Catena 193 (2020) 104603

Contents lists available at ScienceDirect

Catena

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

Archaeoanthrosol formation in the Brazilian semiarid

José João Lelis Leal de Souza[a,*], Bartolomeu Israel de Souza[b], Rafael Albuquerque Xavier[c], Anderson Almeida Pacheco[d], Luiz Carlos Ruiz Pessenda[e], Edson dos Santos Brito[f]

[a] Soil Science Department, Federal University of Viçosa. Professor Peter Henry Rolfs Ave., Viçosa-MG 36570-900, Brazil
[b] Geosciences Department, Federal University of Paraíba. Governador Antônio Mariz Ave, João Pessoa-PB 58051-900, Brazil
[c] Geography Department, State University of Paraíba. 351 Baraúnas St., Campina Grande-PB, 58429-500, Brazil
[d] Renova Foundation, 671 Getúlio Vargas Ave., Funcionários. Belo Horizonte-MG, 30112-020, Brazil
[e] Agriculture Nuclear Energy Center, University of São Paulo. 303 Centenário Ave., Piracicaba - SP, 13400-970, Brazil
[f] Geography Department, Federal University of Rio Grande do Norte. Joaquim Gregório St., Penedo. Caicó-RN, 59300-000, Brazil

ARTICLE INFO

Keywords:
Anthrosols
Caatinga
Dry forest
South America

ABSTRACT

Multiple waves of dispersion populated South America throughout the late Pleistocene and early Holocene. The oldest rock art and artifacts in Caatinga are dated from 10,000 BP. Besides that, there is no register of ancient activities in soils in Caatinga. Four pedons were taken, described and classified in sites with a high number of artifacts littering the surface and/or rock art. Five more pedons were described to represent soil without anthropic influence. Soils are shallow and transition between horizons was predominantly clear or abrupt. Anthrosols in Caatinga have value and chroma similar to the anthropic horizons described in Amazonian dark earths. The pedons are strongly acid to slightly alkaline and predominantly have base saturation above 50% in all horizons. Anthrosols in Caatinga have up to 6 and 544 times, respectively, more soil organic carbon and phosphorus compared to adjacent soils without anthropic influence. Besides illite and kaolinite, apatite and calcite compose the clay and silt fractions and confirm the human influence in soil formation. Radiocarbon and thermoluminescence dating indicate that Anthrosols in Caatinga are contemporaneous to the majority of Amazonian dark earths.

1. Introduction

Humans migrated along South America about 15,500 years ago before present (BP) (Cramon-taubadel et al., 2017) and produced evidences of occupation in wet tropical and subtropical biomes, as the Amazonia rainforest (Clement et al., 2015), Atlantic rainforest (Araujo et al., 2017), Brazilian cerrado (Souza et al., 2016), pampas region (Dubois and Politis, 2017) and others. These humans did not only hunt animals but transported plants and intentionally or accidentally burned areas, which altered the vegetable composition of local habitats (Dillehay, 2008; Hecht, 2003; Levis et al., 2017; Neves et al., 2004a,b; Roosevelt, 2000).

Ancient human communities can be traceable by soil properties. In Brazil, activities of indigenous populations in the pre-Columbian era created high fertile soils in the Amazon rainforest. These soils are classified as Anthrosols and commonly they are called Amazonian Dark Earth due to their singular properties (German, 2003; Sombroek, 1966). Anthrosols are described as profoundly modified soils by human activities (IUSS Working Group WRB, 2014). Addition of organic or mineral material, charcoal or household wastes, or irrigation and cultivation through time produce soils with high fertility, black or dark brown color, strong grade structure and granular type, fragments of ceramic, higher organic carbon, and higher P and Ca contents than the surrounding pristine soils (Cunha et al., 2007).

Caatinga is the largest dry forest fragment in South America. It remains suggested that humans occupied Caatinga at 9,670 years BP (Alvim, 2008). Despite abundant non-dated paintings in caves and boulders in the Brazilian Northeastern (Azevedo Netto and Oliveira, 2015), there is no register of ancient activities in soils. Caatinga is the largest unit of seasonally dry forest biome in the Neotropics (DRYFLOR et al., 2016). Amazonia and Caatinga soils differ considerably in terms of depth, mineralogy, texture and water availability. These differences can modify the interactions between soil processes and the conditions of human artifacts, especially those of organic origin (bones, charcoal, ash, shells, etc.), which are used as pedological indicators of ancient human occupation. The hypothesis of the study is that ancient anthropic activities, like these in Amazonian dark earths, were installed and promoted favorable contrasting physic-chemical characteristics

* Corresponding author.
E-mail addresses: jjlelis@ufv.br, jjlelis@gmail.com (J.J.L.L. de Souza), xavierra@uol.com.br (R.A. Xavier), pessenda@cena.usp.br (L.C.R. Pessenda).

https://doi.org/10.1016/j.catena.2020.104603
Received 24 November 2019; Received in revised form 5 March 2020; Accepted 9 April 2020

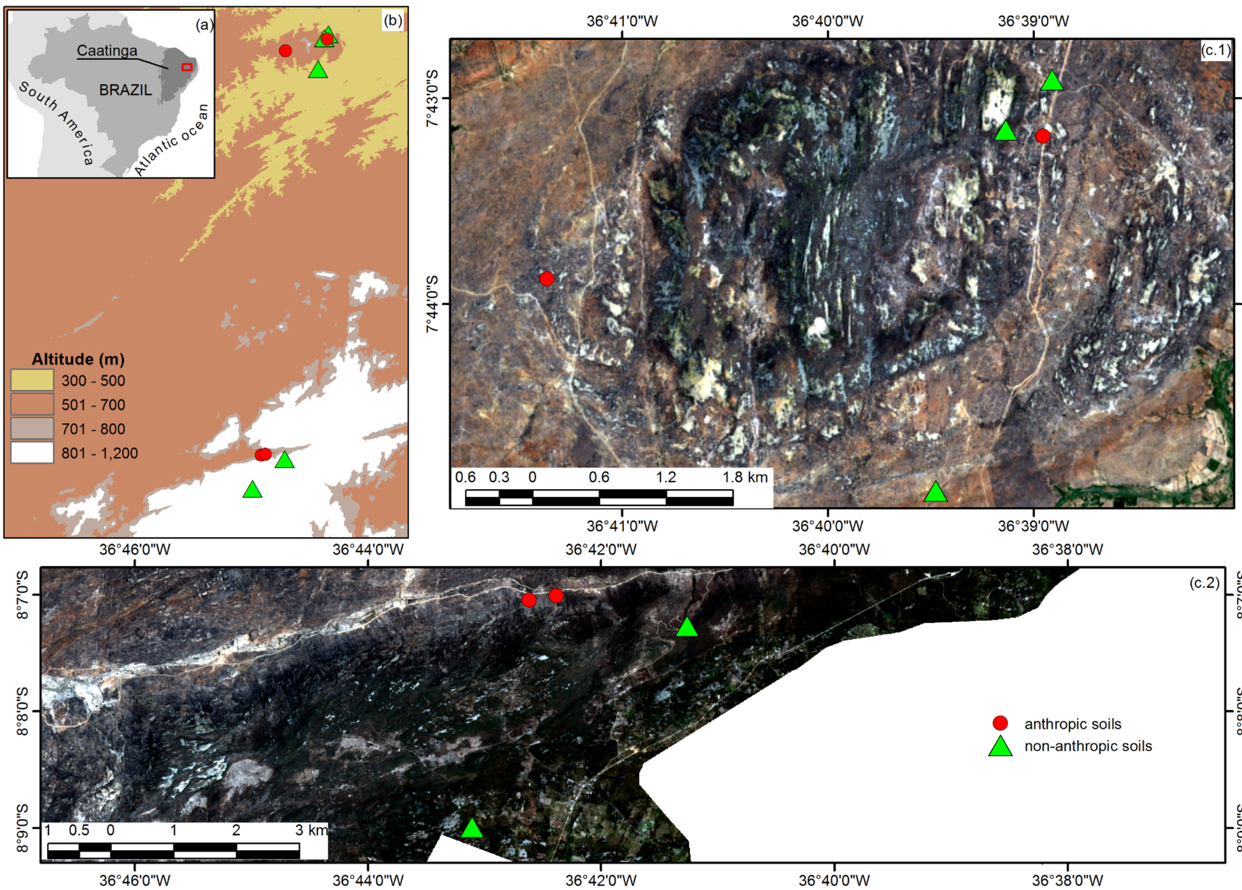

Fig. 1. Location of Cariri Velhas (a); samples collected in the study area according to altitude (b); Sentinel 2A image of study area (c.1 and c.2).

compared to the surrounding soils in Caatinga. Therefore, the objective of this study was to present anthropic soils in the Caatinga. These results may extend the current debate of ancient human occupation in the Brazilian Northeast and the landscape evolution. Besides the report of soils affected by ancient humans in semiarid climate being able to improve the definitions and diagnostic criteria of Anthrosols in soil classification systems.

2. Study area

The study area encompasses the Cariri Velhas region, located in the Paraíba state. It has a total area of approximately 11,225.736 km^2 and a particular landscape diversity (Fig. 1). Altitudes vary between 400 m, in pediment surface, and 1,100 m, in highlands, cliffs and inselbergs associated with resistant rocks and horst–graben systems (Xavier et al., 2016). Faults created by uplift of granite and granitoid during the Brasiliano cycle and weathering favored individualization and rounding of blocks (Correa et al., 2010). Mass movements of these blocks formed fields of giant granitic boulders in the talus of inselbergs and cliffs.

Cariri Velhas is one of the driest regions in Brazil. Areas at lower altitudes (in the pediment surface) have a mean precipitation of 350 mm year^{-1} and potential evapotranspiration four times higher than precipitation and mean temperature of 27 °C (Kayano and Andreoli, 2009). On the other hand, areas at higher altitudes (on and around the highlands), have peculiar climatic dynamics derived from a local type of “valley-mountain” circulation, thus favoring the occurrence of orographic rains, fog and high number of springs. A meteorological station installed in 2017 indicated mean precipitation and temperature of 466.2 mm year^{-1} and 20.9 °C in highlands, respectively (non-published data). Although the data series is shorter than 30 years, we highlight that it is the first and the only meteorological station in the highlands.

The vegetable cover in Cariri Velhas has large endemic biodiversity (APG, 2016; Costa and Peralta, 2015; Maia et al., 2015). Shrubs, 3–9 m height-trees that shed their leaves seasonally, cacti and arid-adapted grasses partially cover the soil (Prado, 2000; Santos et al., 2012). Weathering of minerals and rocks is incipient, and the soil is intensively eroded during the four rainy months. Luvisols (40.9% of the total area), Leptosols (35.6%) and Regosols (3.9%) dominates the Cariri Velhas (Araújo Filho et al., 2017). These soils are dominantly loamic, shallow (< 1 m deep), eutrophic and have low organic carbon content (Ferreira et al., 2018; Giongo et al., 2011; Menezes et al., 2012; Rückamp et al., 2010).

The register of ancient human activities dated from 12,400 to 8,000 years BP are abundant in Northeastern Brazil (Bueno, 2011). In general, the archaeological sites are close to perennial rivers, which are important to water and wood supply, and indicate that the largest rivers were migration routes to the interior of Northeastern Brazil during Pleistocene-Holocene (Bueno et al., 2013; Kelly, 2003).

Little is known about archaeological context of the Cariri Velho once there is no register of archaeological sites (Brazil. Ministry of Culture. Artistic Heritage, 2018). The study area encompasses the highlands occupied by ancestrals of the Kariri, an indigenous population from which information is scarce (Lima et al., 2002). The scarce studies suggest that these ancient communities were hunters and gatherers living in mobile bands, but it included fishermen as well as hunter-gatherers who practiced some cultivation and were, consequently, sedentary for at least part of the year (Araújo et al., 2003; Kelly, 2003).

3. Material and methods

Four soil profiles were taken, described and sampled in sites with evidences of ancient human occupation (painting ash, ceramic and bones in the soil surface, etc.). Another five soil profiles were taken to represent non-anthropic soils in the main geological materials and soil groups from Caatinga (Fig. 1). All pedons were classified according to the World Reference Base soil classification system (IUSS Working Group WRB, 2014), Soil Taxonomy (Soil Survey Staff, 2010) and Brazilian Soil Classification System (Santos et al., 2013). Soil samples were collected in order to represent each horizon from the surface down to the lithic contact at each pedon. For deeper soils, a 100 cm control section was used. The archaeological material discovered was reported to National Historical and Artistic Heritage Institute (IPHAN).

Samples were air dried and sieved through a 2 mm sieve prior to texture and chemical analyzes according to methods established for tropical soils (Donagema et al., 2011). Coarse sand (CS), fine sand (FS), silt and clay were determined by the pipette method after dispersion with 0.1 M NaOH. Soil pH was measured with a glass electrode in a 1:2.5 suspension v/v soil and deionized water (pH H_2O) and 1 M KCl solution (KCl pH). The potential acidity (H + Al) was extracted by 1 M ammonium acetate solution at pH 7. The content of exchangeable Ca^{2+}, Mg^{2+} and Al^{3+} was determined in a 1 M KCl extract. Exchangeable K^{+} and Na^{+} were determined after Melhich-1 extraction. From these results, the sum of bases (SB), base saturation (V), aluminum saturation (m), equivalent cation exchange capacity (ECEC), total cation exchange capacity (CEC) and Na saturation (ISNA) were calculated.

The available phosphorus content (P_M) was determined by a Mehlich-1 extraction solution. The total organic carbon (C) was determined by wet combustion (Yeomans and Bremner, 1988). The P adsorption capacity of the soil was determined after stirring it for 1 h with 2.5 g of soil in 0.01 M $CaCl_2$ containing 60 mg of P L^{-1}. The suspension was filtered and the remaining P in the solution (P_{REM}) was determined by photocolorimetry (Alvarez et al., 2000). Therefore, the lower the value of P-rem, the higher the affinity of soils for the P in the solution.

X-ray diffraction (XRD) analyses were conducted on clay, silt and sand-size fractions from the soil profile n° 3, because of its higher quantity of ash, bones and artifacts. XRD patterns were collected using a PanalyticalX'Pert PRO (CoKα radiation) between 4 and 50 °2θ, at a scan speed of 0.1 °2θsec^{-1}, working with a potential of 40 kV and a current of 40 mA.

Aluminum and Fe concentrations were quantified after five sequential extractions, using the dithionite-citrate-bicarbonate method (DCB) at pH 7.3 (Mehra and Jackson, 1953) and after one extraction by the acid oxalate method (AOD) in darkness at pH 3.0 (McKeague and Day, 1966); these procedures were executed in the horizons which have the highest and lowest P content. Molecular Feo/Fed was calculated using the Fe concentrations extracted by ammoniumoxalate (Feo) and dithionite-citrate-bicarbonate (Fed). This ratio was used as an index of crystallinity degree of Fe oxides, interpretation of pedogenic processes and intensity of weathering (Kämpf and Curi, 2000). The Al and Fe concentrations extracted via selective dissolution with DCB and AOD were quantified by atomic absorption spectrophotometry.

A charcoal sample of soil profile n° 3 was dated by ^{14}C. The dating process was carried out by benzene synthesis/liquid scintillation counting at the Radiocarbon Laboratory at the Center for Nuclear Energy in Agriculture, University of São Paulo (Pessenda and Camargo, 1991). Prior to dating, the sample was chemically pretreated with HCl 4% for 4 h at 60 °C, washed with deionized water to neutral pH conditions and dried at 50 °C. The radiocarbon age is expressed in years BP (Before Present, CE 1950, 1σ), normalized to δ13C of −25‰ VPDB and calibrated (2σ) as cal years BP (Reimer et al., 2004). The result is representative of the mean age of the charcoal fragment in the horizon 10–20 cm depth of soil profile n°. 3. Lab number is CEN 1280.

A ceramic in 14 cm depth of soil profile n° 3 was dated according to the thermoluminescence technique. This soil profile was chosen because its abundance of archaeological materials. Thermoluminescence dating is a common procedure utilized to this determination, by means of measuring the accumulated radiation dose, of the time elapsed since minerals in anthropogenically heated materials were heated above 450 °C.

The remaining ceramic sample was gently crushed using a benchtop vice. Carbonates were removed by HCl treatment. Multimineral silt-size grains were obtained using standard luminescence sample preparation techniques and treated with 10% H_2O_2 to consume organic compounds. The total radiation dose accrued in quartz grains (De) was determined through thermoluminescence glow curve analysis (Supplementary material Figure S.1). Four aliquots were used for equivalent dose determination. ^{232}Th, $^{238}U + ^{235}U$ and ^{40}K contents were utilized to calculate the dose rate (R). Fine particles found in the same profile were utilized to estimate the dose rate from the radioactive elements to which the ceramics were exposed. The age of the ceramic is deduced from the ratio of the accrued dose (De) to dose rate (R) plus burial adjustment. Thermoluminescence measurement was performed by the DATAÇÃO Laboratory (Dating, Commerce & Services Provision LTDA – São Paulo/SP).

4. Results

4.1. Soils with anthropic influence

All soil profiles were dug in fields of giant granitic boulders in the talus of inselbergs and cliffs (Table 1 and Fig. 2). Quartz and feldspar occur as gravel in all soil profile and indicates that SP2 is derived from granite. All soil profiles were described in caves in granite. The area of sites varies between 100 and 18,205 m^2. Elaborated Pre Columbian-painting style, notably including red- and/or black-on-white painted, and complicated modeled designs are observed in all sites (Supplementary material Figure S.2). Future archaeological studies should analyze these paintings.

Pedons were classified as Entisols according to Soil Taxonomy, which corresponds to the order of *Neossolos*, respectively, in the Brazilian Soil Classification System. Topsoils are classified as anthropic epipedon according to the Soil Taxonomy and as *horizonte A antrópico* according to the Brazilian Soil Classification Sytem. In general, the following criteria of pretic epipedon are fulfilled: (i) Munsell color value of ≤4 and a chroma of ≤3, both moist; (ii) 2. ≥ 1% organic carbon; (iii) exchangeable Ca plus Mg (by 1 *M* NH4OAc, pH 7) of ≥2 cmolc kg^{-1} fine earth; (*iv*) ≥30 mg kg^{-1} of extractable P (Mehlich-1); (v) ≥ 1% charcoal, and; (vi) < 25% (by volume, by weighted average) of animal pores, coprolites or other traces of soil animal activity. So, except by the thickness, all criteria of pretic horizon are fulfilled. The thickness of pretic horizon ranges from 12 to 30 cm. We classified all soils with anthropic influence as Anthrosols according to the World Reference Base soil classification system. The depth of the Anthrosols varied between 10 and 50 cm with a mean of 29.25 cm. All soil profiles did not respond to a hand magnet suggesting the absence of ferrimagnetic material.

The texture is dominantly sandy loam and coarse sand (CS) dominates fine particles. The pedons are strongly acid to strongly alkaline and have predominantly base saturation (V) above 50% in all horizons (Fig. 3). $Ca^{2+} > Mg^{2+} > K^{+} > Na^{+}$ is the base dominance in the exchange complex (Supplementary material Table S.1). The Ca^{2+} concentration is dominantly above 1 cmolc kg^{-1}. In general, the total organic carbon (C), Ca^{2+} and extractable P by Mehlich-1 (P_M) content decrease with the increase of depth. The C content in the upper horizon ranged between 0.47% and 15.94%. In the 10–50 cm increment, the C concentrations ranged from 0.31% to 2.95%. The P_M content in the upper horizon ranged from 196.6 mg kg^{-1} to 5,231.2 mg kg^{-1}.

The first soil profile (SP1) was classified as Pretic Anthrosol (Pantoothodystric, Pantoloamic, Epiprotechnic). SP1 was described inside a cave in granite at 509 m. Soil is well-drained, with evidences of slight laminar erosion. The surface of the soil is barely covered by sparse grasses and no litter occur. Rock art in the cave indicate ancient human occupation in an area of 2,829 m^2. At the surface, the SP1 shows

Table 1
General description of pedons.

Pedon	Soil ClassificationWRB/ ST/ SiBCS	Coordinates ǂ	Altitude (m)	General description
Soils with anthropic influence				
SP1	Pretic Anthrosol (Pantoothodystric, Pantoloamic, Epiprotechnic)/ 'Anthropic' Lithic Ustothents/ NEOSSOLO LITÓLICO Distrófico antrópico	7.719761° S W	509	Soil described in a cave in granite giant boulder which is in pediment plain. Well-drained soil, with slight laminar erosion and derived from colluvium on granite. Quartz and feldspar occur as gravel in all soil profile. Postsherd occurs in the soil surface. Rock art and bones indicate ancient human occupation in an area of 2,829 m^2. Sparse grasses and no litter on soil. Pretic horizon (WRB), anthropic epipedon (ST) and *horizonte A antrópico* (SiBCS) were identified.
SP2	Pantopretic Anthrosol (Pantohypereutric, Pantoloamic, Epienfoleptic, Pantotechnic)/ 'Anthropic' Lithic Ustorthents/ NEOSSOLO LITÓLICO Hístico antrópico	7.731333° S 36.68942° W	552	Soil described in a cave in granite giant boulder which is in pediment plain. Well-drained soil, with slight laminar erosion and derived from colluvium on granite. Quartz and feldspar occur as gravel in all soil profile. Postsherd occurs in the soil surface. Rock art and bones indicate ancient human occupation in an area of 18,205 m^2. Vegetation is absent. Pretic horizon (WRB), anthropic epipedon (ST) and *horizonte A antrópico* (SiBCS) were identified.
SP3	Pantopretic Anthrosol (Pantoalcalic, Pantoloamic, Escalic, Endoleptic, Epiprototechnic)/ 'Anthropic' Lithic Ustorthents/ NEOSSOLO LITÓLICO Distroúmbrico antrópico	8.117472° S 36.71028° W	722	Soil described in a small human made terrace comprised of earth which has been heaped up to mark a burial site. The site is in a cave in granite giant boulder which is on a 'V' shape valley. Well-drained soil, with slight laminar erosion and derived from colluvium on granite. Quartz and feldspar occur as gravel in the first 10 cm depth. Rock art, postsherd, bones and charcoal indicate ancient human occupation in an area of 2,710 m^2. Walls and roof of the boulder are painted. Sparse grasses and no litter on soil. Pretic horizon (WRB), anthropic epipedon (ST) and *horizonte A antrópico* (SiBCS) were identified.
SP4	Pantopretic Anthrosol (Pantoalcalic, Pantoloamic, Escalic, Endoleptic, Epitechnic)/ 'Anthropic' Lithic Ustorthents/ NEOSSOLO LITÓLICO Eutrófico antrópicoantrópico	8.116817° S 36.70892° W	703	Soil described in a cave in granite giant boulder which is on a 'V' shape valley. Well-drained soil, with slight laminar erosion and derived from colluvium on granite. Quartz and feldspar occur as gravel in all soil profile. Rock art, debitage and ash indicate ancient human occupation in an area of 100 m2. Cave paintings in the walls and roof of a boulder. Vegetation is absent. Petric horizon (WRB), anthropic epipedon (ST) and *horizonte A antrópico* (SiBCS) were identified.
Soils without anthropic influence				
SP5	Pantohypereutric Leptic Regosol (Pantoarenic, Ochric)/ Xeric Torripsamments/ NEOSSOLO REGOLÍTICO Eutrófico saprolítico arênico	7.71515° S36.64848° W	496	Soil described in a pediment plain. Well-drained soil, with slight laminar erosion and derived from colluvium on granitoid. Quartz and feldspar occur as gravel in all soil profile. Sparse grasses and litter on soil. Ochric epipedon (ST) and *horizonte A moderado* (SiBCS) were identified.
SP6	Pantohypereutric Leptic Regosol (Pantoloamic, Ochric)/ Lithic Torripsamments/ NEOSSOLO LITÓLICO Eutrófico fragmentário	7.71921° S36.65224° W	528	Soil described in a footslope. Well-drained soil, with slight laminar erosion and derived from colluvium on granitoid. Quartz and feldspar occur as gravel in all soil profile. Sparse grasses and litter on soil. Ochric epipedon (ST) and *horizonte A moderado* (SiBCS) were identified.
SP7	Pantorhodic Endovertic Leptic Luvisol (Clayic, Pantohypereutric, Ochric)/ Lithic Rhodustalfs/ LUVISSOLO CRÔMICO Órtico vertissólico	7.74847° S36.65791° W	483	Soil described in a pediment plain. Poorly drained soil, with apparent laminar erosion and derived from colluvium on gneiss. Litter is absent due to sparse cover of herbaceous and deciduous arboreal specimens. Desert pavement is observed on soil surface. Ochric epipedon (ST) and *horizonte A fraco* (SiBCS) were identified.
SP8	Endoleptic Umbrisol (Pantoloamic, Hyperdystric)/ Ustic Torriorthents/ NEOSSOLO REGOLÍTICO Húmico léptico	8.14991° S36.71843° W	1,126	Soil described in a plateau. Well-drained soil, with slight laminar erosion and derived from colluvium on granitoid. Quartz and feldspar occur as gravel in all soil profile. Sparse grasses and litter on soil. Umbric epipedon (WRB), umbric epipedon (ST) and *horizonte A húmico* (SiBCS) were identified.
SP9	Pantooligeoeutric Leptic Pantofluvic Fluvisol (Arenic, Ochric, Nechic)/ Aquic Torrifluvents/ NEOSSOLO FLÚVICO Psamíticos Ta Eutrófico léptico	8.12115° S36.68772° W	859	Soil described in a fluvial channel. Well-drained soil, with slight laminar erosion and derived from alluvium on granitoid. Vegetation is absent. Ochric epipedon (ST) and *horizonte A moderado* (SiBCS) were identified.

ǂ/ World Geodetic System (WGS84).

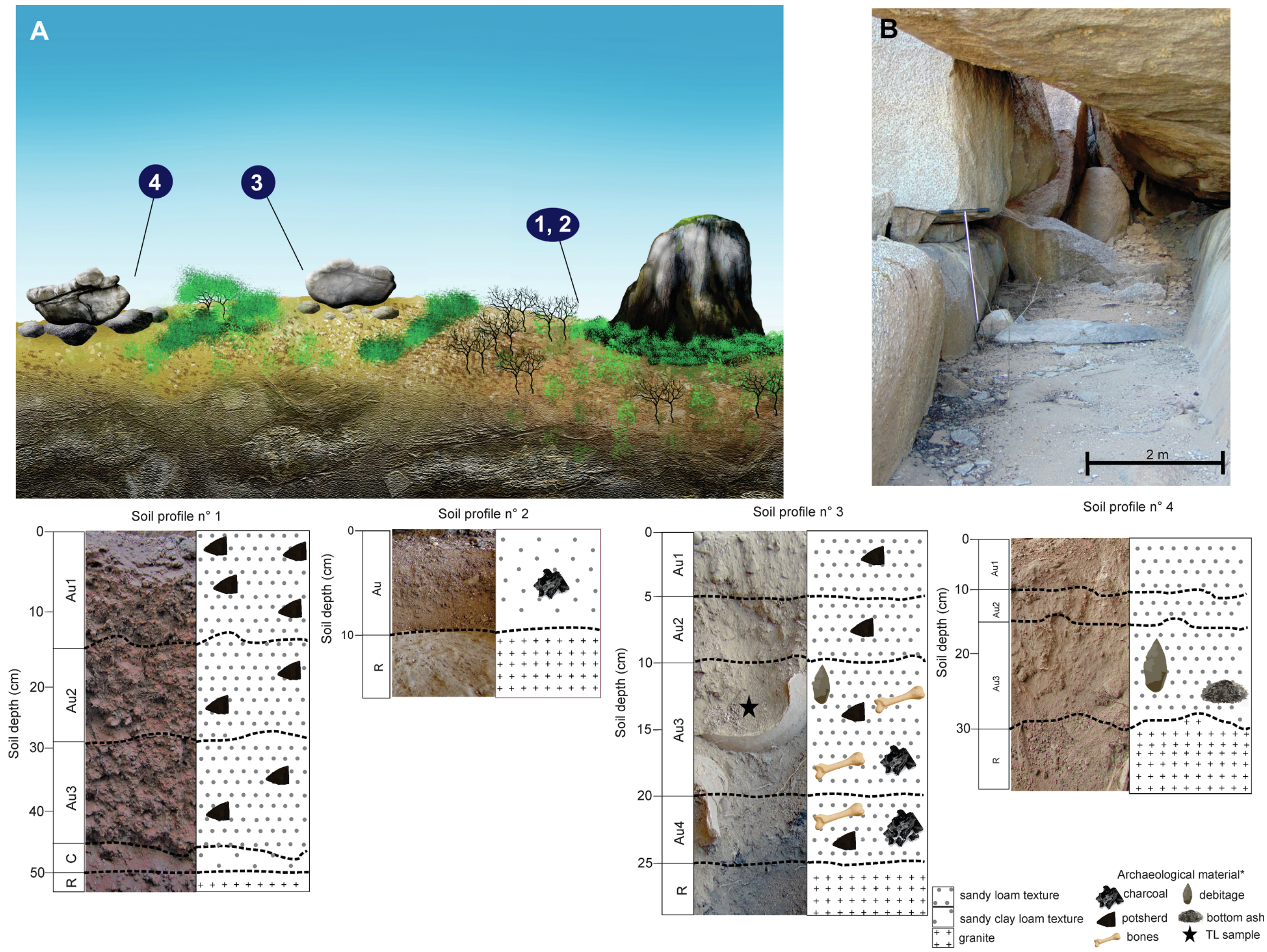

Fig. 2. Location of soil profile with anthropic influence (a); the archaeological site of soil profile n° 1 (b), and stratigraphy of soil profiles n° 1 to 4 (c).

irregular and angular potsherd (Table 2). All horizons have archaeological materials with the same characteristics as the surface soil, although a decrease of its content is observed. The first horizon is dark grayish brown (10YR 4/2) and its structure is strong medium subangular block that is hardly manually disturbed. The second, third and fourth horizons were discriminated by a slightly increase of clay content. The color of the three deeper horizons is dark yellowish brown (10YR 3/4). A weak fine and subangular block structure is observed from the second horizon to lithic contact. Roots and pores are common in the all horizons. The texture of SP1 is dominantly sandy loam and a slightly increase of clay content in deeper horizons was noticed (Fig. 3). SP1 is strongly acid to moderately acid (Supplementary material Table S.1). Anthropic epipedon (ST) and *horizonte A antrópico* (SiBCS) were identified. Although the content of Ca^{2+}, Mg^{2+} and C are below the defined to the pretic horizon (WRB), we defined the topsoil as pretic horizon due to its marked human influence.

The second soil profile (SP2) was classified as Pantopretic Anthrosol (Pantohypereutric, Pantoloamic, Epienfoleptic, Pantotechnic). SP2 was described inside a cave in granite at 552 m. Soil is well-drained, with evidences of slight laminar erosion. Vegetation cover and litter are absent. Rock art in the cave indicate ancient human occupation in an area of 18,205 m^2. The SP2 shows charcoal fragments since the surface (Table 2). The first horizon is black (5Y 1/1) and its structure is weak fine subangular block that is easily manually disturbed. The continuum rock is at 12 cm depth. Roots are absent and pores are few and fine. The texture of SP2 is sandy clay loam. SP2 is neutral and has expressive high values of P_M, Ca^{2+}, Mg^{2+} and C contents (Fig. 3). Pretic horizon (WRB), anthropic epipedon (ST) and *horizonte A antrópico* (SiBCS) were identified.

The third soil profile (SP3) was classified as Pantopretic Anthrosol (Pantoalcalic, Pantoloamic, Escalic, Endoleptic, Epiprototechnic). SP3 was described in a human terrace made inside a cave in granite at 722 m. Soil is well-drained, with evidences of slight laminar erosion. The surface of the soil is barely covered by sparse grasses and no litter occur. Rock art in the cave indicate ancient human occupation in an area of 2,710 m^2. At the surface, the SP3 shows irregular and very angular potsherd (Table 2). The first and second horizons have archaeological materials with the same characteristics as the surface soil. The first horizon is very dark grayish brown (10YR 3/2) and its structure is weak fine subangular block that is easily manually disturbed. The color of the second horizon is olive brown (2.5Y 4/3) and its structure is weak medium subangular block. The third and fourth horizons have a fine subangular block structure poorly developed. The content of archaeological materials increases considerably at the contact between second and third horizons. Besides potsherd, the third and fourth horizons contain debitage and charcoal fragments. In addition to coal, the use of fire is indicated by the presence of bones and small charred materials. The colors of the third and fourth horizons are very dark grayish brown (2.5Y 3/2) and very dark gray (2.5Y 3/1), respectively, due to the concentration of charcoal. Radiocarbon dating on charcoal indicates 1,100 ± 80 years B.P. Similar age was obtained on quartz grains in ceramic by thermoluminescence (Table 3).

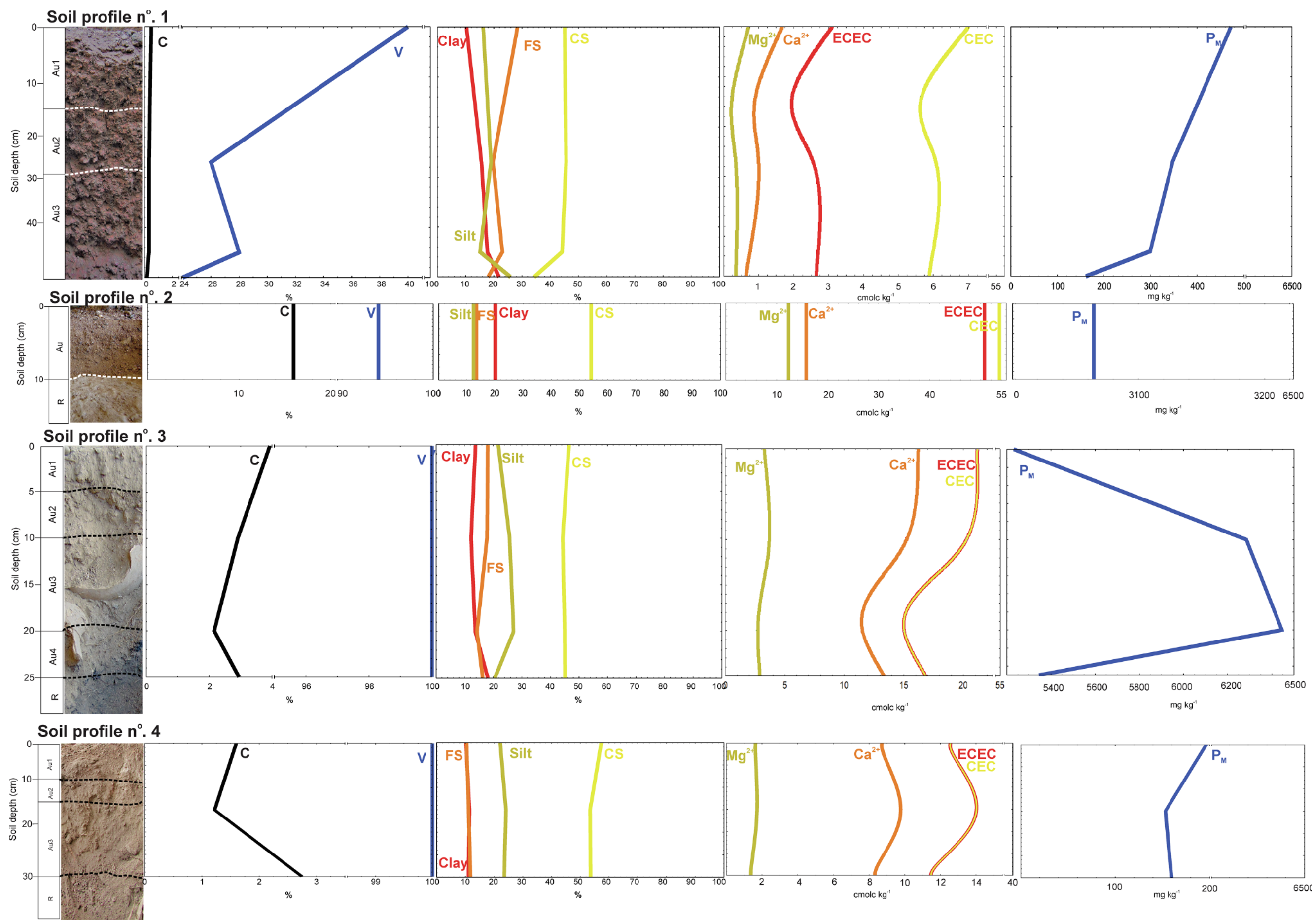

Fig. 3. Physic-chemical soil properties of soil profiles with anthropic influence.

The texture of SP3 is sandy loam. The clay fraction of SP3, identified via XRD pattern, was composed by illite, kaolinite, calcite and apatite (Fig. 4). The presence of illite and kaolinite was confirmed in the clay fraction via interplanar spacing (*d*) of 1.014 and 0.726 nm, respectively. The phosphate minerals showed interplanar spacing (*d*) of 0.303 and 0.278 nm to calcite and apatite, once they have very close reflection and chemical composition. Quartz, mica, anatase, albite, oligoclase, apatite, calcite and traces of kaolinite were identified in the XRD pattern from silt and sand fractions (Fig. 5). Iron concentrations extracted by ammoniumoxalate (Feo) and dithionite-citrate-bicarbonate (Fed) in the third horizon were lower than 1% (Table 3). Aluminum concentrations extracted by DCB and AOD were up to 21 and 156 times higher than Fe, respectively. SP3 is slightly alkaline to moderately alkaline. The second and third horizons have some the highest contents of Ca^{2+} and P_M (Fig. 3).

The fourth soil profile (SP4) was classified as Pantopretic Anthrosol (Pantoalcalic, Pantoloamic, Escalic, Endoleptic, Epitechnic). SP4 was described inside a cave in granite at 703 m. Soil is well-drained, with evidences of slight laminar erosion. Vegetation cover and litter are absent. Rock art in the cave indicate ancient human occupation in an area of 100 m^2. SP4 has no archaeological materials in the surface (Table 2). The color of the first and second horizons are gray (5Y 5/1) and their structure is medium subangular block. In the third horizon are observed lithic materials, such as chalcedony and quartz. It also contains bottom ash. The black (5Y 2.5/1) color of this horizon indicates that it is remnant of a bonfire. The texture of SP4 is sandy loam. SP4 is moderately alkaline to strongly alkaline (Supplementary material Table S.1) and has the lowest P_M contents (Fig. 3). Pretic horizon (WRB), anthropic epipedon (ST) and *horizonte A antrópico* (SiBCS) were identified.

4.2. Soils without anthropic influence

The soil profiles were dug in partially dissected pediments, slopes, cliffs and a fluvial channel to represent the soil diversity of Caatinga without anthropic influence (Table 1). These soils were classified as Regosols, Fluvisols, Luvisols and Umbrisols, which are equivalent to Neossolos and Luvissolos (Entisols and Alfisols) according to the Brazilian Soil Classification System (Soil Taxonomy). Ochric epipedon is dominant. Evidences of ancient anthropic influence (ash, bones, ceramic etc.) are absent.

The depth of soils without anthropic influence is slightly deeper than Anthrosols; they varied between 40 and 70 cm, with a mean of 51 cm. The thickness of ochric horizon ranges from 5 to 20 cm. The structure is absent to strong developed, with subangular blocky type dominantly (Table 2). The soil hue varies from Gley to 2.5YR. All soils are shallow and transition between horizons was predominantly clear.

The texture of soils without anthropic influence varies from sandy to clay. The coarse sand (CS) dominates fine particles (Fig. 6). The pedons are strongly acid neutral and have base saturation (V) above 50% in all horizons, except those of Umbrisol (Supplementary material Table S.1). The Ca^{2+} concentration is dominantly above 1 cmolc kg^{-1}. As Anthrosols, the total organic carbon (C) and extractable P by Mehlich-1 (P_M) content decrease with the increase of depth. The C content in the

Table 2
Morphological properties of soils.

Horizon	Depth (cm)	Boundary (distinctness, topography)	Color (moist, dry)	Structure (grade, size, type)	Consistence (dry, moist, wetter, cementation)	Roots (quantity, size)	Pores (quantity, size, shape)	Artifacts (kind, quantity, roundness, shape, cohesion, penetrability, persistence)
Soils with anthropic influence								
Pantoplaggic Anthrosols (Pantoothodystric, Pantoloamic, Epiprotechnic)/ 'Anthropic' Typic Ustothents/ NEOSSOLO REGOLÍTICO Distrófico antrópico								
Au1	0–14	G-S	10YR 4/2,2.5Y 5/4	2, m, sbk	SH, SH, ss, po, NC	2, f	2, f, DT	postsherd, 40, AN, -, I, C, P, P
Au2	14–27	G-S	10YR 3/4,2.5Y 6/4	1, f, sbk	S, FR, ss, po, NC	2, f	2, m, DT	postsherd, 20, AN, -, I, C, P, P
Au3	27–45	C-S	10YR 3/4, 2.5Y 5/4	1, f, sbk	S, FR, ss, ps, NC	2, f	2, m, TU	postsherd, 20, AN, -, I, C, P, P
C	45–50 +	–	10YR 3/4,2.5Y 5/4	1, f, sbk	L, L, so, po, NC	2, f	1, f, VE	
Pantopretic Anthrosols (Pantohypereutric, Pantoloamic, Epienfoleptic, Pantotechnic)/ 'Anthropic' Lithic Ustorthents/ NEOSSOLO LITÓLICO Hístico antrópico								
Au	0–12	A-S	5Y 1/1,5Y 3/2	1, f, sbk	L, L, so, po, NC	absent	1, f, VE	charcoal, 2
R	12 +							
Pantopretic Anthrosols (Pantoalcalic, Pantoloamic, Escalic, Endoleptic, Epiprototechnic)/ 'Anthropic' Lithic Ustorthents/ NEOSSOLO LITÓLICO Distroúmbrico antrópico								
Au1	0–5	G-S	10YR 3/2,10YR 6/2	1, f, sbk	S, FR, so, po, NC	1, vf	1, f, IR	postsherd, 10, VA, -, C, P
Au2	5–10	G-S	2.5Y 4/3,2.5Y 7/3	1, m, sbk	S, FR, so, po, NC	1, f	1, f, IR	postsherd, 10, VA, -, C, P
Au3	10–20	G-S	2.5Y 3/2,2.5Y 6/2	1, m, sbk	S, FR, so, po, NC	1, f	1, f, IR	postsherd, 10, VA, -, C, P
Au4	20–25	A-S	10YR 3/1,2.5Y 5/1	1, m, sbk	S, FR, so, po, NC	1, vf	1, f, IR	bottom ash, 20/ charcoal, 2
R	25 +							
Pantopretic Anthrosols (Pantoalcalic, Pantoloamic, Escalic, Endoleptic, Epitechnic)/ 'Anthropic' Lithic Ustorthents/ NEOSSOLO LITÓLICO Eutrófico antrópico								
Au1	0–10	C-S	5Y 2.5/1,5Y 5/1	2, m, sbk	S, FR, ss, po, NC	1, vf	1, vf, f, TU	
Au2	10–15	C-S	5Y 2.5/1,5Y 7/1	2, f, sbk	S, FR, ss, po, NC	2/1, vf/f, m	2, f, m, TU	
Au3	15–30	C-S	5Y 2/1,5Y 3/1	1, f, sbk	S, FR, so, po, NC	1, m, f, co	1, m, f, TU	debitage, 10, VA, E, C, P, P/bottom ash, 10
R	30 +							
Soils without anthropic influence								
Pantohypereutric Leptic Regosols (Pantoarenic, Ochric)/ Xeric Torripsamments/ NEOSSOLO REGOLÍTICO Eutrófico saprolítico arênico								
A	0–4	C-S	2.5Y 4/2,2.5Y 6/2	1, f, gr	SH, FR, so, po, NC	2, f	3, m, TU	
C_1	4–25	G-S	5Y 3/2,2.5Y 4/2	1, m, sbk	SH, FR, so, po, NC	1, m, co	2, m, IR	
C_2	25–60	C-S	5Y 3/2,2.5Y 6/2	1, m, sbk	SH, FR, so, po, NC	1, m, co	1, m, VE	
R	60 +							
Pantohypereutric Leptic Regosols (Pantoloamic, Ochric)/ Lithic Torripsamments/ NEOSSOLO LITÓLICO Eutrófico fragmentário								
A	0–20	C-S	7.5YR 3/4,7.5YR 6/6	1, m, sbk	SH, FR, so, po, NC	3, f, m, co	2, m, TU	
Cr	20–40	C-S	7.5YR 5/4,7.5YR 6/6	0, -, m	L, L, so, po, NC	absent	1, f, VE	
R	40 +							
Pantorhodic Endovertic Leptic Luvisols (Clayic, Pantohypereutric, Ochric)/ Lithic Rhodustalfs/ LUVISSOLO CRÔMICO Órtico vertissólico								
A	0–10	C-S	2.5YR 2/3	2, f, gr	S, FR, so, p, NC	absent	1, m, VE	
Bt	10–40	C-S	2.5YR 2/4	3, co, abk	H, FI, s, p, NC	1, m	1, f, VE	
Btss	40–45	A-S	2.5YR ¾	3, m, pr	EH, EF, vs, vp, NC	absent	1, f, VE	
R	45 +							
Endoleptic Umbrisols (Pantoloamic, Hyperdystric)/ Ustic Torriorthents/ NEOSSOLO REGOLÍTICO Húmico léptico								
A1	0–5	D-S	5Y 1/1,5Y 2.5/1	2, m, gr	S, L, so, po, NC	3/2, f-vf/m	3, m-f, DT	
A2	5–40	D-S	5Y 2.5/1,5Y 2.5/2	2, m, gr	S, FR, so, po, NC	3/2, f-vf/m-co	3, f-m-vf, DT	
A3	40–55	C-S	5Y 2.5/2,5Y 4/4	1, m, sbk	S, FR, so, po, NC	3, m-f-vf	3, m-f, TU	
Cr	55–70 (60–80)	A-W	5Y 3/2,5Y 4/4	0, -, m	L, FR, so, ps, NC	2, f-vf	1, f-m, IR	
R	70 +							

(*continued on next page*)

Table 2 (*continued*)

Horizon	Depth (cm)	Boundary (distinctness, topography)	Color (moist, dry)	Structure (grade, size, type)	Consistence (dry, moist, wetter, cementation)	Roots (quantity, size)	Pores (quantity, size, shape)	Artifacts (kind, quantity, roundness, shape, cohesion, penetrability, persistence)
Pantooligeoeutric Leptic Pantofluvic Fluvisols (Arenic, Ochric, Nechic)/ Aquic Torrifluvents/ NEOSSOLO FLÚVICO Psamíticos Ta Eutrófico léptico								
A	0–7	C-S	5Y 3/2,5Y 4/6	2, m, sbk	SH, FI, so, po, NC	1, vf	2, f, TU	
C_1	7–11	A-S	5Y 5/4,5Y 6/6	1, m, sbk	SH, FI, so, po, NC	1, vf	1, f, TU	
C_2/C_3	11–12	A-B	Gley 1 3/10Y,Gley 1 4/10Y	0, -, m	S, FI, s, po, NC	absent	1, f, IR	
C_3	11–20	C-W	2.5Y 4/3,2.5Y 6/4	1, co, sbk	L, L, so, po, NC	absent	1, f, VE	
C_4	20–29	C-S	Variegated	1, co, sbk	L, L, so, po, NC	absent	1, vf, IR	
C_5	29–40	A-S	Variegated	1, co, sbk	L, L, so, po, NC	absent	2, m, IR	
R	40+							

Distinctness: A = abrupt, C = Clear, D = diffuse, G = gradual. Topography: B = broken, S = smooth, W = wavy. Structure: Grade: 0 = structureless, 1 = weak, 2 = moderate, 3 = strong. Size: co = coarse, f = fine, m = medium. Type: abk = angular block, gr = granular, m = massive, pr = prismatic, sbk = subangular block, sg = single grain. Consistence: Dry: EH = extreme hard, H = hard, L = loose, S = soft, SH = slightly hard. Moist: EF = extreme firm, FI = firm, FR = friable, L = loose, SH = slightly hard. Wetter: s = sticky, so = nonsticky, ss = slightly sticky, p = plastic, po = nonplastic, ps = slightly plastic, vp = very plastic, vs = very sticky. Cementation: NC = non-cemented. Roots and pores: 1 = few, 2 = common, 3 = abundant, co = coarse, f = fine, m = medium, vf = very fine, DT = dendritic tubular, IR = interstitial, TU = tubular, VE = vesicular. Artifacts: Roundness: AN = angular, VA = very angular. Shape: E = elongated, I = irregular. Cohesion: C = cohesive. Penetrability: P = penetrable. Persistence: P = persistent.

Table 3
Thermoluminescence age and related data.

Sample	Anual dose				Accumulated dose	Burial adjustament				Age
	Th ($mg\ kg^{-1}$)	U ($mg\ kg^{-1}$)	K (%)	Dose rate µGy/y	Gy	Th ($mg\ kg^{-1}$)	U ($mg\ kg^{-1}$)	K (%)	Dose rate µGy/y	(y B. P.)
Ceramic of SP3	6.831 ± 0.345	1.750 ± 0.121	5.261 ± 0.230	6.097 ± 191	4.3	19.346 ± 0.850	5.929 ± 0.264	10.288 ± 0.338	12.778 ± 285	490 ± 69

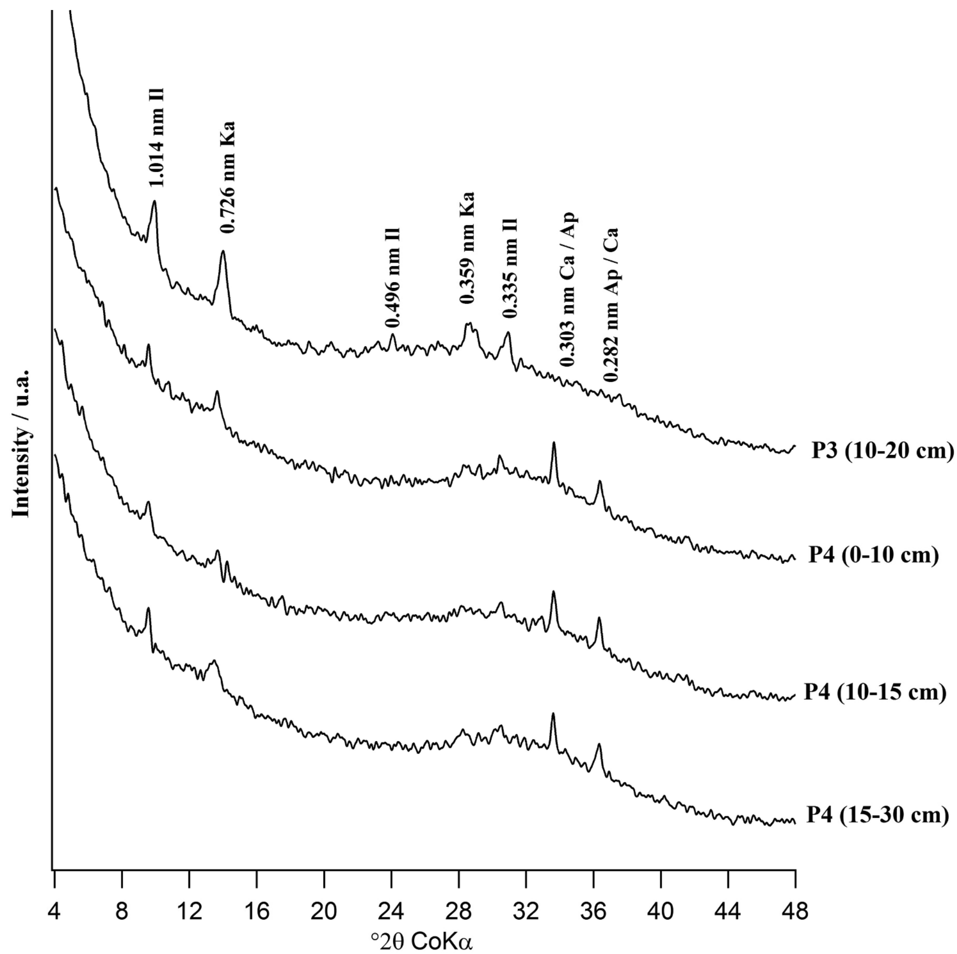

Fig. 4. XRD patterns collected from clay mineral (oriented powder). Il = Illite; Ka = Kaolinite; Ca = Calcite; Ap = Apatite.

upper horizon ranged between 0.58% and 3.44%. In the 10–50 cm increment, the C concentrations ranged from 0.23% to 1.33%. The P_M content in the upper horizon ranged from 1.3 mg kg^{-1} to 98.2 mg kg^{-1}.

5. Discussion

5.1. How are Anthrosols in Caatinga different?

The pedological properties of Anthrosols are anomalous in Caatinga. They exhibit evidences of ancient anthropic occupation, in which the combination of relatively intense erosion of surface horizon, low precipitation and high potential evapotranspiration favors the formation of soils with high organic C and P contents compared to soil without anthropic influence. These soils have up to three, six and 671 times, respectively, more soil organic carbon, exchangeable calcium and phosphorus compared to adjacent soils (Supplementary material Table S.1).

These anomalies are attributed to the anthropic influence. Even when the artifacts are present in relative small quantities they affect significantly physical and chemical soil properties (Glaser, 2007). Anthrosols in Caatinga have H_2O pH similar to Anthrosols described in the Amazonia rainforest (Supplementary material Table S.1). Neutral to alkaline pH is attributed to the abrasion pH of ceramic. The hydrolysis of base cations from abraded surfaces of phyllosilicates which compose ceramics releases hydroxyls (Howard, 2017). Furthermore, less common slightly acid pH, as observed in 'Anthropic' Typic Ustothents, can be attributed to hydrolysis of Al^{3+} (or Fe^{3+}) exposed at the broken edges of phyllosilicates. High Ca and P contents are attributed to bones and organic-metallic complexes (Glaser et al., 2000; Novotny et al., 2007; Howard, 2017).

The more developed structure of Anthrosols compared to soils without anthropic influence is attributed to the high organic carbon content (Campos et al., 2011; Macedo et al., 2017). Although the proportion of charcoal of Anthrosols in Caatinga is 5 times lower than in Amazonian dark earths (Macedo et al., 2017), it seems enough to reduce value and chroma. The value and chroma are similar to the anthropic horizon described in Amazonian dark earths (Campos et al., 2011). The melanization is attributed to the incorporation of organic remains (German, 2003) and to the stabilization of organic compounds such as charcoal (Cunha et al., 2007).

The high background in diffractogram and low reflection intensity indicate low crystallinity minerals (Fig. 4). Presence of phosphate minerals, even in the clay fraction, can be justified by anthropic addition of bones and low weathering under semiarid climate of the study area (Oliveira et al., 2018). This promotes the formation of poorly crystallized minerals (Klug and Alexander, 1974), increase in XRD background and decrease in reflection intensity. The low degree of crystallinity of clay minerals can be attributed to high pH, P and Ca contents, as well as to organic carbon graphitized compounds and calcined remnants of shell temper used in the manufacture of the ceramic vessels (Souza et al., 2016).

High values of P_{REM} indicates virtual absence of Fe oxides. Goethite, hematite and other Fe oxides have a high affinity for phosphate (Fontes and Weed, 1996; Weng, 2014). Besides that, the low Feo and Fed indicates the inhibitory effect to Fe-oxide and vivianite formation exerted by semiarid climate, leucocratic parental material and soil organic matter (Glasauer et al., 2003). The overall mineralogy from silt and sand are in agreement with the parent material of these soils and its maintenance in these fractions by semiarid climate (Cunha et al., 2010).

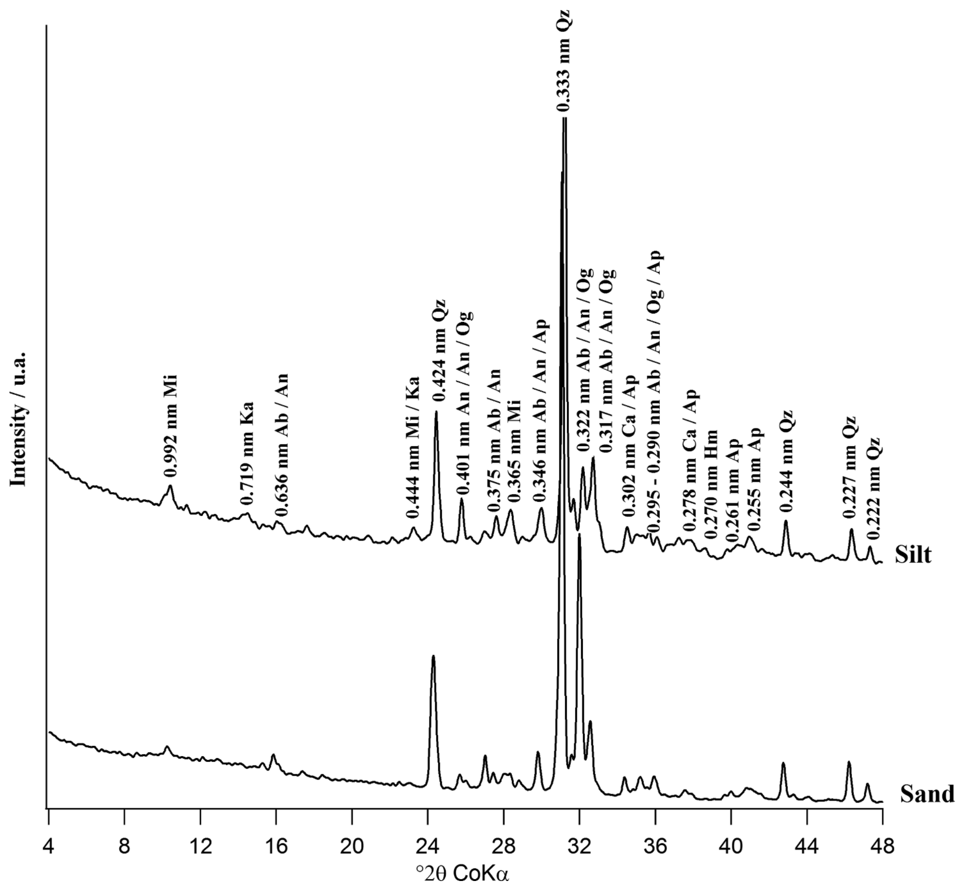

Fig. 5. XRD patterns collected from sand and silt fractions (random powder). Qz = quartz; Mi = mica; An = anatase; Ab = albite; Og = oligoclase; Ap = apatite; Ca = calcite; Ka = Kaolinite; Hm = Hematite.

Distinct to Amazonian dark earth (Novotny et al., 2007; Petrovsky et al., 2001), low magnetization in Anthrosols in Caatinga is attributed to low Fe content and virtual absence of Fe oxides (Table 4 and Fig. 4). The degree of magnetization depends on the amount of magnetite, maghemite, element iron and heavy metals present in earth material.

High organic carbon and P contents below 30 cm depth can be attributed to leaching. Loamic or coarser texture of shallow Caatinga soils favors lessivage of organic compounds and melanization of all pedon. Particles of density < 2.0 g cm^{-3} have the highest contents of black carbon and can be easily leached from surface horizons. P leaching is favored by low clay content and virtual absence of Fe oxides, which would otherwise adsorb P as mono and polydentate forms (Novais and Smyth, 1999).

The incomplete combustion creates highly reactive and stable condensed aromatic structures known as black carbon. The higher organic C content in dark earths compared to non-anthropic soils in Caatinga is attributed to ash and charcoal (Glaser et al., 2000). Higher humification in dark earths can also be related to the high Ca contents, which reduces solubility of organic matter by forming more stable aggregates (Lima et al., 2002).

5.2. *Genesis of Anthrosols in Caatinga*

Properties of anthropic horizon are highly variable according to pedoenvironments and intensity of occupation (Fraser and Clement, 2008; Heckenberger et al., 1999; Kern et al., 2009; McMichael et al., 2012). The data suggest that the sites are degraded and/or, were less populated compared to the Amazonian dark earth.

Radiocarbon dating and thermoluminescence indicate that Anthrosols in Caatinga have the same age of the majority of Amazonian dark earth (Heckenberger et al., 1999; Neves et al., 2004a,b; Meggers & Miller, 2006; Silveira et al., 2011). Palynological evidence indicates establishment of the current semiarid climate in the region approximately 8,500 years before the present (Medeiros et al., 2018). So, these results reveal the past cultures from Caatinga in a new, much more complex light. Amazonian dark earth is commonly located between 5 and 25 m above the closest river (Kern et al., 2009). If this trend is kept in xeric climates, Caatinga dark earth can indicate paleochannels. Eighty percent of Amazonian dark earths cover areas between 0.5 and 2 ha and commonly the anthropic horizon has 30 to 60 cm of thickness (Kern et al., 2009). Once Caatinga dark earths cover smaller areas and are shallower, we think that these soils are evidences of paleochannels and nomadism.

Contrary to the patterns recognized in the Amazonian lands (Schmidt et al., 2014), Anthrosols in Caatinga are found in small shelters in crystalline rocks, regionally known as "*locas*", near to springs and, or, cavities in rocks (tafone), denominated popularly as "*tanques*". These tafone accumulate water, even during severe droughts. This strengthens the idea of a pattern of displacement of these ancient communities to refuges, traced by cave paintings (Azevedo Netto and Oliveira, 2015).

It is stated that Amazonian dark earth was a "kitchen midden" soil, where fishing, cultivation or occupation sites of pre-Colombian indigenous incorporate a quantity of organic matter which is enough to improve soil fertility (Sombroek, 1966). Although the high fertile soils dominance in Caatinga, lack of agricultural potential due to semiarid climate induces nomadism (Leal, 2001; Pompeu Sobrinho, 1934; Rull, 2010). Besides the absence of plant refuse and animal and fish bones suggest that these humans did not cultivate or try to incorporate nitrogen and other nutrients in soil. A small human made terrace observed suggest the intention to reduce soil erosion in occupied areas (Table 1). Such habits can be attributed as adaptation to establishment

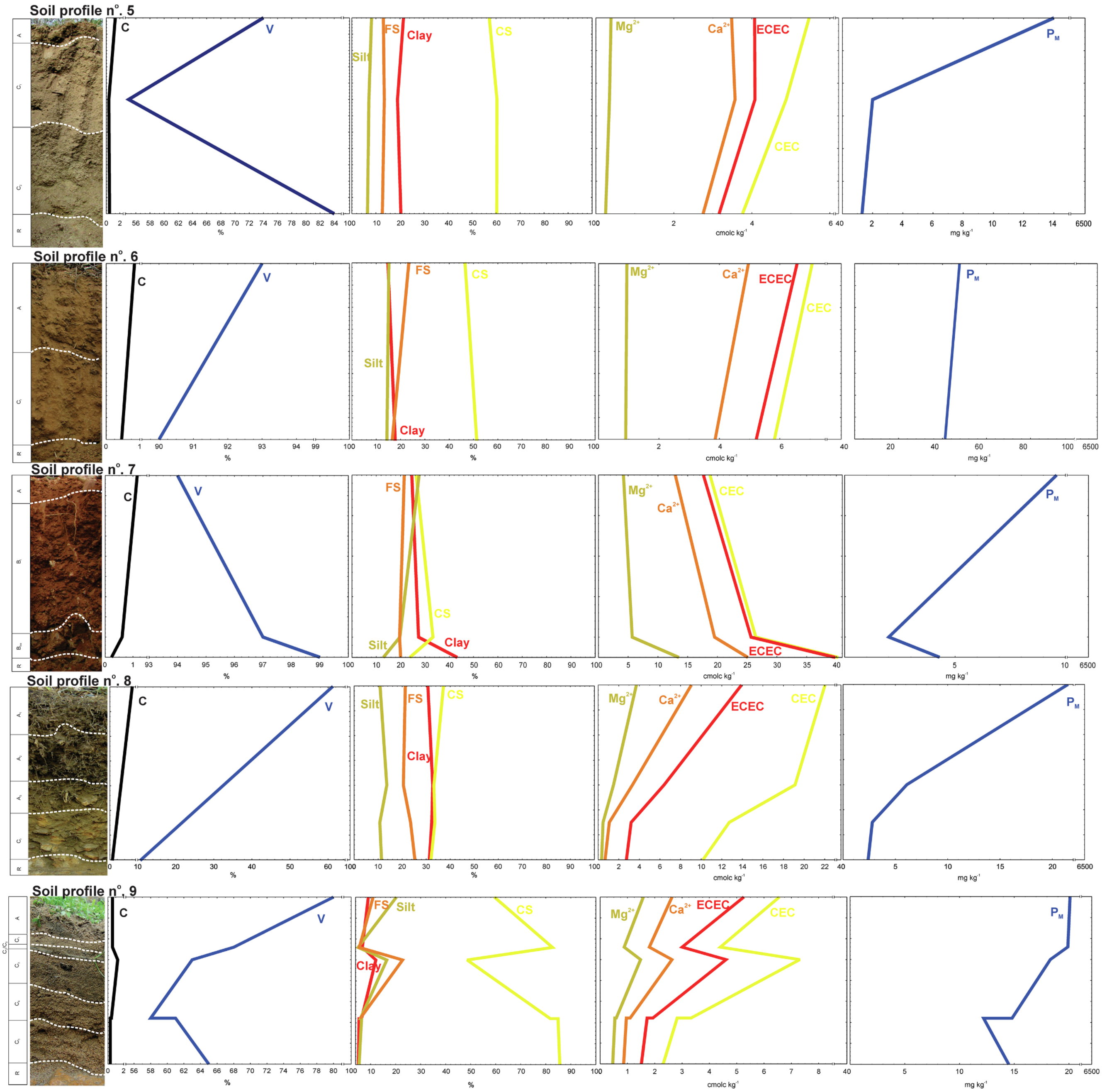

Fig. 6. Physic-chemical soil properties of soil profiles without anthropic influence.

Table 4
Dithionite-citrate-bicarbonate (DCB), acid oxalate method at darkness (AOD), and molar ratios of selected samples.

Soil profile	Depth	DCB		AOD		Feo/Fed
		Fe_2O_3	Al_2O_3	Fe_2O_3	Al_2O_3	
	cm	%				
SP3	10–20	0.21	4.43	0.06	9.53	0.30
SP4	10–15	0.26	3.89	0.03	2.49	0.12

of drier and hot climates in the past 6,790 years BP (Alvim, 2008). Based on abundance of paintings and ceramic, we believe that highlands may have been a refuge to ancient humans in the Brazilian Northeastern during extreme dry years.

5.3. Conclusions

Anthropic influence in soil formation in Caatinga were traceable by higher P, Ca^{2+} and organic carbon contents. Although these soils are contemporaneous of Amazonian dark earth, they have different physic-chemical and mineralogical properties derived from incipient weathering and pedogenesis.

Amazonian dark earth and high productive soils of the Aztec civilization are commonly classified as Pretic Anthrosols. Soil profiles n° 2, 3 and 4 have all requirements to be classified as Anthroposols, except by the thickness below 50 cm. So, we suggest a review of its thickness. Furthermore, we suggest the inclusion of the class 'Antrosolos' in the Brazilian Soil Classification System and 'Anthrosols' in the Soil Taxonomy, once soils that have been profoundly modified by human activities occur beyond the borders of Amazonia and of the Atlantic coast.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2020.104603.

References

Alvarez V., V.H., Novais, R.F., Dias, L.E., Oliveira, J.A., 2000. Determinação e uso do fósforo remanescente. Bol. Inf. da Soc. Bras. Ciência do Solo 25, 27–32.
Alvim, M.C.M., 2008. A antiguidade do Homem no Nordeste do Brasil. In: Pré-História Do Nordeste Do Brasil. UFPE Recife, pp. 61–86.
APG, 2016. An update of the Angiosperm Phylogeny Group classification for the orders and families of flowering plants. Bot. J. Linn. Soc. 181, 1–20. https://doi.org/10.1111/boj.12385.
Araújo, A., Neves, W.A., Piló, L.B., Atui, J.P.V., 2003. Holocene dryness and human occupation in Brazil during the "Archaic Gap". Quat. Res. 64, 298–307.
Araujo, A.G.M., Paisani, J.C., Schrage, T.J., Feathers, J.K., Hartmann, G.A., Ricci, O., 2017. The " Lagoa do Camargo 1 " Paleoindian site : some implications for tropical geomorphology, pedology, and paleoenvironments in southeastern Brazil. Geoarchaeology 32, 662–677. https://doi.org/10.1002/gea.21628.
Araújo Filho, J.C., Ribeiro, M.R., Burgos, N., Marques, F.A., 2017. Solos da Caatinga. In: Curi, N., Ker, J.C., Novais, R.F., Vidal-Torrado, P., Schaefe, C.E.G.R. (Eds.), Pedologia - Solos Dos Biomas Brasileiros. Sociedade Brasileira de Ciência do Solo, Viçosa-MG, pp. 227–260.
Azevedo Netto, C.X., Oliveira, A.M.P., 2015. Documentos arqueológicos e históricos: a relação da cultura material e do ambiente nos sítios arqueológicos do Cariri Paraibano. História Unicap 2, 8–27.
Brazil. Ministry of Culture. Artistic Heritage, 2018. Cadastro Nacional de Sítios Arqueológicos [WWW Document]. Cadastro Nac. Sítios Arqueol. URL (accessed 11. 12.17). http://portal.iphan.gov.br/pagina/detalhes/1699.
Bueno, L., 2011. L'occupation initiale du Brésil dans une perspective macro-régionale: les cas de l'Amazonie, du Nordeste et du centre du Brésil., in: Vialou, D. (Ed.), Peuplements et Préhistoire En Amériques. Éditions du Comité des travaux historiques et scientifiques, pp. 210–220.
Bueno, L., Dias, A.S., Steele, J., 2013. The late pleistocene/early holocene archaeological record in Brazil: a geo-referenced database. Quaternay Int. 301, 74–93.
Campos, M.C.C., Ribeiro, M.R., Júnior, V.S.S., Filho, M.R.R., Souza, R.V.C.C., Almeida, M.C., 2011. Caracterização e classificação de terras pretas arqueológicas na região do médio rio madeira. Bragantia 70, 598–608. https://doi.org/10.1590/S0006-87052011000300016.
Clement, C.R., Denevan, W.M., Heckenberger, M.J., Junqueira, B., Neves, E.G., Teixeira, W.G., Woods, W.I., Andre, A., Clement, C.R., 2015. The domestication of Amazonia before. European conquest.
Correa, A.C.B., Tavares, B.A.C., Monteiro, K.A., Cavalcanti, L.C., Lira, D.R., 2010. Megageomorfologia e morfoestrutura do planalto da Borborema. Rev. do Inst. Geológico 31, 35–52.
Costa, D.P., Peralta, D.F., 2015. Bryophytes diversity in Brazil. Rodriguésia 66, 1063–1071. https://doi.org/10.1590/2175-7860201566409.
Cramon-taubadel, N. Von, Strauss, A., Hubbe, M., 2017. Evolutionary population history of early Paleoamerican cranial morphology. Sci. Adv. 3, e1602289. https://doi.org/10.1126/sciadv.1602289.
Cunha, T.J.F., Madari, B.E., Benites, V. de M., Canellas, L.P., Novotny, E.H., Moutta, R. de O., Trompowsky, P.M., Santos, G. de A., 2007. Fracionamento químico da matéria orgânica e características de ácidos húmicos de solos com horizonte a antrópico da amazônia (Terra Preta). Acta Amaz. 37, 91–98. doi:10.1590/S0044-59672007000100010.
Cunha, T.J.F., Petrete, V.G., Silva, D.J., Mendes, A.M.A., de Melo, R.F., de Oliveira Neto, M.B., da Silva, M.S.L., Alvarez, I.A., 2010. Principais solos do Semiárido tropical brasileiro: caracterização, potencialidades, limitações, fertilidade e manejo. Pesqui. Desenvolv. e inovação, Semiárido Bras.
Dillehay, T.D., 2008. Profiles in Pleistocene History. In: Silverman, H., Isbell, W.H. (Eds.), Handbook of South American Archaeology. Springer, New York, pp. 29–44.
Donagema, G.K., de Campos, D.V.B., Calderano, S.B., Teixeira, W.G., Viana, J.H.M., 2011. Manual de métodos de análise de solos, 2nd ed. Embrapa Solos, Rio de Janeiro.
DRYFLOR, Banda-R, K., Delgado-Salinas, A., Dexter, K.G., Linares-Palomino, R., Oliveira-Filho, A.T., Prado, D., Pullan, M., Quintana, C., Riina, R., Rodriguez M., G.M., Weintritt, J., Acevedo-Rodriguez, P., Adarve, J., Alvarez, E., Aranguren B., A., Arteaga, J.C., Aymard, G., Castano, A., Ceballos-Mago, N., Cogollo, A., Cuadros, H., Delgado, F., Devia, W., Duenas, H., Fajardo, L., Fernandez, A., Fernandez, M.A., Franklin, J., Freid, E.H., Galetti, L.A., Gonto, R., Gonzalez-M., R., Graveson, R., Helmer, E.H., Idarraga, A., Lopez, R., Marcano-Vega, H., Martinez, O.G., Maturo, H. M., McDonald, M., McLaren, K., Melo, O., Mijares, F., Mogni, V., Molina, D., Moreno, N. D. P., Nassar, J.M., Neves, D.M., Oakley, L.J., Oatham, M., Olvera-Luna, A.R., Pezzini, F.F., Dominguez, O.J.R., Rios, M.E., Rivera, O., Rodriguez, N., Rojas, A., Sarkinen, T., Sanchez, R., Smith, M., Vargas, C., Villanueva, B., Pennington, R.T., 2016. Plant diversity patterns in neotropical dry forests and their conservation implications. Science (80-.). 353, 1383–1387. doi:10.1126/science.aaf5080.
Dubois, C.M.F., Politis, G.G., 2017. Environmental dynamics and formation processes at the pampean archaeological locality Zanjón Seco, Argentina. Geoarchaeology 32, 622–632. https://doi.org/10.1002/gea.21630.
Ferreira, C.R.P.C., Antonino, A.C.D., Sampaio, E.V. de S.B., Correia, K.G., Lima, J.R. de S., Soares, W. de A., Menezes, R.S.C., 2018. Soil CO2efflux measurements by alkali absorption and infrared gas analyzer in the Brazilian semiarid region. Rev. Bras. Cienc. do Solo 42, 1–10. doi:10.1590/18069657rbcs20160563.
Fontes, F., Weed, S.B., 1996. Phosphate adsorption by clays from Brazilian Oxisols: relationships with specific surface area and mineralogy. Geoderma 72, 37–51.
Fraser, J.A., Clement, C.R., 2008. Dark Earths and manioc cultivation in Central Amazonia: a window on pre-Columbian agricultural systems? Terras Pretas e o cultivo de mandioca na Amazônia Central : uma janela para os sistemas agrícolas pré-colombianos ? Bol. Mus. Par. Emilio Goeldi 3, 175–194. https://doi.org/10.1590/S1981-81222008000200004.
German, L.A., 2003. Historical contingencies in the coevolution of environment and livelihood: contributions to the debate on Amazonian Black Earth. Geoderma 111, 307–331. https://doi.org/10.1016/S0016-7061(02)00270-7.
Giongo, V., Cunha, T.J.F., Mendes, A.S., Gava, C.A.T., 2011. Carbono no sistem solo-planta no semiárido brasileiro. Rev. Bras. Geogr. Física 06, 1233–1253. https://doi.org/10.5935/1984-2295.20140015.
Glasauer, S., Weidler, P.G., Langley, S., Beveridge, T.J., 2003. Controls on Fe reduction and mineral formation by a subsurface bacterium. Geochim. Cosmochim. Acta 67, 1277–1288.
Glaser, B., 2007. Prehistorically modified soils of central Amazonia: a model for sustainable agriculture in the twenty-first century. Philos. Trans. R. Soc. B Biol. Sci. 362, 187–196. https://doi.org/10.1098/rstb.2006.1978.
Glaser, B., Balashov, E., Haumaier, L., Guggenberger, G., Zech, W., 2000. Black carbon in density fractions of anthropogenic soils of the Brazilian Amazon region. Org. Geochem. 31, 669–678. https://doi.org/10.1016/S0146-6380(00)00044-9.
Hecht, S.B., 2003. Indigenous soil management and the creation of Amazonian Dark Earths: Implications of Kayapó practices. In: Lehmann, J., Kern, D.C., Glaser, B., Woods, W.I. (Eds.), Amazonian Dark Earths Origin, Properties and Management. Kluwer Academic Publishers, Dordrecht, pp. 355–372.
Heckenberger, M.J., Petersen, J.B., Neves, E.G., 1999. Village size and permanence in amazonia: two archaeological examples from brazil. Lat. Am. Antiq. 10, 353–376.
Howard, J., 2017. Anthropogenic Soils. https://doi.org/10.1007/978-90-481-9328-8_5.
IUSS Working Group WRB, 2014. World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps. doi:10.1017/S0014479706394902.
Kämpf, N., Curi, N., 2000. Óxidos de ferro: indicadores de ambientes pedogênicos e geoquímicos. In: Novais, R.F., Alvarez, V.V.H., Schaefer, C.E.G.R. (Eds.), Tópicos Em Ciência Do Solo. SBCS, Viçosa-MG, pp. 107–138.
Kayano, M.T., Andreoli, R.V., 2009. Clima da Região Nordeste do Brasil. In: Cavalcanti, I.F., Ferreira, N.J., Silva, M.G.A.J., Dias, M.A.F.S. (Eds.), Tempo e Clima No Brasil. Oficina de textos, São Paulo, pp. 213–234.
Kelly, R., 2003. Colonization of new land by hunteregatherers: expectations and implications based on ethnographic data, in: ROCKMAN, M., STEELE, J. (Eds.), Colonization of Unfamiliar Landscapes. Routledge, London, pp. 55–58.
Kern, D.C., Kämpf, N., Woods, W.I., Denevan, W.M., Costa, M.L., Frazão, F.J.L., Sombroek, W.G., 2009. As terras preta de índio na Amazônia. In: Teixeira, W.G., Kern, D.C., Madari, B.E., Lima, H.N., Woods, W. (Eds.), As Terras Pretas de Índio Da Amazônia: Sua Caracterização e Uso Deste Conhecimento Na Criação de Novas Áreas. Embrapa Amazônia Ocidental, Manaus- AM, pp. 72–81.
Klug, H.P., Alexander, L.E., 1974. X-ray Diflraction Procedures for Polycrystalline and Amorphous Materials, 2nd ed. John Wiley & Sons.
Leal, M.E., 2001. Microrefugia, small scale ice age forest remnants. Syst. Geogr. Plants 71, 1073–1077.
Levis, C., Costa, F.R.C., Bongers, F., Peña-Claros, M., Clement, C.R., Junqueira, A.B., Neves, E.G., Tamanaha, E.K., Figueiredo, F.O.G., Salomão, R.P., Castilho, C.V., Magnusson, W.E., Phillips, O.L., Guevara, J.E., Sabatier, D., Molino, J.F., Cárdena, D., ter Steege, H., 2017. Persistent effects of pre-Columbian plant domestication on Amazonian forest composition. Science (80-.) 355, 925–931 doi:science.aal0157.
Lima, H.N., Schaefer, C.E.R., Mello, J.W.V., Gilkes, R.J., Ker, J.C., 2002. Pedogenesis and pre-Colombian land use of "Terra Preta Anthrosols" ("Indian black earth") of Western Amazonia. Geoderma 110, 1–17. https://doi.org/10.1016/S0016-7061(02)00141-6.
Macedo, R.S., Teixeira, W.G., Corrêa, M.M., Martins, G.C., Vidal-Torrado, P., 2017. Pedogenetic processes in anthrosols with pretic horizon (Amazonian Dark Earth) in Central Amazon, Brazil. PLoS One 12, 1–19. https://doi.org/10.1371/journal.pone.0178038.
Maia, L.C., Júnior, A.A.D.C., Cavalcanti, L.D.H., Gugliotta, A.D.M., Elisandro, R., Santiago, A.L.M.D.A., Cáceres, M.E.S., Gibertoni, T.B., Aptroot, A., Giachini, A.J., Soares, A.M.S., Silva, A.C.G., Magnago, A.C., Goto, B.T., De, C.R.S., Montoya, C.A.S., Pires-zottarelli, C.L.A., Silva, D.K.A., Soares, D.J., Diogo, H.C., Luz, E.D.M.N., Gumboski, E.L., Wartchow, F., Karstedt, F., Freire, F.M., Coutinho, F.P., Melo, G.S.N. De, Sotão, H.M.P., Baseia, I.G., Pereira, J., Jadson, J.S., Oliveira, D., Souza, J.F., Bezerra, J.L., Neta, L.S.A., Pfenning, L.H., Gusmão, L.F.P., Maria, A., Capelari, M., Jaeger, M.C.W., Pulgarín, M.P., Junior, N.M., Medeiros, P.S. De, Friedrich, R.C.S., Chikowski, R.S., Pires, R.M., Melo, R.F., Silveira, R.M.B., Cortez, V.G., Silva, V.F., 2015. Diversity of Brazilian Fungi Knowledge about the Brazilian fungal diversity was, until 2010, recorded in few taxonomy and ecology. Rodriguésia 66, 1033–1045. https://doi.org/10.1590/2175-7860201566407.
McKeague, J.A., Day, J.H., 1966. Dithionite- and oxalate-extractable Fe and Al as aids in differentiating various classes of soils. Can. J. Soil Sci. 46, 13–22.
McMichael, C.H., Pipersno, D.R., Bush, M.B., Silman, M.R., Zimmerman, A.R., Raczka,

M.F., Lobato, L.C., 2012. Sparse pre-columbian human habitation in Western Amazonia. Science (80-.) 336, 1429–1432.

Medeiros, V.B., Oliveira, P.E., Santos, R.A., Barreto, A.M.F., Oliveira, M.A.T., Pinaya, J.L.D., 2018. New Holocene pollen records from the Brazilian Caatinga. An Acad Bras Cienc 90, 2011–2023.

Meggers, B., Miller, E.T., 2006. Evidência Arqueológica para el comportamiento social y habitacional en la amazonía prehistórica. In: Ríos, G.M., Mora, S., Calvo, F.C. (Eds.), Pueblos y Paisajes Antiguos de La Selva Amazónica. Taraxacum, Washington, D.C., pp. 325–348.

Mehra, O.P., Jackson, M.L., 1953. Iron oxide removal from soils and clays by a dithionite-citrate system buffered with sodium bicarbonate. Clays and 7, 317–327.

Menezes, R., Sampaio, E., Giongo, V., Pérez-Marin, A., 2012. Biogeochemical cycling in terrestrial ecosystems of the Caatinga Biome. Brazilian J. Biol. 72, 643–653. https://doi.org/10.1590/S1519-69842012000400004.

Neves, E.G., Petersen, J.B., Bartone, R.N., Silva, C.A., 2004a. Historical and socio-cultural origins of Amazonian dark earths. In: Lehmann, J., Kern, D.C., Glaser, B., Woods, W.I. (Eds.), Amazonian Dark Earths: Origins, Properties, Manegement. KLUWER ACADEMIC PUBLISHERS, New York, pp. 29–50.

Neves, R.N., Petersen, J.B., Bartone, R.N., Heckenberger, M.J., 2004b. The timing of terra preta formation in the central amazon: archaeological data from three sites. In: Glaser, B., Woods, W.I. (Eds.), Amazonian Dark Earths: Explorations in Space and Time. Springer- Verlag, Berlin, Heidelberg, pp. 125–144 10.1007/978-3-662-0 5683-7.

Novais, R.F., Smyth, T.J., 1999. Fósforo em solo e planta em condições tropicais. Editora Universidade Federal de Viçosa, Viçosa-MG.

Novotny, E.H., Deazevedo, E.R., Bonagamba, T.J., Cunha, T.J.F., Madari, B.E., Benites, V.D.M., Hayes, M.H.B., 2007. Studies of the compositions of humic acids from Amazonian Dark Earth soils. Environ. Sci. Technol. 41, 400–405. https://doi.org/10.1021/es060941x.

Oliveira, D.P., Sartor, L.R., Júnior, V.S.S., Corrêa, M.M., Romero, R.E., Andrade, G.R.P., 2018. Catena Weathering and clay formation in semi-arid calcareous soils from Northeastern Brazil. Catena 162, 325–332. https://doi.org/10.1016/j.catena.2017.10.030.

Pessenda, L.C.R., Camargo, P.B., 1991. Datação radiocarbônica de amostras de interesse arqueológico e geológico por espectrometria de cintilação líquida de baixa radiação de fundo. Quim. Nova 14, 98–103.

Petrovsky, E., Kapicka, A., Jordanova, N., Boruvka, L., 2001. Magnetic properties of alluvial soils contaminated with lead, zinc and cadmium. J. Appl. Geophusics 48, 127–136.

Pompeu Sobrinho, T., 1934. Os Tapuias do Nordeste e a monografia de Elias Herckman. Rev. do Instituo do Ceará XLVIII 7–28.

Prado, D.E., 2000. Seasonally dry forests of tropical South America : From forgotten ecosystems to a new phytogeographic unit. Edinburgh J. Bot. 57, 437–461. https://doi.org/10.1017/S096042860000041X.

Reimer PJ, Baillie MGL, Bard E, Bayliss A, Beck JW, Bertrand CJH, Blackwell PG, Buck CE, Burr GS, Cutler KB, Damon PE, Edwards RL, Fairbanks RG, Friedrich M, Guilderson TP, Hogg AG, Hughen KA, Kromer B, McCormac FG, Manning SW, Ramsey CB, Reimer RW, Remmele S, Southon JR, Stuiver M, Talamo S, Taylor FW, Van der Plicht J, Weyhenmeyer CE (2004) IntCal04 Terrestrial radiocarbon age calibration 26–0 ka B.P. Radiocarbon 46:1,029–1,058.

Roosevelt, A.C., 2000. The Lower Amazon: A dynamic human habitat. In: Lentz, D.L. (Ed.), Imperfect Balance: Landscape Transformations in the Precolumbian Americas. Columbia University Press, New York, pp. 455–491.

Rückamp, D., Amelung, W., Theisz, N., Bandeira, A.G., Martius, C., 2010. Phosphorus forms in Brazilian termite nests and soils: Relevance of feeding guild and ecosystems. Geoderma 155, 269–279. https://doi.org/10.1016/j.geoderma.2009.12.010.

Rull, V., 2010. On microrefugia and cryptic refugia. J. Biogeogr. 37, 1623–1625. https://doi.org/10.1111/j.1365-2699.2010.02300.x.Journal.

Santos, H.G.S., Jacomine, P.K., Anjos, L.H.C., Oliveira, V.A., Lumbreras, J.F., Coelho, M. R., Almeida, J.A., Cunha, T.J.F., Oliveira, J.B., 2013. Sistema brasileiro de classificação de solos. Embrapa, Rio de Janeiro. doi:ISBN 978-85-7035-198-2.

Santos, R.M., Oliveira-filho, A.T., Eisenlohr, P.V., Queiroz, L.P., Cardoso, D.B.O.S., Rodal, M.J.N., 2012. Identity and relationships of the Arboreal Caatinga among other floristic units of seasonally dry tropical forests (SDTFs) of north-eastern and Central Brazil. Ecol. Evol. 2, 409–428. https://doi.org/10.1002/ece3.91.

Schmidt, M.J., Py-Daniel, A.R., Moraes, C.P., Valle, R.B.M., Caromano, C.F., Teixeira, W.G., Barbosa, C.A., Fonseca, J.A., Magalhães, M.P., Santos, D.S.C., Silva, R.S., Guapindaia, V.L., Moraes, B., Lima, H.P., Neves, E.G., Heckenberger, M.J., 2014. Dark earths and the human built landscape in Amazonia: a widespread pattern of anthrosol formation. J. Archaeol. Sci. 42, 152–165. https://doi.org/10.1016/j.jas.2013.11.002.

Silveira, M.I., Oliveira, E.R., Kern, D.C., Costa, M.L., Rodrigues, S.F.S., 2011. O sítio Jabuti, em Bragança, Pará, no cenário arqueológico do litoral amazônico Site Jabuti, in Bragança, State of Pará, in the archaeological scenario of the Amazonian coastal landscape. Bol. do Mus. Para. Emílio Goeldi 6, 335–345.

Soil Survey Staff, 2010. Keys to Soil Taxonomy, 2010, eleventh ed. SCS, USDA.

Sombroek, W.G., 1966. Amazon Soils: A Reconnaissance of the Soils of the Brazilian Amazon Region. Centre for Agricultural Publications and Documentation, Wageningen.

Souza, L.C. de, Lima, H.V. de, Rodrigues, S., Kern, D.C., Silva, Á.P. da, Piccinin, J.L., 2016. Chemical and physical properties of an anthropogenic dark earth soil from Bragança, Para, Eastern Amazon. Acta Amaz. 46, 337–344. doi:10.1590/1809-4392201505663.

Weng, L., 2014. Factors Controlling Phosphate Interaction with Iron Oxides. doi:10.2134/jeq2011.025.

Xavier, R.A., Seabra, V.S., Damasceno, J., Dornellas, P.C., 2016. Mapeamento geomorfológico da bacia do Rio Paraíba (PB) utilizando classificação baseada em objetos. Acta geográfica 10, 139–152.

Yeomans, J.C., Bremner, J.M., 1988. A rapid and precise method for routine determination of organic carbon in soil 1. Commun. Soil Sci. Plant Anal. 19, 1467–1476. https://doi.org/10.1080/00103628809368027.