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Spatial analysis of Amazonian Dark Earth formation supports an anthropic origin at the Caldeirão site, Brazil

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ABSTRACT

Amazonian Dark Earths (ADEs) are distinct archaeological sites in the Amazon, characterized by their enriched nutrient content in soil layers. While activities related to human occupation are acknowledged as the primary driver of the geochemical properties of ADEs, the intra-site spatial variations in their formation processes, and how they relate to human settlement, are not completely documented. In this study, we employ geostatistical analysis to investigate spatial variations in the geochemical signature and pottery concentration of ADE at the Caldeirão site, Central Amazon, a site that has sparked ongoing debates due to the revival of a natural genesis hypothesis of ADEs. Our findings reveal non-homogeneous spatial distribution of the ADE geochemical signature at the site, suggesting multiple foci of human activity at different temporal stages. Notably, we document the possible emergence of a semi-circular village pattern, prevalent in other Amazonian contexts, gradually transitioning to a more homogeneous ADE cover during the final stage of occupation. This observed pattern, consistent with archaeological and ethnographic evidence, provides compelling evidence for human activity as the primary driver of ADE formation at Caldeirão, laying to rest the hypothesis of a natural origin.

1. Introduction

Amazonian Dark Earths (ADEs), also known as Terra Preta de Índio, are one of the most distinctive types of sites in Amazonian archaeology. They exhibit dark-colored A soil horizons, the so called pretic horizons (IUSS Working Group WRB, 2022), attributed to the presence of high concentrations of pyrogenic carbon (Glaser and Birk, 2012; Lehmann et al., 2003; Schellekens et al., 2017; Woods et al., 2009). ADEs are especially enriched in phosphorus (P), calcium (Ca), magnesium (Mg), Strontium (Sr) and Zinc (Zn) along with Carbon (C). Moreover, they display higher pH levels and enhanced cation exchange capacity, significantly increasing their fertility compared to the natural upland Amazonian oxisols and ultisols (Alho et al., 2019; IUSS Working Group WRB, 2022; Macedo, 2014).

The geochemical properties of ADEs have often been attributed to human activities, involving the accumulation of various materials such as middens, feces, bones, plant tissues, and ash (Macedo, 2014). Recently, there has been a revival of the hypothesis that natural processes, such as alluvial deposition of carbon and minerals, were the primary cause of ADE formation prior to human occupation (Silva et al., 2021). However, the existing geochemical and pedological evidence overwhelmingly favors alternative explanations, since alluvial processes alone cannot account for the distinct characteristics observed in the majority of investigated ADEs (Lombardo et al., 2022). Instead, the enrichment of P, Ca, Sr, Zn, and other elements found in ADEs is better explained by inputs resulting from human activities such as burning and waste disposal (Lombardo et al., 2022).

Based on bioclimatic and terrain variables, as well as indices derived

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from satellite imagery, predictive models suggest that ca. 150,000 km^2 of ADEs can be found in the Amazon - approximately 3% of the total forest coverage - distributed with a high degree of heterogeneity (McMichael et al., 2014; Palace et al., 2017). In addition to their regional distribution, an understanding of the internal structure of ADE sites is essential for gaining insights into their human-related formation processes. However, the spatial structure of Amazonian sites in general can be obscured by pedoturbation processes, making it difficult to discern their internal structure and layout, except in cases where visible earthworks are present on the surface. As an alternative, the spatial distribution of geochemical variables serves as a valuable proxy for understanding intra-site variation (Rebellato et al., 2009). However, studies that consider the entire variation in the chemical composition of ADE through the application of advanced geospatial techniques are still lacking.

Here, we present an example from the Caldeirão site. The mapped site spans an area of 12 ha and is situated within an experimental field of the Brazilian Agricultural Research Corporation (Embrapa) in the municipality of Iranduba, Amazonas state, Brazil. The topographical location of Caldeirão is similar to that of other ADE sites, located on a bluff of a fluvial terrace, nowadays approximately 350 m away from the Solimões river (Fig. 1). The Caldeirão site is part of a larger archaeological landscape that encompasses numerous sites in the Negro-Solimões confluence (Moraes, 2013, 2007; Moraes et al., 2012).

1.1. *Previous work at Caldeirão*

Archaeological survey and excavations were carried out at Caldeirão between 2006 and 2011 (Alho et al., 2019; Macedo et al., 2017a; Schmidt et al., 2014). Various earthworks, including mounds and incised roadways leading to ponds, were documented at the site. Mounds, positioned along the bluff edge, exhibited a horseshoe or ring arrangement, resembling middens encircling a central space. Excavations on the mounds uncovered thick layers of ADE containing abundant ceramics. In contrast, the flat areas displayed only a thin layer of ADE with numerous features such as post holes, hearths, and pits (Alho et al., 2019; Schmidt et al., 2014).

Previous geochemical studies analyzed the concentration of 27 elements on transects within both the ADE and ultisol areas of the site (Barbosa et al., 2020). The results revealed enrichments of P, Ca, Mg, and Zn in the ADE, confirming previous observations. Other elements that exhibited enrichment within the Caldeirão ADE included Ba, Be, Cd, Co, Cs, Cu, K, Li, Mn, Ni, Rb, Sr, and Ti. The highest inputs observed in the ADE were of P and Ca, which is often the case in such soils. Elevated concentrations of P, Ca, K, Ba, and Cd were interpreted as originating from anthropogenic sources, such as bones, fish, meat and other food waste, plant charcoal, ash, and human feces. Exchangeable Al was found to be depleted, which was attributed to disaggregation resulting from the high concentrations of organic matter. Additionally, a decrease in Se levels was observed, likely due to the effects of fire (Barbosa et al., 2020).

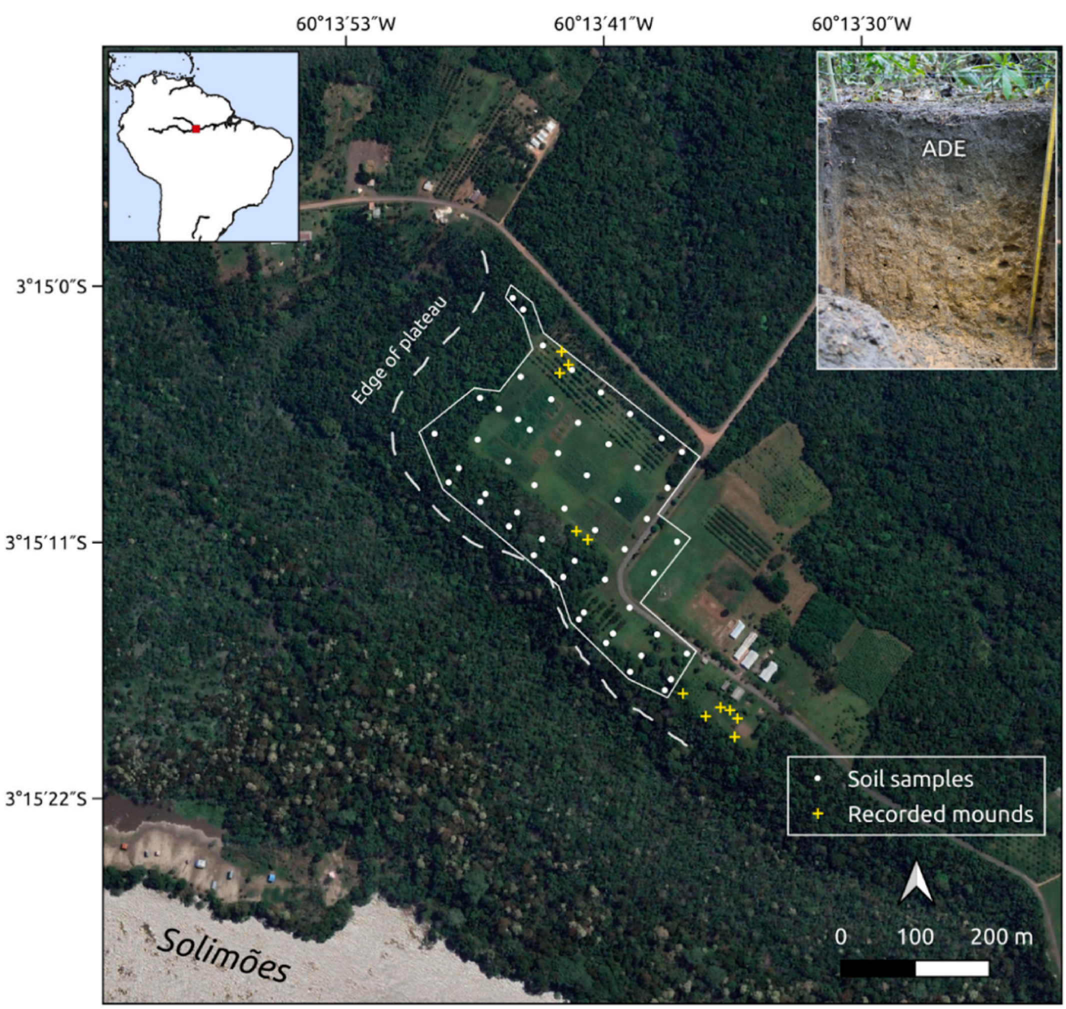

Fig. 1. Location of the Caldeirão site showing the limits of the area where soil samples were collected, recorded mounds (Lombardo et al., 2022), and soil profile evidencing the difference between the ADE and the natural soil (ultisol) at the site.

Spatial models for predicting the distribution of ADE were also developed for the site. Alho (Alho et al., 2019) employed total C, Ca, and P, along with an expected enrichment gradient (based on distance from the river and current land use) as covariates in the model, with the aim of estimating the extent of the pretic horizon. The pretic anthropic horizon is defined as a dark surface horizon with a depth of 20 cm or more, an organic C content of 6 g kg^{-1} or higher, an exchangeable Ca + Mg (by 1 M NH4OAc, pH 7) content of 1 cmolc kg^{-1} or higher, and 100 mg kg^{-1} extractable P (Mehlich-3) or higher (IUSS Working Group WRB, 2022). However, previous modelling attempts focused on pedogenesis and were not directed at identifying significant spatial patterns related to the formation and development of the human settlement.

In this paper, we build on those previous geochemical analyses and spatial models to further explore ADE formation as related to human dynamics at the settlement. By performing kriging interpolation of the first principal component obtained from the concentration of 11 elements, together with the distribution of ceramics and radiocarbon dating, we unveiled previously undetected spatial patterns in the site's stratigraphy, consistent with archaeological and ethnographic data on the spatial organization of Amazonian villages - laying to rest the hypothesis of a natural origin for ADE at the site and highlighting the dynamics of site formation in such settlements.

2. Materials and methods

2.1. Soil samples

We used data from the Terra Preta project, a collaboration between Embrapa and the Wageningen University, available in a free data repository (https://www.pedometria.org/febr/ctb0018/). Soil samples were obtained from 53 grid points and collected from five artificial levels with a depth of 20 cm each (ranging from 0 to 100 cm), resulting in a total of 265 samples. For each sample, ceramic fragments larger than 2 mm were weighed and quantified. Several parameters were determined, including Total C, Total Ca, Total P, Exchangeable Ca + Mg, Extractable P, K, and Na, soil pH, potential cation exchange capacity (CEC) at pH 7.0, and clay content. For details on the processing of the samples and extraction methods, see (Alho, 2019).

2.2. PCA and kriging interpolation

To explore spatial patterns in the data, principal component analysis (PCA) was initially performed after centering and scaling the dataset (Mardia et al., 1979; Venables and Ripley, 2002). We then kriged the first principal component (PC1) in three dimensions (x, y, and depth) to visualize these patterns within the reduced dimensionality space (Bivand et al., 2008; Hengl, 2007; Pebesma, 2004). All computations were conducted in R v.4.3 using the *gstat* library for kriging (Pebesma, 2004).

2.3. Radiocarbon dating

We obtained five radiocarbon dates from different points and depths, excluding the topmost level, with the aim of understanding the chronology of ADE formation at different locations of the site. Dating was conducted by Beta Analytics on the humin fraction of the sediment samples (Table 1).

Table 1
Radiocarbon dates obtained for Caldeirão.

Sample	Depth (cm)	14C Age	Lab code	Material dated	d13C	Calibrated date
50	20–40	600 ± 30 BP	Beta-467071	Humin	−25.9	1319–1431 cal AD
16	40–60	1060 ± 30 BP	Beta-467068	Humin	−26.5	982–1144 cal AD
19	40–60	1280 ± 30 BP	Beta-467069	Humin	−25.4	684–881 cal AD
8	80–100	1700 ± 30 BP	Beta-467067	Humin	−25	252–475 cal AD
32	80–100	1740 ± 30 BP	Beta-467070	Humin	−24.3	254–386 cal AD

3. Results and discussion

3.1. Principal component analysis

The first dimension from the PCA accounted for approximately 45% of the variance, while the second dimension explained an additional 24% (Fig. 2). Classification of soil samples from the Caldeirão site into pretic and non-pretic (Alho, 2019) suggests that the first dimension captures the distinction between the two, serving as a proxy for ADE. Both the first and the second dimensions also reflect variability associated with sample depth, which correlates with differences in sand content at surface levels and clay content at deeper levels. Higher values of exchangeable Al in the non-pretic areas (Fig. 2) were observed, which is expected given the characteristic depletion of exchangeable Al in ADEs compared to natural Amazonian soils. This is one of the factors behind the higher fertility of ADEs, considering the toxic effects of Al (Lombardo et al., 2015). The concentration of exchangeable Al is sensitive to alterations in pH due to alkaline reactions (Havlin et al., 2016). In the case of ADEs, this is possibly due to the addition of ash. Moreover, the degradation of $CaCO_3$, found mainly in bones, also reacts with and precipitates exchangeable Al. Overall, exchangeable Al seems to be a good proxy for chemical alterations caused by anthropic additions to the soil.

The role of ash in ADE formation is debated. Glaser and Birk (2012) suggest that while ash was added through human activities, it was not a key component, as only phosphorus (P) showed significant enrichment in their study. However, our findings indicate that ash may have been crucial at the Caldeirão site, as high calcium (Ca) levels strongly correlate with the first principal component. This aligns with Lombardo et al. (2022), who noted Sr/Ca ratios in ADEs similar to wood ash, and micromorphological evidence of ash deposition (Macedo et al., 2017b). Arroyo-Kalin (2017) further emphasized the role of activities like cooking, pottery production, and waste disposal in incorporating ash and charcoal into ADEs.

Another trend worth noting is the enrichment of C near the surface, as previously observed (Alho et al., 2019; Silva et al., 2021). Finally, pottery weight per sample appears to correlate well with the first dimension, reinforcing the interpretation of the first dimension as a proxy for the intensity of anthropization at the site.

3.2. Kriging and settlement layout

The spatial variation of the first principal component exhibited distinct patterns across different levels of the site's stratigraphy (Fig. 3), reminiscent of observed settlement layout changes in other ADE sites in the Central Amazon (Rebellato et al., 2009). The deepest anomalies, which coincide with high density of ceramics, may be related to pit features documented in the archaeological excavations of other parts of the site (Lombardo et al., 2022), although the available chronology seems to suggest otherwise (see session *Radiocarbon Dating* below). A possible semicircular layout can be visualized at intermediate levels, specifically between 20 and 60 cm. This arrangement partially coincides with the distribution of ceramics. However, it remains uncertain whether this layout was present from the early stages of site occupation.

Between 0 and 20 cm, no discernible pattern is evident. Concurrently, a separate activity area within the settlement emerges in the

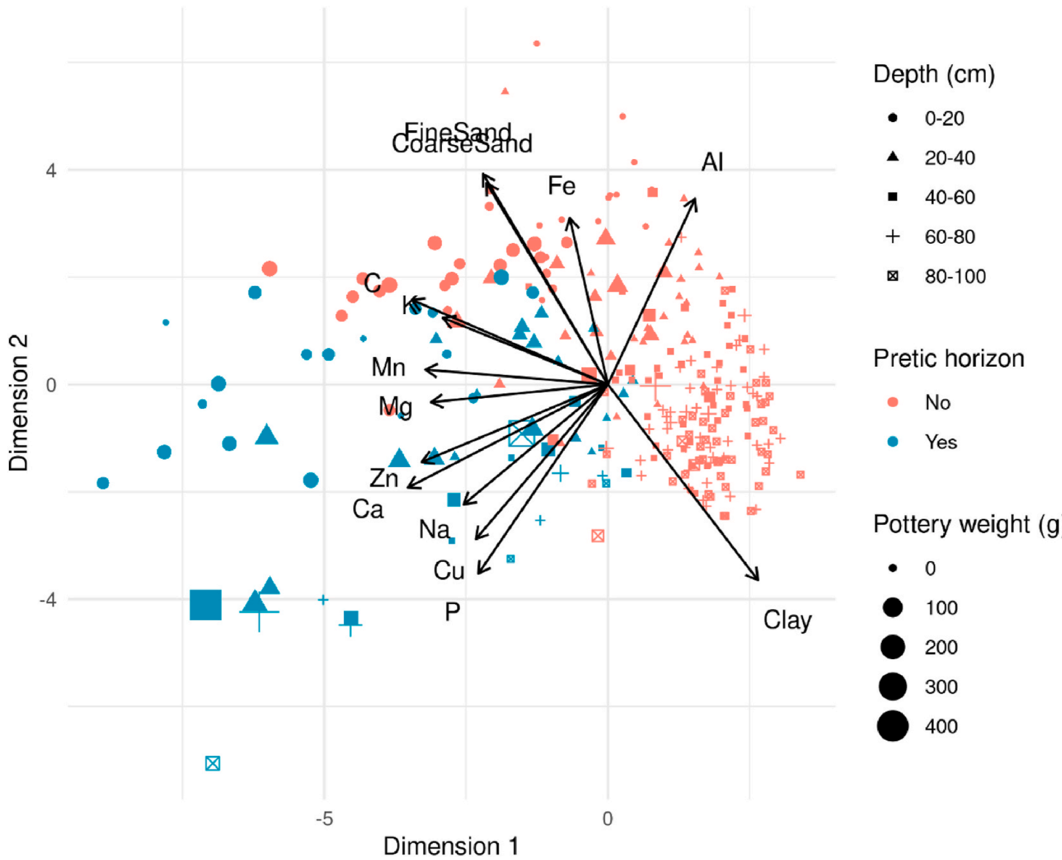

Fig. 2. Biplot of the first two principal components from the PCA on the geochemical data from Caldeirão. Samples are classified according to the pretic criteria (IUSS Working Group WRB, 2022), depth and pottery weight.

southeastern corner, becoming more prominent between 0 and 40 cm. This suggests that, in general terms, caution is needed when interpreting the current distribution of ADE at a site as a representation of the settlement layout throughout its occupation history.

It is evident that ADE, whose distribution can be partly inferred from the first principal component, did not start as a homogeneous surface, but was formed at different times in different points of the site, gradually expanding (and eventually converging) from those original centers to occupy its current extent (Fig. 3). Some foci of ADE formation appear to be continuous in time, while others are discontinuous, and some are relatively shallow and appear late in the history of the site. We argue that this pattern is difficult to reconcile with the natural genesis hypothesis, but coherent with ADE formation due to human activity - with small areas occupied at first, a later expansion that could be assumed to have had a circular layout, and the concomitant emergence of separate activity areas at different parts of the site.

In the central Amazon, the transition from circular to linear village layouts coincides with the shift from the Paredão (Incised-Rim) to the Guarita (Polychrome) traditions (Neves, 2011). Among the former, circular layouts are common - both in the distribution of ADE and in the arrangement of earthworks, such as mounds. These circular patterns bear resemblance to plaza villages that can still be observed among contemporary Amazonian populations (Moraes, 2007, 2013; Rebellato et al., 2009). The change in village organization (from circular to linear) is reflected in the distribution of mounds, soil geochemistry, and soil color variations (Neves, 2010; Rebellato et al., 2009). For example, at the Hatahara site, located approximately 3 km from Caldeirão, the spatial variation in P and Ca concentrations exhibits a circular pattern between 50 and 70 cm, later transitioning to a linear arrangement - a trend that is mirrored by the distribution of black, brown and yellow soils (Rebellato et al., 2009).

Although large mounds surrounding a central plaza are evident at sites like Hatahara, facilitating the identification of the original settlement layout, there is currently no documented evidence of this pattern at Caldeirão. However, small clusters of mounds, interpreted as middens, have been identified (Lombardo et al., 2022; Schmidt et al., 2014). Notably, one such cluster of mounds is located outside the area covered by the soil samples analyzed in this study, but adjacent to the southeastern anomaly observed in the kriging interpolation (Fig. 3). This reinforces the possibility that mounded features at the site represent middens around heavily anthropised areas. In support of this hypothesis, modern observations of ADE formation in the Upper Xingu evidence rings of middens containing dark anthrosols formed in the backyard of dwellings. Such middens contain the highest values of pH, organic carbon, Ba, Ca, Cu, Mg, Mn, P, Sr and Zn, all consistent with archaeological ADEs (Schmidt, 2010).

The presence of earthworks raises an important consideration regarding differences in modern terrain elevation, which have not been accounted for in the aforementioned stratigraphic levels. However, it is worth noting that the possible semi-circular layout at Caldeirão aligns with the presence of similar layouts at Hatahara, also documented through the use of archaeological levels (Rebellato et al., 2009). This correspondence reinforces the similarity in the internal organization of Caldeirão with other central Amazonian sites. Mounds have been recorded along the plateau, particularly just outside the sampled area, which is largely within a relatively flat or leveled experimental field (Lombardo et al., 2022; Schmidt et al., 2014). This suggests that topographic differences likely do not influence the main features identified, a conclusion further supported by the coherence in the chronological sequence.

Finally, it remains uncertain whether the spreading of ADE in the final occupation of the site is a result of contemporary processes or past

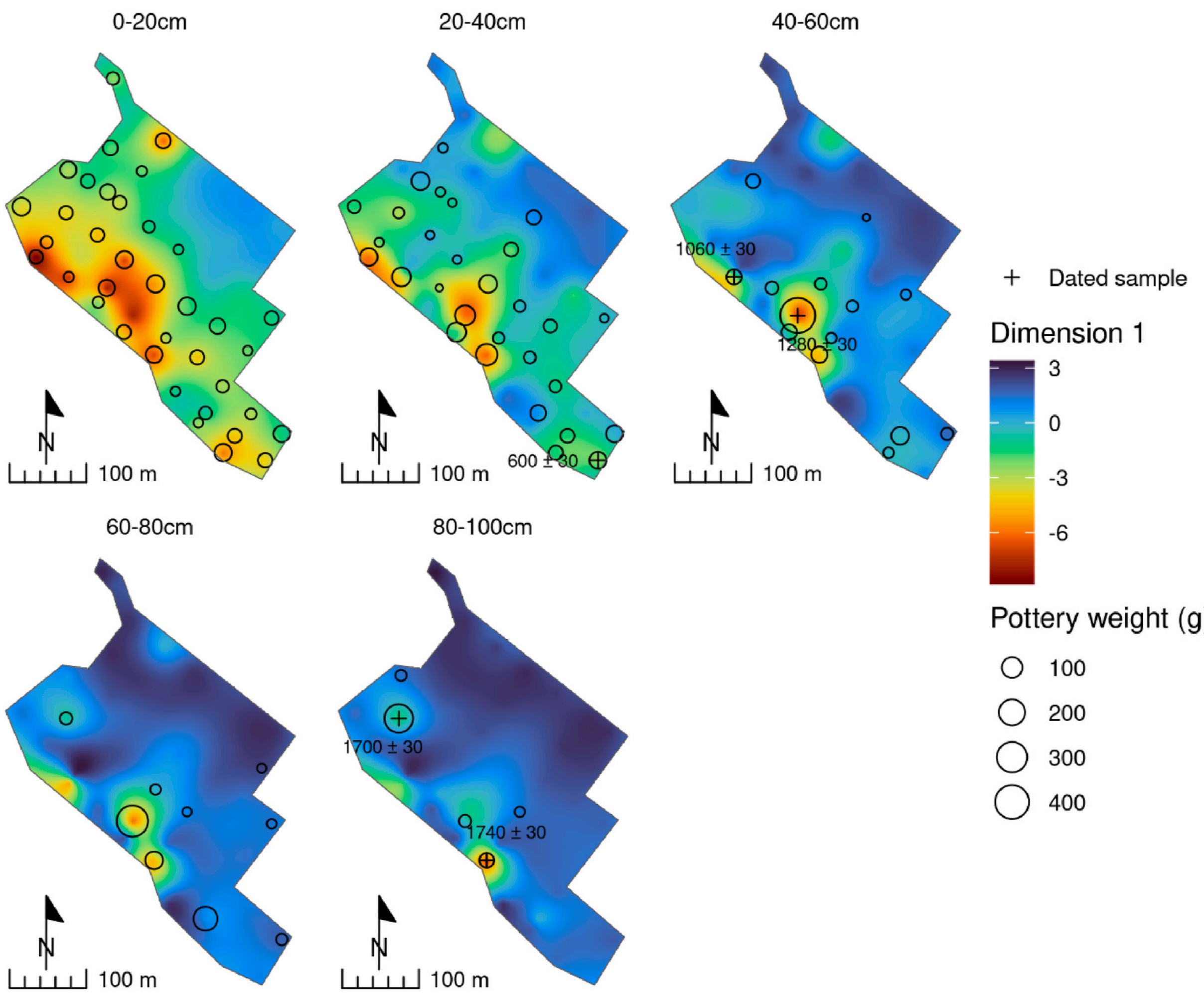

Fig. 3. Kriging on the first dimension of the PCA. Pottery weight for each sample depth is also shown, along the radiocarbon dates obtained for the site.

occupation dynamics. Rebellato et al. (2009) suggest potential factors such as soil movement or population growth, which could contribute to the expansion of ADE areas, but for the moment we cannot evaluate such hypotheses at Caldeirão. It is also possible that agricultural activities that have taken place at the experimental field of Embrapa, such as ploughing, have been responsible for spreading the ADE at the topmost levels of the site. The site is located in an experimental cultivation field, with approximately 30% - primarily along the western and southwestern edges - covered by secondary forest untouched for the past 40 years. Most samples were taken from the cultivated area, which has undergone soil management for at least four decades (Alho, 2019) suggesting that any patterns in the topmost level might have been obscured by such activities.

3.3. Radiocarbon dating

The occupation of Caldeirão fits within the established chronology for the Central Amazon (Table 1; Fig. 3). The earliest ceramic occupations of the region are those of the Pocó-Açutuba tradition, dated to ca. 2300 BP, and part of the broader Saladoid-Barrancoid horizon (Neves et al., 2014). Formation of ADE, however, appears to start only with the onset of the Manacapuru phase, ca. 1500 BP (Neves et al., 2014), with the initial occupation of Caldeirão seemingly starting at the transition between these two traditions.

During the following Paredão phase, the circular village layout with a central plaza becomes commonplace - attested in the arrangement of mounds, ceramic distribution, and soil geochemistry (Neves, 2022). The latest occupations of the central Amazon belong to the Polychrome tradition (Guarita), starting between ca. 1000 and 700 BP depending on the site. Although many sites show a superimposition of the Guarita ceramics on top of the Paredão villages - changing its layout due to the arrival of a new village architecture - and sometimes the construction of ditches and palisades (potentially for defensive purposes), other sites appear to have been unaffected (Moraes et al., 2012; Neves, 2010, 2022; Tamanaha and Neves, 2014). Caldeirão is most likely one of such cases, based on the late date of 600 ± 30 BP, although it is important to notice that such date has been obtained from an area detached from the main circular village (Fig. 3). In sites with high organic matter turnover, such as Amazonian Dark Earths (ADEs) in tropical environments, rejuvenation can present significant challenges for accurately dating soil organic matter due to the continual incorporation of younger materials (Wang et al., 1996). However, this does not appear to be a concern at Caldeirão. The site's chronological data demonstrate consistency and align well with the established regional chronology, suggesting that the dating results are reliable despite the high turnover environment.

In summary, based on the spatial variation of the PCA and radiocarbon chronology, we propose that Caldeirão can be understood as part of the regional network of circular villages that had its apex ca. 1200-1000 BP (Neves, 2010), and may be one of the latest sites where this horizon persisted. Whether the circular period of the site can be attributed to the Paredão phase or its final occupation to a Guarita superimposition, as in other sites, needs to be confirmed by independent ceramic evidence - although visual observations in the field during the sampling appear to confirm a Paredão affiliation. It is important to notice that, although the final extent of ADE at the site could be the result of obliteration due to ploughing and levelling of the terrain, it is also apparent that the final layout of the site represents an extension of the ADE along the edges of the fluvial terrace (Figs. 1 and 3). This linear arrangement along the river margins or bluffs is typical of the late occupations of Central Amazon, associated with the Guarita Tradition (Neves, 2010, 2022).

4. Conclusion

Recently, the hypothesis of a natural genesis for ADEs has been revived using data from the Caldeirão site (Silva et al., 2021). This sparked considerable controversy, prompting a response from Lombardo et al. Lombardo et al. (2022), where substantial shortcomings of the natural genesis hypothesis are exposed - for instance, the height of the plateau where Caldeirão is located, which precludes significant flooding during the Holocene; discrepancies in the expected clay to minerals ratio for alluvial deposits; and inconsistencies in the mineral assemblage of the site compared to that of the Solimões river, among other inconsistencies.

In this study, we used spatial analysis to address the anthropic origins of ADE. By identifying a potential anthropization signal from PCA performed on the concentration of 11 chemical elements and examining its spatial distribution through the site's stratigraphy, we show that Caldeirão possibly conformed to the same circular plaza village pattern widely observed across the Amazon. This finding aligns with ethnographic observations and geochemical measurements of contemporary anthrosol formation (Schmidt, 2010). Taken together, the evidence provides strong support for the hypothesis that ADE formation at Caldeirão cannot be attributed to natural processes.

CRediT authorship contribution statement

Jonas Gregorio de Souza: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Jonas Alcaina-Mateos:** Methodology, Formal analysis, Conceptualization. **Carla Lancelotti:** Writing – review & editing, Writing – original draft, Conceptualization. **Pablo Vidal-Torrado:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Marcia R. Calegari:** Writing – review & editing, Writing – original draft, Conceptualization. **Wenceslau Geraldes Teixeira:** Writing – review & editing, Writing – original draft, Validation, Data curation. **Gilvan Martins:** Investigation, Data curation. **Rodrigo Santana Macedo:** Investigation, Data curation, Conceptualization. **Marco Madella:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Data availability

Source code and data for replicating the results are available in the repository: https://doi.org/10.5281/zenodo.14792966.

Declaration of competing interest

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

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