood, 1971; McBrearty, 1990). This incorporates the ingestion and transportation of organic material in the soil to build the mounds, resulting in an enrichment of carbon, nitrogen and phosphorus (Brauman, 2000; McBrearty, 1990; Sarcinelli et al., 2009; Watson, 1967).

Although macroscopic shape is the most diagnostic feature to distinguish between soil aggregates and termite mound fragments, it can be disguised by the random cutting of blocks for thin sectioning and may not be so evident in small-sized fragments. In this sense, the volumetric data obtained by micro-CT scanning facilitate the three-dimensional visualization of the characteristic shape of termite mounds. At the same time, the technique can potentially reveal the distribution of the organic material cementing the microaggregates in the mound matrix. Organic materials have lower density and lower atomic numbers than the clay and iron oxides that termites burrow from the oxisol to build the mounds.

To search for termite mound fragments in the sediments from Lapa do Santo we used the same impregnated blocks for micromorphological analyses. By observing the three-dimensional distribution of materials inside the blocks at the micrometric scale, we achieve a different insight into the composition of the sediments and overcome some of the limitations of micromorphology.

2. Termite mounds in the archaeological record of Lapa do Santo

The site of Lapa do Santo, located in the karstic region of Lagoa Santa (State of Minas Gerais, East-Central Brazil), was occupied during three different chronological periods: 12.7–7.9 cal ky BP, 5.4–3.9 cal ky BP and 2.1–0.0 cal ky BP (intervals of 95.4%) (Strauss et al., 2016). A total of 40 human burials have been recovered from this rockshelter, mostly stacked in the first meter of sediment in a deposit that can reach up to five meters in depth. The interments from Lapa do Santo represent one of earliest and most intriguing well-documented funerary practices in the Americas, shifting from single primary burials to include dismemberment of the bodies, decapitation and amputation.
by the early Holocene (Strauss et al., 2015, 2016). The sedimentary matrix is made of ashes from hearths lit in the proximities of the burials (Fig. 1C). Geogenic sedimentation was the second most significant source of material, with unsorted soil aggregates falling into the rock-shelter from the red oxisol developed on the limestone cliff. The hearths at Lapa do Santo are both intact and remobilized and their proximity to the interments suggests that fire was essential in the ritual behavior of the early Holocene settlers (Villagran et al., 2017).

The soil aggregates found in the sediments at Lapa do Santo show a diversity of colors under the microscope (e.g., red, orange, yellow and brown) (Fig. 3A–D) and most show signs of heating above 500–600 °C. The micromorphological study coupled with μFTIR analyses (a microscope coupled with a Fourier transform infrared spectrometer) showed that red soil aggregates are commonly non-heated, while orange, yellow and brown aggregates are always heated (Villagran et al., 2017). Yellow, orange and brown-colored aggregates showed micromorphological resemblance to heated termite mound fragments used in an experimental hearth lit on the red oxisol near the site (Fig. 2C–H). Both the termite mound fragments used in the experiment and the heated soil aggregates in the thin sections from Lapa do Santo share the following attributes: massive and sometimes striated yellow, orange or brown microstructures with lower order interference colors (Fig. 3A, C and D); color gradients from bright orange to yellow and brown to yellow (Fig. 3A, Fragment 3); and occasional red rims. In some cases,
resemblance in shape with termite mound fragments were already seen in the thin sections (e.g., aggregates with curved smooth walls similar to mound galleries) (Fig. 3A, Fragment 1) (Villagran et al., 2017). All this evidence pointed at the possibility that fragments of the ubiquitous termite mounds may be present in the archaeological sediments and may have been used by the prehistoric inhabitants of Lapa do Santo.

3. Materials and methods

Computerized tomography (CT) allows the virtual three-dimensional reconstruction of external and internal structures including information on density. A sequence of radiographs taken at distinct angles (a.k.a. sinograms) are obtained with x-rays and transformed through mathematical algorithms into a stack of two-dimensional matrices of pixels coding for x-ray intensity that are axially oriented and equally spaced (i.e., a CT scan) (Bushong, 2012).

Each sinogram is created by a polychromatic range of x-rays that is produced by the impact of an electron beam, generated through thermionic emissions and accelerated by a high electric potential difference (kVp) into a rotating tungsten target (Johns and Cunningham, 1984). Depending on the resistance of the constituent material (i.e., the attenuation coefficient), which is a positive function of density and atomic number, the object is differentially transposed by x-rays of varying energetic levels (Chhem and Brothwell, 2008). A digital image receptor, consisting of an orthogonal mesh of individual detectors made of scintillating materials, receive the x-rays and record their relative intensity (Ketcham and Carlson, 2001). The sensitivity, density and size of individual detectors are key components in determining the final resolution of the tomography.

The angular and translational variation necessary to obtain the sequential sinograms is achieved by the mechanical dislocation either of the object or the source/receptor pair, and the final resolution is a direct result of the intervals adopted (Scherf, 2013). The mathematical process through which several sinograms are transformed into a CT scan is known as “reconstruction” (Ramachandran and Lakshminarayanan, 1971). Ideally, the resulting data are a three-dimensional map of linear attenuation coefficients that could inform on density. Nevertheless, caution is needed for interpretation since the energy of the x-rays reaching the receptor is also affected by extrinsic factors (Davis and Elliott, 2006; Ketcham and Carlson, 2001) such as: 1)
the range of emitted x-rays (increases with higher kVp); 2) the energy of emitted x-rays (increases with higher mA); 3) the relative distance of the x-ray source, the object and the receptor; 4) the thickness of the object; 5) the absolute size of the focal spot (phantom structures); 6) the resolution of the receptor (partial volume effect); and 7) the progressive energy increase during transposition (i.e., beam hardening).

In this work, we performed the micro-CT scanning of archaeological and reference samples to verify the possible presence of termite mound fragments in the sediments of Lapa do Santo. The location of the archaeological samples in the excavation is shown in Fig. 1D. Both archaeological samples (LDS-12-1 and LDS-12-8) were collected from the early Holocene level (10.15–9.70 cal ky BP, Oxford-31,014). A fresh, non-impregnated soil aggregate from natural deposits was also scanned using micro-CT to serve as a reference for the identification of oxisol aggregates. Two non-impregnated heated termite mound fragments from the experimental hearth were also scanned to compare with the material identified in the archaeological sediments. Micro-CT scans from reference and archaeological samples could reveal the two diagnostic features of termite mounds that are not always evidenced by micromorphology: the characteristic shape, with galleries and smooth, curved walls; and the organic material cementing the microaggregates.

The two archaeological samples and the oxisol fragment used in this study were scanned with a BIR ACTIS 225/300 high-resolution CT system at the Department of Human Evolution, Max Planck Institute for Evolutionary Anthropology (Leipzig, Germany). The system counts with a microfocus x-ray tube with a maximum acceleration voltage of 225 kV and a detector with 1920 × 1536 pixels. The two termite mound fragments were scanned with a SkyScan 1176 Bruker micro-CT at the Department of Genetics and Evolutionary Biology, University of São Paulo (São Paulo, Brazil). Table 1 contains the main scanning parameters used in this study.

The resulting micro-CT scans were processed in AVIZO 7.1 (Visualization Science Group) for visualization. For general visualization, the volume rendering method was applied (VolRen) in which the points of the data volume are assumed to emit and absorb light as a direct function of their corresponding scalar data. Additionally, slices orthogonal to the three larger dimensions of the samples, mimicking traditional micromorphological thin-sections, were obtained by mapping the CT values into gray levels by a contrast limited histogram equalization technique that was manually adjusted for optimal visualization. Based on the slices, a video was rendered showing a complete screening of each of the three main dimensions of the samples. No filters were applied because the quality of the scans was sufficiently good. Downsampled versions of the micro-CT scans used in this study are available for download in Strauss et al. (2019). The raw data is available upon request.

4. Results

Fig. 4 and Video 1 show the micro-CT scan of the oxisol fragment. The grayish matrix comprises micro-aggregates of clay with various root and faunal channels. The light gray blocky aggregates dispersed within the gray matrix are made of dense and cohesive clay. These are more stable aggregates not affected by bioturbation. Rock fragments are identified by bright white colors.

The micro-CT scan of two termite mound fragments show the distinctive inner galleries with smooth, curved walls, both in the three-dimensional image and the slices (Fig. 5; Videos 2 and 3). Different from soil aggregates, the surface of the termite mound fragments is made of fused pellets, something not visible in the thin sections. The walls are usually dense, without porosity, while the inner section of the termite mounds revealed what seems to be a spongy and porous, black microstructure in-between welded, gray and rounded microaggregates. This peculiar type of microstructure is not visible in the micro-CT scan of the natural soil (Fig. 4, Video 1). A similar type of microstructure is observed in the thin sections from the termite mound fragments (Fig. 2C, D and H). However, the size of the supposed pores in the spongy microstructure seen in the CT scan of the termite mounds (Fig. 5) is larger than the actual voids (the micromorphological term for pore) in the thin sections (Fig. 2C, D and H). In this respect, one has to bear in mind that with micro-CT it is impossible to know whether the black texture is made of actual pores, as in spaces filled with air within the matrix, or a type of organic material with a very low attenuation coefficient (or both).

The micro-CT scan of an impregnated sediment block from Lapa do Santo (sample LDS-12-8) shows the recurrent presence of a material with the same spongy, black microstructure seen in the micro-CT scan of the termite mound fragments (Fig. 6B–E; Video 4). This same microstructure was not observed in the thin sections produced from the same block (Fig. 3), and nothing similar was described in the micromorphological analyses of Lapa do Santo (33 thin sections from different levels and locations in the site were analyzed by Villagran et al., 2017). Finally, some of the clay aggregates in the micro-CT scan of Sample LDS-12-8 display a peculiar shape and massive microstructure, similar to the walls of the inner galleries of termite mounds (Fig. 6B–F).

Differences in the micromass within Sample LDS-12-8 are also evidenced by contrasting attenuation coefficients in the CT scan (seen as different shades of gray), and correspond to the microfacies described in micromorphological analyses (Figs. 3A and 6B–D). Microfacies 1 (mF 1) is made of ash crystals and silica phytoliths embedded in a phathic matrix (Fig. 3E and F), and Microfacies 2 (mF 2) contains closely packed ash crystals with blocky clay aggregates of different sizes.

The micromorphology of Sample LDS-12-1 is slightly different from Sample LDS-12-8. It contains an area of carbonate cementation across the middle part of the thin section (Fig. 7A–D). Outside the cemented area, the micromass is similar to Sample LDS-12-8, consisting of ash crystals and clay aggregates of diverse sizes. Clay aggregates are widespread in the thin section, most of them are heated (according to the results of Villagran et al., 2017) and some of the heated aggregates show an internal porosity similar to the termite mounds (Fig. 7A, B, E and F).

The thickness of the resin in Sample LDS-12-1, combined with the energy properties of the x-ray beam, compromised the resolution of the micro-CT scan. Nonetheless, the carbonate cement is visible as an area of lighter color in the three-dimensional image (Fig. 8A; Video 5) and as a white zone with sharp boundaries with the remaining gray matrix in the slices (Fig. 8B–D). Inside the gray matrix a few shadows of mostly dense clay aggregates are visible, but the low resolution of the CT scan compromised their clear visualization (Fig. 8B–D).

5. Discussion

The presence of termite mound fragments in Lapa do Santo was first suggested by the micromorphological study. Some of the heated clay aggregates in the site were similar to termite mound fragments in color, microstructure and, in a few cases, shape (with smooth, curved edges). The micro-CT scan of a block of sediment (Sample LDS-12-8) revealed a component with an unusual spongy microstructure not visible in the thin sections. The same type of microstructure is present in the micro-CT scan of termite mound fragments, suggesting they could be part of the archaeological sediments. Oxisol aggregates are dense in the micro-

<table>
<thead>
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<th>Sample</th>
<th>Equipment</th>
<th>Voxel size (mm)</th>
<th>Xray Kv</th>
<th>Xray Ma</th>
<th>Xray Filter</th>
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<td>Oxisol</td>
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<td>130</td>
<td>0.10</td>
<td>0.5 mm Brass</td>
</tr>
<tr>
<td>LDS-12-1</td>
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<td>0.063957</td>
<td>160</td>
<td>0.11</td>
<td>1.0 mm Brass</td>
</tr>
<tr>
<td>LDS-12-8</td>
<td>BIR</td>
<td>0.063957</td>
<td>130</td>
<td>0.10</td>
<td>1.0 mm Brass</td>
</tr>
<tr>
<td>Termite Small</td>
<td>SkyScan</td>
<td>0.008710</td>
<td>65</td>
<td>0.385</td>
<td>Al 1 mm</td>
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<tr>
<td>Termite Large</td>
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CT scan, and do not show the same spongy microstructure as the termite mounds and the unknown material in the archaeological sample.

The black areas in the spongy microstructure could either be pores filled with resin or a type of low-density organic material with low attenuation coefficient. In both cases, the micro-CT scan discloses a black color. If the black, spongy areas were indeed pores, filled with air in the sediment and with resin in the impregnated block, then the same type of porosity should be observed in the thin sections, which does not happen. Consequently, the black, spongy microstructure could in fact consist of organic material.

Termites ingest litter and organic particles in the soil (e.g., leaves, grass) creating stable organo-mineral, clay-humic complexes (Brauman, 2000). The feces and saliva play the role of cement, holding the organo-mineral complexes stable inside the microaggregates in the mound galleries (Brauman, 2000). Clay minerals are also altered after ingestion by termites or reworking in their mandibles, becoming less crystalline (Schaefer, 2001). In the termite mounds from Minas Gerais, the mix of low crystallinity clay minerals with minute particles of organic matter and termite feces is observed in thin sections as yellowish, striated cement bridging microaggregates (Sarcinelli et al., 2009).

The material cementing the microaggregates in the fresh termite mound fragment is not visible in thin sections (Fig. 2D). This may be due to the composition of the cement, which consisted of a mix of clay and organic matter (Cosarinsky and Roces, 2007; Sarcinelli et al., 2009) with the same appearance and b-fabric as the microaggregates it binds together. However, when the termite mound fragments are heated some parts become charred, unveiling a black organic material inside the fragments (Fig. 2E and F). A closer look at a yellowish, termite mound fragment heated at low-temperature shows the existence of a fibrous, light yellow coating that is also dispersed within the seemingly massive microstructure (Fig. 2G). In a termite mound fragment heated at higher temperature there are only minute traces of the fibrous material and the voids are larger, indicating the complete combustion of the organic cement (Fig. 3H).

This explains why none of the thin sections from Lapa do Santo showed the spongy porosity revealed in the micro-CT scan (i.e., the material cementing the microaggregates). In thin sections, the cement can be indistinguishable from the matrix of the termite mounds as both are mixtures of saliva, excrements and soil particles of fecal origin. The organo-mineral cement is visible under the microscope only when it is fully charred. Jungerius et al. (1999) conducted the micromorphological study of a termite mound from Kenya, and also report that the material used for cementing the microaggregates in the matrix (saliva, feces and other body fluids) is not visible in thin sections. Consequently, it was only with the aid of micro-CT and its ability to reveal low-density materials such as the organo-mineral cement that we could determine with a higher degree of certainty that termite mound fragments are present in the archaeological sediments.

Different parts of the termite mounds and nest show distinct micromorphology (Cosarinsky and Roces, 2007; Lee and Wood, 1971; Mermut et al., 1984). This explains why the fragments of termite mounds found in the sediments of Lapa do Santo do not have an identical micromorphology. For instance, gallery linings may show a fibrous microstructure made of clay and organic matter (see Lee and Wood, 1971, Fig. 16), similar to the brown aggregate in Fig. 3D. The outer walls of the mounds have massive microstructures made of cemented microaggregates (see Lee and Wood, 1971, Fig. 8; Cosarinsky and Roces, 2007, Fig. 6; Sarcinelli et al., 2009, Fig. 1), similar to the yellow aggregate in Fig. 3C.

This raises the question of how and for what proposes the early Holocene groups of Lagoa Santa may have used the termite mounds. Termite mounds are a common feature in the Cerrado landscape of Central Brazil and part of the daily lives of local indigenous communities. They are found in mythologies (Lévi-Strauss, 1970), used for medical purposes and as “hot rocks” in earth ovens for cooking (Costa Neto et al., 2006). The pre-colonial foragers of Central Brazil could have also built earth ovens using the termite mound fragments to preserve heat. Such cooking structures are well known worldwide, and consist of a layer of pre-heated materials (e.g., stones or clay) where food items are placed and covered by a layer of packed plant material or soil to

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Fig. 4. Micro-CT scan of an oxisol aggregate. Three-dimensional render and orthoslices xy, xz and yz. The reader is referred to Video 1 for the sequential orthoslices (YZ, XY and XZ orthoviews).
retain low temperature for long periods of time (Black and Thoms, 2014).

In the South American eastern lowlands, earth ovens are described among the Jê-speaking farmers, such as the ethnographic Xavante (Coelho, 2007), Xerente (Nimuendajú, 1942), Apinayé (Nimuendajú, 1939), Kayapó (Dreyfus, 1963), Krahô (Lévi-Strauss, 1970), Panará (Schwartzman, 1987) and Kaingang (Métraux, 1946). The colonial chronicles from the seventeenth century mention the use of earth ovens by non-Tupispeaking groups known as “Tapuyas”, possibly speakers of Jê languages (Maybury-Lewis, 1965). Features made of charcoal, burnt sediments and rocks were identified in recent pre-colonial archaeological sites (dated 1000–1500 CE) in areas where Jê-speaking groups have traditionally lived. In the south of Argentina they have been interpreted as the archaeological counterpart of the cooking techniques mentioned in the ethnographies (tríarte et al., 2008). Hunter-gatherers have traditionally used earth oven technology more than farmers. In fact, the oldest archaeological earth oven is dated 35–31 ky BP in Europe (Straus, 2006), and in America it is dated 10 ky BP (Black and Thoms, 2014).

A wide spectrum of materials can be used to build earth ovens (Thoms, 2017). Among the Jê-speaking groups of Central Brazil, earth ovens are usually built in a pit, but also on the soil surface (Fig. 9A and B). The heated material can be either rocks or fragments of the ubiquitous termite mounds. Ethnographic references only mention earthen ovens made of termite mounds built on the soils and not in pits. For instance, the Apinayé and Xavante prepare a maize cake that is wrapped in banana leaves, placed for cooking on heated termite mound fragments, and covered by ashes and soil to retain the heat (Fig. 9C–E) (Nimuendajú, 1939; Coelho, 2007).

Termite mounds are also used in other cooking structures. For instance, Welch (2015) describe the hunting trips of Xavante men who hollow termite mounds to use as stoves for preparing rice and coffee. Non-indigenous local communities of Minas Gerais have used the termite mounds as stoves since at least the nineteenth century (Freyreiss, 1907; Lima, 2015). In the countryside of the State of São Paulo, the termite mound fragments serve as grills or as a support for food placed over the fire or embers (De Souza, 1939).

The choice for termite mounds in different cooking structures is certainly related to their capacity to retain heat. Xavante women claim that termite mounds do not let the heat from the embers escape away (Coelho, 2007). The malleability and lightness of termite mounds, with thousands of air channels inside, may have also influenced their choice. Termite mound fragments can be more easily transported than stones to the areas for food preparation, where they will be used as earth ovens or as a cooking support for food.

At Lapa do Santo the fragments of termite mounds are found dispersed in the ashy sediments. This is consistent with the composition of the archaeological deposit, comprising reworked hearths with only a few intact combustion features. In this sense, the sediments at Lapa do Santo may include reworked earth ovens built with termite mounds as a heat source. Some of the reworked combustion features at the site may derive from what Black and Thoms (2014) referred to as “earth ovens.
facilities", or accretional accumulations resulting from the recurrent and cyclic use of earth ovens. This may explain the dispersed fragments of termite mounds, mixed with outstanding amounts of ashes in the deposit. We cannot however rule out the possibility that – at least partially – the termite mound fragments arrived as part of the geogenic soil aggregates falling from above the limestone cliff. The combination of multiple anthropogenic and geogenic inputs points at the complexity of site formation, involving the interplay of human and natural sources building the site for thousands of years.

6. Conclusion

The application of micro-CT scanning to study the three-dimensional distribution of components in archaeological sediments has been recommended to complement micromorphological studies (Huisman et al., 2014; Ngan-Tillard and Huisman, 2017; Ward and Maksimenko, 2019). In the early Holocene levels of Lapa do Santo, micro-CT scanning of undisturbed, resin-impregnated sediment samples revealed the presence of termite mound fragments in the deposit. The termite mound fragments look like common oxisol aggregates in the two-dimensional, micromorphological analyses. However, the micro-CT scan allowed the visualization of the pelletty surface and the organo-mineral cement in the termite mound matrix that is not readily visible in thin sections. Most of the termite mound fragments in Lapa do Santo are heated, and we interpreted them as part of ancient earth ovens. Several authors and ethnographies describe the use of termite mounds as a substitute for hot-rocks in earth ovens among the indigenous groups of Central Brazil.

This study contributes to the development of complimentary techniques in thin section analysis by introducing a novel application of micro-CT. Recent developments in geoarchaeology have stressed the need to combine micromorphology with complimentary techniques to enhance its resolution and interpretative potential. The combination of micromorphology with micro-CT scanning of blocks (i.e. virtual micromorphology) overcomes the limitation associated with the two-dimensional data of thin section analysis and revealed the presence of an unexpected component in the archaeological sediments.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2019.02.035.
Fig. 7. A) Scan of thin section LDS-12-1 with indication of two clay aggregates; B) Area of recrystallized ashes and sparitic cement (PPL), notice the orange clay aggregate with spongy voids; C) Same as B in XPL; D) Detail of recrystallized and articulated ashes with sparite infillings in the fissures (PPL); E) Photomicrograph of Heated Clay Aggregate 2 in A (PPL); F) Photomicrograph of Heated Clay Aggregate 1 in A (PPL).

Fig. 8. Micro-CT scan of sample LDS-12-1 from Lapa do Santo. Three-dimensional render and orthoslices xy and xz. Notice the dense, white area containing recrystallized ashes and sparitic cement (see Fig. 7). The reader is referred to Video 5 for the sequential orthoslices (YZ, XY and XZ orthoview).
Acknowledgements

This work was supported by the São Paulo Research Foundation (Brazil, FAPESP grant 2015/19405-6 and 2017/16451-2), the Alexander von Humboldt Foundation (Germany, post-doctoral fellowship to X.S.V.), the Max Planck Society (Germany) and the National Council for Scientific and Technological Development (Brazil, CNPq grant 409474/2016-9). We thank all participants in the excavations at Lapa do Santo; José Hein, Rogério Tavares de Oliveira and Leandro Vieira (IEF); Rosangela Albano and Cleito Ribeiro (CAALE); Brazilian authorities (IPHAN and IBAMA); João Bárbara Filho; Walter Neves. The author would like to thank the two anonymous reviewers for their comments.

References


Kilfeather, A.A., van der Merwe, J.J.M., 2008. Poresize, shape and connectivity in till sands and mounds above the food; and E) sealing the oven with a layer of soil. (Adapted from Nimuendajú, 1956)