Association of Post-Barreiras and Barreiras Formation strata and influence on soil genesis, Southern Bahia – Brazil

Cristiano Marcelo Pereira de Souza(1)*, Liovando Marciano da Costa(2), Francis Henrique Tenório Firmino(3), Carlos César Uchôa de Lima(3), Ana Maria Souza dos Santos Moreau(4) and Marcos Esdras Leite(1)

(1) Universidade Estadual de Montes Claros, Departamento de Geociências, Pós-Graduação em Geografia, Montes Claros, Minas Gerais, Brasil.
(2) Universidade Federal de Viçosa, Departamento de Solos, Programa de Pós-Graduação em Solos e Nutrição de Plantas, Viçosa, Minas Gerais, Brasil.
(3) Universidade Estadual de Feira de Santana, Departamento de Ciências Exatas, Programa de Pós-graduação em Modelagem em Ciências da Terra e do Ambiente, Feira de Santana, Bahia, Brasil.
(4) Universidade Estadual de Santa Cruz, Departamento de Ciências Agrárias e Ambientais, Ilhéus, Bahia, Brasil.

ABSTRACT: The term Post-Barreiras is a definition for sediments above the deposits of the Barreiras Formation, and the genesis of soils in these environments must be related to sedimentary deposition. Our objective was to apply multi-technique analyses to characterize the sediments and soils to understand pedogenesis in these environments. We analysed sedimentological parameters and the geochronology of sediments. Morphological, chemical, and mineralogical analyses allowed the characterization of the soil. Also, these data supported the analysis of lithological discontinuity. We considered the contents of Ti and Zr, uniformity value, the fraction of organic material, morphology, and palynological analysis. The age of Post-Barreiras sediments is from the Pleistocene, and they have a more significant variation of sedimentological parameters concerning Barreiras Formation layers. In general, the soils are sandy, acidic, have a low level of exchangeable cations. Mineralogy has a predominance of quartz and kaolinite minerals. In the region, there are soils with low morphological variation, classified as Quartzipsamments. In other cases, there are soils with apparent spodic morphology, which is conditioned by four aspects: (i) Podzolization in Post-Barreiras sandy sediments without evidence of lithological discontinuity, forming Bs horizon (Spodosols); (ii) contact zones (Post-Barreiras/Barreiras Formation) with physical, chemical, and morphological evidence of discontinuity, forming Quartzipsamments or Ultisols; (iii) layers of the Barreiras Formation buried by Post-Barreiras sediments and the subsequent podzolization process, forming Bhm horizon (Spodosols); and (iv) destruction of Ultisols clay, forming Bs horizon (Spodosols). The sedimentary association (Post-Barreiras/Barreiras Formation) favors the development of different soils. The contact zones generate a morphological aspect similar to the Spodosols, associated or not with podzolization processes.

Keywords: Coastal Tablelands, lithological discontinuity, podzolization, Quaternary sediments.
INTRODUCTION

The Barreiras Formation are siliciclastic sediments of mostly continental origin with marine influence on sedimentation. These deposits occur on the Brazilian coast from the parallel -22° S to 04° N, sometimes forming Coastal Tablelands (Bigarella, 1975; Vilas Boas et al., 2001; Rossetti et al., 2013). Occasionally, above the Coastal Tablelands, there are discordant or concordant formations. The origin of these features varies between pedological processes forming sandy depressions (Moreau et al., 2006a; Oliveira et al., 2010; Schiavo et al., 2020). Also, by sedimentary deposition, forming the Post-Barreiras sediments (Tatumi et al., 2008; Rossetti et al., 2011; Gandini et al., 2014). In the literature, there are several pedological studies on sediments from the Barreiras Formation (Demattê et al., 1996; Moreau et al., 2006b; Cunha et al., 2019). However, studies with Post-Barreiras sediments do not focus on pedology.

Post-Barreiras sediments are geographically casual along the Brazilian coast, and it can present different granulometric characteristics due to environmental influences. In the Northern region, they are sandy deposits with structures for dissipating dunes (Tatumi et al., 2008). In the northeast region, in the Paraiba Basin, there are dune structures, and also there are hardened sandstones, mudstone, or complex types of soft-sediment deformation structures (Rossetti et al., 2011). In the state of Bahia, are sandy with dune features (Tricart and Silva, 1968), where the sands have a low degree of roundness, ranging from white and yellowish colors (Souza et al., 2016a). In general, these studies with Post-Barreiras are focused on lithostratigraphy and the origin of sediments. While pedological studies only mention Post-Barreiras sediments as parent material (Horbe and Costa, 1997).

The wind origin of the Post-Barreiras sediments in the state of Bahia (municipality of Ilhéus) is the main factor for granulometric selection of sand, generating features in the landscape similar to the mussunungas sandy areas (Souza et al., 2016b). However, the origin of the mussunungas involves the action process of acidolysis on Ultisols clay (Moreau et al., 2006a; Oliveira et al., 2010; Schiavo et al., 2020). On the other hand, the origin of Post-Barreiras is due to sedimentary deposition (Rossetti et al., 2011; Gandini et al., 2014; Souza et al., 2016a), and this aspect can influence pedogenesis.

Considering the soil as an open system, the dynamic translocation and transformation processes, can tend to mask the evidence of morphogenetic changes (Phillips and Lorz, 2008), especially in tropical environments (Cooper et al., 2002). For example, morphology with a spodic appearance, but without podzolization, is a condition influenced by the deposition of sediments (Nott et al., 1994; Anjos et al., 2013). On the other hand, podzolization can occur in allochthonous soils, generating spodic features (Waroszewski et al., 2015). Therefore, sometimes the soil morphological analysis alone is not enough (Silva et al., 2002), and recognition of geogenic heterogeneity and layer distinction requires other analyses (Waroszewski et al., 2013).

The multidisciplinary approach involves the morphological analysis of the soil, allowing the identification of the pebble line, the abrupt difference in particle-size distribution, or color between horizons unrelated from pedogenesis (Phillips, 2007; IUSS Working Group WRB, 2015). Quantitatively, the data of soil granulometric fractions allow the calculation of soil uniformity indices (Schaetzl, 1998; Ferreira et al., 2015). The fractionation of organic matter indicates the presence or absence of pedogenetic translocation processes, assisting in the identification of illuvial horizons (González-Pérez et al., 2008; Tadini et al., 2017). In the geochemical context, the Ti and Zr contents provide the idea of allochthonous or autochthonous soils (Novaes Filho et al., 2012). Furthermore, palynology geochronology allows the understanding of the geological and paleoenvironmental context of the soil (Waroszewski et al., 2015; Buso Junior et al., 2019).
Considering that the Post-Barreiras environment originates from sedimentary deposition, we believe that this process influences the genesis of soils. Our objective was to apply multi-technique analyses to characterize the sediments and soils, to understand the processes of soil genesis in the Post-Barreiras environment.

MATERIALS AND METHODS

Study area

The area of study is in the South of Bahia along the coast of the municipality of Ilhéus, between the coordinates -14° 41’ to -15° 11’ S and -39° 55’ to -38° 99’ W of Gr. The region is under the domain Atlantic Forest vegetation, with precipitation ranging from 1900 to 2200 mm annually in the coastal zone (Figure 1a).

In the coastal portion, there is the presence of Coastal Tablelands (Barreiras Formation), configured as paleociffs, formed due to the marine progression and regression. Above the Coastal Tablelands, there is sandy material (Post-Barreiras), which is the result of deposition (Souza et al., 2016a). Sediments occur at a maximum of 5 km after the coastline, in altitudes ranging from 15 to 120 m, with a mean elevation of 60 m (Figure 1b). In the area, we collect sediment and soil samples.

Analytical procedures

We performed the dating of four Post-Barreiras sediment samples using the Optically Stimulated Luminescence (OSL) method. We use dark PVC tubes 30-cm-long and 5 cm in diameter and inserted horizontally in previously cleaned layers. They had no transparency to prevent renewed whitening by sunlight. The treatment and analysis of the samples were performed at the DATA LTDA laboratory in São Paulo, Brazil. The ages were obtained from the relationship between the Paleodose values (De) and annual dose values (Dose Rate). The OSL dating protocol was the Single Aliquot Regeneration (SAR), with 15 aliquots (grain samples). The procedures were based on Aitken (1985) and Murray and Wintle (2000).

We performed sedimentological parameters analysis in samples of Post-Barreiras and Barreiras Formation (Folk and Ward, 1957). We used 40 g samples, free of clay, silt, and organic matter, sieved in a range of 1/5 in the phi (ϕ), with sieves between -1 to 4 ϕ. From the sand weights retained in each sieve, we entered the values in the Sysgran software (Camargo, 2006). The software allows us to automatically obtain the values of median, mean, standard deviation, asymmetry, and graphical kurtosis (Folk and Ward, 1957).

We performed the morphological description on six soil profiles based on Santos et al. (2015). We collected samples of the horizons for physical, chemical, mineralogical, and palynological analysis. The collected soil was air-dried and sieved (2 mm). The soil fractions were separated into five fractions of sand using sieves, and clay and silt determined by the pipette method (Ruiz, 2005).

For chemical characterization, we used the procedures described by Teixeira et al. (2017). The pH(H2O) and pH(KCl) were determined using a potentiometer with ratio soil:liquid equal to 1:2.5 v/v. The elements Ca\(^{2+}\), Mg\(^{2+}\), and Al\(^{3+}\) (cmol, dm\(^{-3}\)) were extracted with KCl 1 mol L\(^{-1}\) solution, to determine the concentration of these three metals we use atomic absorption spectrophotometry. The contents of K\(^{+}\) and Na\(^{+}\) (cmol, dm\(^{-3}\)) and available P (mg dm\(^{-3}\)) were extracted using Mehlich-1 solution. For the determination of K\(^{+}\) and Na\(^{+}\), the flame spectrophotometry was used, and P was based on colorimetry. For the potential acidity levels (H+Al cmol dm\(^{-3}\)) it was used 0.5 mol L\(^{-1}\) calcium acetate solution buffered at pH 7.0. From the chemical analyses were calculated sum of base (SB), effective cation exchange capacity (CEC\(_{E}\)), total cation exchange capacity (CEC\(_{T}\)), base saturation (V%), and Al\(^{3+}\) saturation (m%). The P in solution or remaining (mg L\(^{-1}\))...
was determined with a CaCl₂ solution containing 60 mg L⁻¹ of P; the stirring time was 1 h, and the soil:solution ratio was 1:50.

Soil organic carbon was determined by the Walkley-Black titration method (Mebius, 1960) by wet oxidation with K₂Cr₂O₇ 0.167 mol L⁻¹ in the presence of sulfuric acid with external heating. We fractionated the organic matter based on the differential solubility technique (Swift, 1996) with three repetitions. The fractions humin, fulvic, and humic acids were operationally determined concerning their solubilities in the aqueous environment based on the pH of the extraction solution. From organic matter fractionation data, we sought to identify if the origin of the organic sub-horizons is related to processes of illuviation.

To identify the total contents of some elements, we applied the total attack analysis by alkaline fusion (Guerra et al., 2013). We placed 100 mg of soil (sieved at 0.074 mm) and 125 mg of LiBO₂ below and above the soil (total 250 mg) in graphite crucibles and heated in muffle furnace up to 1000 °C for melting. For solubilization of the beads resulting from the process, we use solution HNO₃ (10 %). The contents of the elements were determined by ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometry).

We perform an analysis of X-ray diffraction (XRD) in some samples free of organic matter. We used PANalytical X’Pert Pro device with CoKα tube, operated between the scanning angles 4 and 50 °2θ at a scan speed of 1 °2θ min⁻¹, with a potential 40 kV generator and a current generator of 40 mA. We considered the Ti/Zr ratio for analysis of lithological discontinuity (LD) (Equation 1) (Maynard, 1992; Novaes Filho et al., 2012). We used the criterion the variability of the coefficient of variation (CV) of the relation Ti/Zr (Wilding and Drees, 1983), which show the probability of the presence of discontinuity: low (CV <15 %), moderate (CV 15-35 %) and high (CV >35 %).
We also determined the index Uniformity Value (UV), according to the Schaetzl (1998) (Equation 2), which considers the levels of total sand, very fine sand, and silt of the horizons. We used as a limit of detection of discontinuity approximate values of UV = -0.60 to 0.60, and values outside this range indicate LD (Cremeens and Mokma, 1986). The closer the LD value is to zero, the more uniform and similar are the materials of the horizons analysed (Ferreira et al., 2015).

\[
UV = -\frac{(S+VFS)/(TS-VFS)}{(S+VFS)/(TS-VFS)} - 1
\]

in which: \( S \) is silt; \( TS \) is the total sand; and \( VFS \) is the content of very fine sand.

In some organic horizons, with a total organic carbon content of more than 4 %, we performed palynological analysis. The purpose was to identify possible elements indicating whether the material was deposited or resulting from illuviation. We selected organic layers due to the possibility of being formed in a reducing environment, essential for the preservation of palynomorphs. For the palynological analysis, we perform the removal of carbonates by HCl (20 %) and dissolution of silicates by HF (70 %). Subsequently, oxidation with nitric acid (HNO₃) to palynomorph concentration, density separation of any resistant minerals, and passing through the sieve for the elimination of disseminated fine organic matter (Vidal, 1988). Samples were placed on slides and examined in detail from images captured with a Zeiss optical microscope.

We used the data set to classify soils according to the Brazilian Soil Classification System (Santos et al., 2018) and the American System (Soil Survey Staff, 2014).

---

**RESULTS**

**Characteristics of sediments**

In the study area, there are sandy sediments above sediments from the Barreiras Formation. They are discordant or concordant formations of white and yellowish colors (Figure 2a), sometimes with cross-stratification (Figure 2b). Geochronology indicates that they are sediments from the Pleistocene (Table 1). In general, the contact zones between Post-Barreiras and Barreiras Formation tend to be more superficial ~1.5 m, but in some cases, they are below ~6 m in depth. The contacts occur by the presence of layers with the accumulation of organic matter and/or by typical layers of the Barreiras Formation with variegated colors (Figures 2d and 2e).

The sedimentological parameters of the sediments Post-Barreiras and the Barreiras Formation (Figure 3) show that Post-Barreiras has a more significant variation in the characteristics. There is a variation of very coarse sand to fine, but with a predominance of average sand. The sands are sorted up until poorly sorted; have a prevalence of negative and very negative asymmetry; in kurtosis, most samples are platykurtic. On the other hand, the sediments of the Barreiras Formation showed more similar clusters in all parameters, with the presence of medium sand, poorly selected, negative asymmetry, and leptokurtic kurtosis.

**Morphologic and physical properties of the soil**

The soils have properties of the parent material and are predominantly sandy. The morphological analysis and fractionation of the soil particles are shown in table 2 and figure 4, respectively. In areas where Post-Barreiras sediments are thicker, and there are no texture changes between layers, the soils are sandy similar to the P1 profile. The
morfology indicates colors when wet from dark gray to very dark gray on A horizons and colors close to light gray on C horizons. In general, they are very friable, with a simple grain structure (Table 2).

We verified five soil profiles with apparent spodic morphology (P2 to P6). The morphology is the result of the presence of layers with yellowish colors or dark colors that occur below the sandy albic horizons. The P2 profile has an apparent spodic morphology due to the presence of a layer at a depth of 0.55 m, which differs abruptly in color (reddish yellow), concerning the upper sandy horizon, which has a light olive-gray color. In this contact zone, there is a line of rounded quartz pebbles, characteristic that is indicative of discontinuity (IUSS Working Group WRB, 2015). In the superficial layer, there are higher

Table 1. Ages of the Post-Barreiras sediments obtained by optically stimulated luminescence (OSL) dating

| Samples (depth) | $^{232}$Th ppm | $^{40}$K % | $P$ | AD $\mu$Gy yr$^{-1}$ | Ages ky (yr BP) |
|----------------|----------------|----------|-----|------------------|-----------------|
| P1 (1.5 m)     | 2.24 ± 0.08    | 1.17 ± 0.37 | 0.36 ± 0.05 | 19.56 | 1.05 ± 150 | 18.750 ± 3.04 |
| P2 (1.2 m)     | 2.38 ± 0.09    | 1.54 ± 0.08 | 0.36 ± 0.05 | 96.96 | 1.13 ± 80 | 85.350 ± 10.41 |
| P4 (0.3 m)     | 2.78 ± 0.20    | 0.08 ± 0.10 | 0.45 ± 0.13 | 34.90 | 990 ± 190 | 35.400 ± 7.87 |
| P6 (4.0 m)     | 9.99 ± 0.45    | 1.01 ± 0.12 | 1.04 ± 0.29 | 189.40 | 1.87 ± 225 | 101.500 ± 18.3 |

Radioactive isotopes $^{232}$Th, $^{238}$U + $^{235}$U, $^{40}$K; P: paleodesis equivalent dose (Gy); AD: annual dose rate ($\mu$Gy yr$^{-1}$); ky (yr BP): years before present.
levels of silt, and the maintenance of this fraction may be associated with aggregation by organic matter; this implies moderate consistency when dry, while the underlying sandy horizons have weak consistency. The smallest amount of silt in the E1 horizon (0.23 to 0.49 m), indicates a probable process of illuviation. There is an increase in silt content, at a depth of 0.49 to 0.55 m, indicating that the illuviation of this fraction was recent. At depth below 0.55 m, the clay content is high.

In the P3 profile, there is a very dark gray horizon in the depth of 0.25 m, with morphology as an illuvial horizon (Bh), another possibility would be evidence of a buried A horizon. However, only with morphological analysis, it is not possible to distinguish them. Moreover, at 0.35 m depth, there is a presence of randomly rolled pebbles in the profile, positioned in a slightly hard (dry) soil matrix, with a reddish yellow color (10YR 7/6). These changes in particle size indicate LD (IUSS Working Group WRB, 2015).

The complete morphology of Spodosol occurs in P4 profile, which has homogeneous structure and consistency in all horizons, and with differentiation of colors among the horizons, characterized by the sequence A - E albic - Bs. The average sand increases in Bs horizons while reducing the fine sand fraction. The profile P5 up to the depth of 0.65 m presents similar morphology, with only color change. Below is a dark yellowish-brown color horizon and has a slightly plastic consistency. In this profile, the E horizon has darker colors and a significant presence of roots (Figure 2g).

The most significant morphological changes occur in the P6 profile. On the upper horizon, there are light colors of the sandy material. Bellow (0.67 m) it appears a horizon cemented with organic matter, of very dark brown colors, with extremely hard consistency, characterized as ortstein. In areas close to the profile, it was possible to observe that the cemented horizon can form a pavement of ortstein (Figure 2f). These are the residual structures left by the anthropic activity of sand extraction, which is common in the region. Below 0.85 m depth, there is an increase in clay content that influences the consistency of the soil, manifesting dark brown and redder colors, showing the variegated color pattern.
We analysed possible lithological discontinuities (LD) by uniformity value index (UV) (Figure 4). In profiles P1 and P5, there was no indication of LD. In the other profiles, there was a variation of UV among the horizons, and UV values are out of range for uniform profiles (UV = -0.60 to 0.60). We observed that in profiles with a sandy texture, there is a variation of UV between horizons, mainly in upper horizons, for example, in profiles P2, P4, and P6, this indicates that there was a process of selection of the sand fraction during sedimentary deposition.

Chemical, mineralogical, and palynological properties of soils

In general, soils are acidic, with low pH(H₂O) and a high level of H+Al that dominates most of CEC (Table 3). In the superficial horizons, there is a tendency of a higher level of Na⁺, Ca⁺, and P, concerning the underlying horizons. The organic carbon content

Table 2. Morphological properties of soils in Barreiras Formation and Post-Barreiras environments, Bahia, Brazil

| Horizon | Layer | Color (Munsell) | Structure | Consistency |
|---------|-------|-----------------|-----------|-------------|
|         |       | Dry | Moist | Dry | Moist | Wet |
| P1 - Neossolos Quartzarênico Órtico típico (Typic Quartzipsamments) | A | 0.00-0.15 | 5Y 2.5/1 | 10YR 4/1 | sg | L | Fr | NP / NST |
|         | C1 | 0.15-0.53 | 5Y 7/1 | 2.5Y 7/2 | sg | S | Vfr | NP / NST |
|         | C2 | 0.53-1.30* | 5Y 7/1 | 2.5Y 7/2 | sg | L | Vfr | NP / NST |
| P2 - Argissolo Vermelho-Amarelo Distrófico arênico abruptico (Arenic Hapludults) | A | 0.00-0.23 | 5Y 5/2 | 10YR 3/1 | sg | S | Fr | NP / NST |
|         | E1 | 0.23-0.49 | 5Y 6/2 | 2.5Y 7/2 | sg | L | L | NP / NST |
|         | E2 | 0.49-0.55 | 5Y 6/2 | 2.5Y 7/1 | sg | L | Fr | NP / NST |
|         | 2Bs | 0.55-1.10* | 5YR 6/8 | 2YR 5/6 | mod. m. sbk | SH | Fi | SP / SST |
| P3 - Neossolo Quartzarênico Órtico leptofragmentário (Typic Quartzipsamments) | A | 0.00-0.25 | 10YR 6/1 | 10YR 5/1 | sg | L | L | NP / NST |
|         | 2C1 | 0.25-0.35 | 7.5YR 3/1 | 10YR 3/1 | gr | L | Fr | LP / NST |
|         | 2C2 | 0.35-1.50* | 10YR 8/4 | 10YR 7/6 | mod. m. sbk | VH | Fi | SP / SST |
| P4 - Espodossolo Ferrilúvico Órtico arênico (Typic Haplorthods) | A | 0.00-0.10 | 10YR 6/1 | 10YR 4/1 | sg | L | Fri | NP / NST |
|         | E | 0.10-0.54 | 5Y 6/1 | 2.5Y 7/2 | sg | L | solta | NP / NST |
|         | Bs1 | 0.54-1.20 | 10YR 5/4 | 10YR 4/4 | sg | L | Fr | NP / NST |
|         | Bs2 | 1.20-2.00 | 10YR 5/6 | 10YR 4/4 | sg | L | Fr | NP / NST |
| P5 - Espodossolo Ferrilúvico Órtico arênico (Ultic Haplorthods) | A | 0.00-0.10 | 10YR 6/1 | 10YR 4/1 | sg | S | Fr | NP / NST |
|         | E | 0.10-0.65 | 5Y 6/1 | 2.5Y 6/1 | sg | S | Fr | NP / NST |
|         | Bs | 0.65-1.50* | 10YR 5/4 | 10YR 3/4 | md.sm.gr | S | Fi | SP / SST |
| P6 - Espodossolo Ferrilúvico Órtico fragipânico (Ultic Fragiorthods) | A | 0.00-0.19 | 10YR 7/1 | 10YR 4/1 | sg | L | Vfr | NP / NST |
|         | E | 0.19-0.67 | 10YR 3/1 | 2.5Y 7/2 | sg | L | L | NP / NST |
|         | Bhm | 0.67-0.84 | 10YR 4/4 | 7.5YR 2.5/3 | st. m. sbk | VH | EF | NP / NST |
|         | Bs | 0.84-0.88 | 10YR 5/4 | 7.5YR 5/3 | md. m. sbk | S | Fi | SP / SST |
|         | 2C1 | 0.88-1.04 | 2.5YR 5/8 | 2.5YR 4/6 | st. m. sbk | SH | Fi | SP / SST |
|         | 2C2 | 1.04-1.50* | 5YR 6/4 | 5YR 5/3 | w. sm. gr | S | Fr | SP / SST |

Key:
- w: weak; mod: moderate; st: strong; sm: small; m: medium; sg: simple grains; gr: granular; sbk: subangular blocks. L: loose; S: soft; SH: slightly hard; VH: very hard; Vrf: very friable; Fr: friable; Fi: firm; EF: extremely firm; NP: non plastic; SP: slightly plastic; NST: non sticky; SST: slightly sticky.
Figure 4. Distribution of particle size, texture, levels of Ti and Zr, and UV: Uniformity Value in soils developed in Post-Barreiras and Barreiras Formation sediments. Texture Class: S: Sandy; SCL: Sandy Clay Loam. * Indicative value of discontinuity and underlined UV values are calculated considering layers with morphological evidence of LD. Grain size classified as VCS: very coarse sand; CS: coarse sand; MS: medium sand; FS: fine sand; VFS: very fine sand; and S: very fine sand.
rises in dark sub horizons; this behavior can indicate illuviation or buried horizon. For example, in the P6 profile, there is an increase of 356% of OC between A and Bhm horizons (Table 3). In some profiles, the rise in OC is followed by an increase in P and H+Al. The P-rem levels were negatively correlated with the clay contents, and the higher clay content sub-horizons have a lower level of P-rem.

The clay fraction identified by the XRD pattern (Figure 5) was composed mainly of quartz and kaolinite. However, mineralogical differences occur in profiles with more significant morphological variation (P2, P4, and P6). In the sub-horizons of these soil profiles, kaolinite, and micas are common. Some horizons, however, present gibbsite, hematite, and goethite.

In profiles P2 to P6, the morphological characteristics indicate the possibility of LD. The profiles P2, P3, and P6 showed more considerable variation in Ti and Zr, while the other profiles showed low variation, with CV% of Ti/Zr below 13% (Figure 4).

Considering the fractionation of organic matter (Figure 6), we observed an increase in the humin fraction in lower horizons, especially in profiles with dark sub-horizons (P3 and P6). However, the humin is not susceptible to the process of illuviation according to the pH variation (Tadini et al., 2017); therefore, this increase in humine in sub-horizons may be a consequence of the presence of LD. In profiles P4 and P5, there is an increase in soluble fractions (fulvic and humic acids), meaning the illuviation process.

### Table 3. Chemical characterization of soils in Barreiras Formation and Post-Barreiras environments, Bahia, Brazil

| Profile | Hor | pH | Al<sup>3+</sup> | H+Al | K<sup>+</sup> | Na<sup>+</sup> | Ca<sup>2+</sup> | Mg<sup>2+</sup> | SB | CEC<sub>e</sub> | CEC<sub>T</sub> | V | m | P | P-rem | OC% | mg dm<sup>-3</sup> | mg L<sup>-1</sup> | g kg<sup>-1</sup> |
|---------|-----|---|----------------|-------|------------|-----------|---------|-------------|----|----------|----------|--|---|---|-------|-----|----------------|----------------|---------|
|         | A   | 5.4 | 3.8 | 0.4 | 12.1 | 0.0 | 21.2 | 6.2 | 0.8 | 28.2 | 28.5 | 40.3 | 69.9 | 52.7 | 1.2 | 54.5 | 40.4 | |
| P1      | C1  | 4.9 | 3.6 | 0.2 | 1.3 | 0.0 | 0.2 | 0.1 | 0.0 | 0.3 | 0.5 | 1.6 | 16.7 | 12.8 | 0.5 | 57.8 | 1.5 | |
|         | C2  | 5.1 | 3.5 | 0.0 | 1.0 | 0.0 | 0.2 | 0.1 | 1.3 | 1.6 | 1.6 | 2.6 | 61.5 | 7.7 | 0.4 | 56.1 | 0.0 | |
|         | A   | 5.4 | 4.5 | 0.3 | 2.4 | 1.0 | 2.2 | 0.0 | 0.0 | 3.2 | 3.5 | 5.6 | 57.1 | 39.3 | 2.6 | 43.7 | 2.2 | |
| P2      | E1  | 6.2 | 4.7 | 0.0 | 0.8 | 0.0 | 0.8 | 0.0 | 0.8 | 0.8 | 0.8 | 1.6 | 50.0 | 50.0 | 0.8 | 57.3 | 0.8 | |
|         | E2  | 6.2 | 4.7 | 0.0 | 1.0 | 0.0 | 0.7 | 0.0 | 0.0 | 0.7 | 0.7 | 1.7 | 41.2 | 41.2 | 0.7 | 52.9 | 0.8 | |
|         | 2Bt | 5.5 | 4.0 | 0.1 | 2.2 | 0.0 | 0.6 | 0.0 | 0.1 | 0.7 | 0.8 | 2.9 | 24.1 | 20.7 | 0.6 | 46.3 | 0.8 | |
|         | A   | 4.6 | 3.2 | 0.4 | 12.1 | 0.0 | 21.2 | 6.2 | 0.8 | 28.2 | 28.6 | 40.3 | 70.0 | 52.6 | 1.1 | 54.5 | 7.4 | |
| P3      | 2C1 | 5.5 | 4.2 | 0.2 | 1.3 | 0.0 | 0.2 | 0.1 | 0.0 | 0.3 | 0.5 | 1.6 | 16.7 | 12.8 | 0.5 | 57.8 | 25.8 | |
|         | 2C2 | 5.3 | 4.6 | 0.0 | 0.0 | 0.2 | 0.2 | 0.1 | 1.3 | 1.8 | 1.8 | 1.8 | 99.4 | 11.0 | 0.4 | 56.1 | 0.0 | |
|         | A   | 5.0 | 3.6 | 0.3 | 0.2 | 0.0 | 12.2 | 4.3 | 16.9 | 17.2 | 17.1 | 98.9 | 71.3 | 0.9 | 53.6 | 9.6 | |
| P4      | E   | 5.3 | 4.2 | 0.4 | 1.6 | 0.0 | 1.2 | 0.0 | 0.0 | 1.2 | 1.6 | 2.8 | 42.9 | 42.9 | 0.9 | 47.7 | 1.5 | |
|         | Bs1 | 5.3 | 4.5 | 0.7 | 4.3 | 0.0 | 2.2 | 0.0 | 0.0 | 2.2 | 2.9 | 6.5 | 34.0 | 33.7 | 1.4 | 22.9 | 3.0 | |
|         | Bs2 | 5.4 | 4.6 | 0.6 | 8.7 | 0.0 | 3.2 | 0.1 | 0.0 | 3.3 | 3.9 | 12.0 | 27.7 | 26.6 | 1.7 | 8.4 | 11.8 | |
|         | A   | 4.2 | 3.0 | 0.3 | 4.0 | 33.0 | 41.2 | 0.4 | 4.0 | 78.6 | 78.9 | 82.6 | 95.2 | 49.9 | 1.3 | 39.2 | 4.4 | |
| P5      | E   | 5.3 | 3.9 | 0.0 | 3.8 | 7.0 | 27.2 | 0.5 | 3.8 | 38.5 | 38.5 | 42.3 | 91.0 | 64.3 | 0.9 | 19.0 | 3.0 | |
|         | Bs  | 5.1 | 4.2 | 0.0 | 3.3 | 0.0 | 9.2 | 0.8 | 3.3 | 13.3 | 13.3 | 16.6 | 80.1 | 55.5 | 1.7 | 19.0 | 4.7 | |
|         | A   | 4.5 | 3.0 | 0.9 | 8.6 | 5.0 | 11.2 | 0.5 | 0.5 | 17.0 | 17.9 | 25.6 | 66.4 | 43.7 | 1.5 | 52.0 | 5.2 | |
| P6      | E   | 5.0 | 3.6 | 0.3 | 1.1 | 0.0 | 1.2 | 0.0 | 0.0 | 1.2 | 1.5 | 2.3 | 53.0 | 51.3 | 0.7 | 53.6 | 0.8 | |
|         | Bhm | 4.2 | 3.0 | 3.7 | 13.6 | 5.0 | 12.0 | 0.6 | 0.3 | 17.8 | 21.5 | 31.4 | 56.7 | 38.2 | 1.6 | 59.6 | 46.3 | |
|         | 2C1 | 5.0 | 4.0 | 2.0 | 6.0 | 3.0 | 0.1 | 2.0 | 1.6 | 6.6 | 8.6 | 12.6 | 52.4 | 0.4 | 1.2 | 12.9 | 16.6 | |
|         | 2C2 | 5.6 | 4.1 | 1.2 | 4.0 | 2.0 | 0.0 | 2.5 | 1.5 | 6.0 | 7.1 | 10.0 | 59.9 | 0.2 | 1.0 | 18.0 | 0.9 | |

Hor: horizon; SB: sum of base; CEC<sub>e</sub>: effective cation exchange capacity; CEC<sub>T</sub>: total cation exchange capacity; V%: base saturation; m: Al<sup>3+</sup> saturation; OC: total organic carbon; P-rem: phosphorus remaining (Teixeira et al., 2017).
Figure 5. X-ray patterns from clay fraction (powder method) in the horizons of soil profiles. P1…P5: soil profiles. Minerals: Gb: gibbsite; Go: goethite; He: hematite; Ka: kaolinite; Mi: mica; Qz: quartz. Numbers between parentheses correspond to distance between adjacent planes in nanometers (nm).

Figure 6. Fractionation of organic matter from the horizons of the collected soils.
In dark sub-horizons, palynological analyses showed the presence of gelified phytoclasts derived from woody tissues (xylem) of higher plants (Tyson, 1995); these phytoclasts were more present in P3 profile (Figure 7a). However, the predominance of the amorphous organic matter suggests the presence of an illuviation process in the P6 profile (Figure 7b).

**DISCUSSION**

**Characteristics of sediments**

For some time, older studies considered Post-Barreiras sediments as a result of the weathering of the Barreiras Formation (Tatumi et al., 2008). In these environments, the intense weathering process can generate features in the landscape that are similar to stratigraphic layers. This process forms the areas of *mussunungas*, whose origin is related to the acidolysis process, creating sandy areas (Oliveira et al., 2010; Schiavo et al., 2020). However, in the study area, pedogenesis is not the main factor for the origin of the sandy regions. Since the end of the 70s, studies classified the deposits as dunes (Tricart and Silva, 1968), and this is evident by the presence of cross-stratification, typical of dune dissipation structures (Figure 2b). Furthermore, certain features allow differentiating the Post-Barreiras sediments from the *mussunungas*, as some deposits are not in depressed areas of the relief, do not have rounded shapes, and they can be up to 6 m in depth (Souza et al., 2016b).

The geochronology confirmed that sandy deposits are not associated with deposits of the underlying Barreiras Formation, whose age is Miocene to Pliocene times (Rossetti et al., 2013). Therefore, they are Post-Barreiras sediments of late Pleistocene age (Table 1), and these results are in line with other studies along the Brazilian coast (Tatumi et al., 2008; Rossetti et al., 2011; Gandini et al., 2014), including the same characteristic, which when collected in greater depth tend to be older.

The sedimentological parameters (Figure 3) in the Post-Barreiras are similar to the pattern for deposits located in northeastern Pará (Tatumi et al., 2008). However, they differ from the characteristics of the Barreiras Formation sediments; these have less variation in sedimentological parameters. The Barreiras Formation sediments showed the presence of medium sand, poorly selected, negative asymmetry, and leptokurtic kurtosis, characteristics reported in the literature (Abrahão et al., 1998; Vilas Boas et al., 2001). These distinct characteristics (Post-Barreiras and Barreiras Formation) indicate that sediments do not have a strong relationship. Furthermore, studies suggest that the sand grains of both deposits have differences in the degree of roundness, mainly in resistant minerals (zircon and tourmaline) (Ochoa et al., 2013; Souza et al., 2016b).
Soil properties and taxonomic considerations

The soils have low fertility due to the influence of pre-weathered parent material (Table 3), which has little mineralogical variation. In the upper horizons, there is a predominance of kaolinite and quartz (Figure 5). On the other hand, sandy clay sub-horizons have more crystallized kaolinite, and there is the presence of hematite, goethite, and gibbsite (P2 and P6). These minerals are common in Brazilian soils, including in Barreiras Formation environments (Moreau et al., 2006a; Cunha et al., 2019). The high regional rainfall also influences the low soil fertility because sandy soils have higher leaching (Rêgo et al., 2019).

In the upper horizons, we verified the high presence of Na$^+$, which is explained by the constant action of saline sprays of the coast (Magnago et al., 2013). The upper horizons show Ca$^{2+}$, Mg$^{2+}$, and mainly P concentration (Mehlich-1), this has to do with nutrient cycling (Gomes et al., 2010), favoring the increase of V% in these horizons. Furthermore, the accumulation of organic carbon (OC) in sandy soils is related to the low microbial activity (Brito et al., 2018).

In general, considering the morphological characteristics of the soil, there are two groups (Table 2 and Figure 4). The first covers profiles with little differentiation of horizons (P1), and have morphological characteristics similar to coastal plain soils (restingas) (Gomes et al., 2007). The second group (P2 to P6), presents substantial morphological variation between the horizons. Generally, there are layers with yellowish colors or dark colors, that occur below the sandy albic horizons, and this variation is followed by a change in texture, and subtle changes in mineralogy (Figure 5).

The Post-Barreiras sedimentation can influence the soil morphology of these environments, generating allochthonous layers. However, the high regional humidity and because they are pre-weathered sediments are factors that can hide some of the morphological criteria established by the IUSS Working Group WRB (2015) to identify discontinuity. Therefore, we consider criteria to identify possible LD to allow a better classification of the soil.

In the P1 profile, the morphology does not indicate lithological discontinuity. There is only an increase in the amount of fine sand in lower horizons (Figure 4), which may be due to wind rework during deposition, which may occur in Post-Barreiras (Tatumi et al., 2008; Souza et al., 2016a). However, this did not affect the Uniformity Value index (UV), which has a uniform behavior across horizons. Furthermore, there were no variations in the Ti and Zr contents, and the relation between both was low (Figure 4). We classify the profile as (Quartzipsamments) Típic Quartzipsamments (Soil Survey Staff, 2014), and Neossolo Quartzarênico órtico típico (Santos et al., 2018).

In the P2 profile, there is an apparent spodic morphology, but morphological characteristics indicate discontinuity. In morphology, there is an abrupt transition in texture and color at a depth of 0.40 to 0.55 m. In the contact zone, there is a line of rolled pebbles. Still, it is not possible to determine whether it belongs to the sandy surface layer or the clay sandy layer below, including, it may be an old superficial rocky pavement later covered by sands. However, chemical analyses of the soil matrix indicated variations of Ti, Zr, and Ti/Zr, mainly in the contact zone (Figure 4). We classify the profile as (Quartzipsamments) Típic Quartzipsamments (Soil Survey Staff, 2014), and Neossolo Quartzarênico órtico típico (Santos et al., 2018).

In the P2 profile, there is an apparent spodic morphology, but morphological characteristics indicate discontinuity. In morphology, there is an abrupt transition in texture and color at a depth of 0.40 to 0.55 m. In the contact zone, there is a line of rolled pebbles. Still, it is not possible to determine whether it belongs to the sandy surface layer or the clay sandy layer below, including, it may be an old superficial rocky pavement later covered by sands. However, chemical analyses of the soil matrix indicated variations of Ti, Zr, and Ti/Zr, mainly in the contact zone (Figure 4). Furthermore, the UV index showed values above the limit for uniform soils (UV = 1.3) (Schaetzl, 1998).

There is no increase in C, P, and Al$^{3+}$ in depth (Table 3), and the levels of fulvic and humic acids are negligible in the sandy clay loam horizon (Figure 6). This behavior does not correspond to the pedogenesis of Spodosols because podzolization is necessary (Oliveira et al., 2010; Martinez et al., 2018; Menezes et al., 2018). However, there is an increase in silt content in E2; this intensity for migration of silt is a possible indication for movement also of clays. Despite the lower clay content in E2 compared to E1, in the absence of micromorphological data, the hypothesis raised is that the drainage restriction in the clay-rich horizon may favor the destruction of clay (ferrolysis). Therefore,
the increase in clay in the last layer does not result exclusively from discontinuity and fits the SiBCS criteria for the Bt horizon (Santos et al., 2018). We classify the profile as (Ultisols) Arenic Hapludults (Soil Survey Staff, 2014), and Argissolo Vermelho-Amarelo Distrófico arênico abruptico (Santos et al., 2018).

Morphology with a spodic appearance occurs in the P3 profile by the accumulation of organic matter in the depth of 0.35 m. However, there are rounded pebbles below the darker sub-horizon (Figure 4). These significant changes in particle size distribution suggest LD (IUSS Working Group WRB, 2015). Quantitatively, there were substantial variations in the UV index; between the first and last layer, the value was UV = 5.3, also indicating LD.

There was variation in the levels of Ti and Ti/Zr (CV = 42.1 %). These elements have low mobility since the source of these elements is resistant minerals. Furthermore, the concentration of these elements in soils of the Barreiras Formation, tend to be relatively uniform in the profile, the variations occur according to the position of the soil profile in the landscape (Bravard and Righi, 1989; Carvalho et al., 2013a). Therefore, the chemical factor also denotes LD.

Still in P3 profile, in the dark-colored sub-horizon, there was a higher content of humin (Figure 6), but, in spodic horizons, there must be a more significant amount of humic and fulvic acids, since these have solubility dependent on pH (Tadini et al., 2017). The presence of gelified phytoclasts derived from woody tissues (xylem) of higher plants (Figure 7a), explains the high content of humin in the organic sub-horizon. On the other hand, amorphous organic matter, which is a component of podzolization by dissolved organic matter (Buurman and Vidal-Torrido, 2015; Lopes-Mazzetto et al., 2018), is not predominant in the sub-horizon. Therefore, considering the physical and chemical indications of LD, and the more significant presence of humin in the organic sub-horizon, the probability of being an A horizon buried gains strength. Based on these considerations, we classify the profile as (Quartzipsamments) Typic Quartzipsamments (Soil Survey Staff, 2014) and Neossolo Quartzarênico Órtico típico (Santos et al., 2018).

In the P4 profile, there is a variation in the UV index between E and Bs1 horizons (UV = 1.7). Still, this granulometric behavior must be related to the process of selecting fine sands on the surface by the wind, and the Post-Barreiras sediments in the region have the aeolian origin (Tricart and Silva, 1968; Souza et al., 2016a). However, the values of Ti, Zr, and Ti/Zr tended to be uniform (Figure 4), and do not indicate LD. Another factor is a reduction of low-mobility organic fractions in lower horizons. At the same time, humic and fulvic acids increase, and the same behavior occurs for OC (organic carbon) and P. These characteristics are indicative of the podzolization process in the genesis of Spodosols (Buurman and Jongmans, 2005; Oliveira et al., 2010; Schiavo et al., 2020). Furthermore, in some areas close to the profile, there are features of depletion of the Bh horizon (Figure 2c), and this feature is the result of increased drainage in the Spodosols profile (Lopes-Mazzetto et al., 2018). We classify the profile as (Spodosol) Typic Haplorthods (Soil Survey Staff, 2014), and Espodossolo Ferrilúvico Órtico arênico (Santos et al., 2018).

In profile 5, the low value of UV index (UV = 0.4), and moderate variation of Ti/Zr (CV = 13.4 %), indicate that the profile has lithological uniformity (Figure 4). However, there is an increase in the clay content below 0.65 m, without criteria for textural gradient (Santos et al., 2018), and others studies have identified the same behavior in Spodosols of Coastal Tablelands (Oliveira et al., 2010; Carvalho et al., 2013b). Moreover, there is an increase of OC and P in the Bs horizon concerning the E horizon (Table 3), and the fractionation of organic matter indicated selective translocation due to the higher content of fulvic and humic acids in the subsurface (Figure 6). Therefore, the combination of these processes shows podzolization (González-Pérez et al., 2008; Oliveira et al., 2010; Tadini et al., 2017).
We attribute the evolution of the P5 profile in a similar way to the Spodosols of *mussunungas* areas (Moreau et al., 2006a; Oliveira et al., 2010). Therefore, the main factors are the destruction of clay by acidolysis, and subsequent migration of humic and fulvic acids. Five factors support this argument: (i) the region has high precipitation (1900 to 2200 mm); (ii) the source material is sediments from the Barreiras Formation; (iii) the sandy surface layer has a lot of root activity, a feature not common in Post-Barreiras in the region (Figure 4); (iv) there was no evidence of lithological discontinuity; and (v) the profile there is a podzolization process. We classify the profile as (Spodosols) Ultic Haplorthods (Soil Survey Staff, 2014) and *Espodossolo Ferrilúvico Órtico arênico* (Santos et al., 2018).

In the P6 profile, the configuration is Post-Barreiras sediments above the Barreiras Formation. This pattern generates a moderate variation in the Ti/Zr ratio (CV = 18.5 %), the UV index was 2.5 in the contact area, and UV = 1.0, between the first and last layer (Figure 4). However, podzolization in the profile is evident by the presence of a cemented sub-horizon with a high content of OC (Table 3), and the has characteristics of ortstein (Figure 2e). Metallic compounds, especially Al levels, influence the degree of cementation (Oliveira et al., 2010; Gomes et al., 2017), and that element is high on the horizon (Table 3).

The fractionation of organic matter in the P6 profile indicated a high content of fulvic and humic acids in the subsurface (Figure 6). Simultaneously, the more significant presence of organic matter in the amorphous horizon ortstein (Figure 7b). Both characteristics indicate podzolization (Silva et al., 2019; Schiavo et al., 2020). However, in the contact zone between the Bhm and 2C1 horizons, the humin content is high (Figure 6). Presumably, there is a simultaneous presence of a buried A horizon, and the podzolization process was strong enough to overcome the old morphological characteristics of A horizon. Similarly, other studies have identified this behavior in the pedogenesis of Spodosols (Dalsgaard and Vad Odgaard, 2001; Waroszewski et al., 2013, 2015).

The Bhm horizon of the P6 profile is formed in the contact zone (Pos-Barreiras/Barreiras Formation), and studies indicate that the difference in porosity between soil layers influences the origin of spodic horizons (Coelho et al., 2012; Gomes et al., 2017). Therefore, in the profile, the Barreiras Formation hinders the infiltration of water, and consequently, the illuviation of dissolved organic matter, favoring the formation of the Bhm spodic horizon (Figure 2e). We classify the profile as (Spodosols) Ultic Fragiorthods (Soil Survey Staff, 2014), and *Espodossolo Ferrilúvico Órtico fragipânico* (Santos et al., 2018).

In general, in the study area, there are different factors to generate a spodic appearance or form real spodic horizons: (i) the Post-Barreiras sedimentation above the Barreiras Formation generates an apparent spodic feature (P2 and P3). However, there is chemical, physical, and morphological evidence of LD. Moreover, there is no podzolization, and this characteristic is reported by Anjos et al. (2013); (ii) podzolization, a typical process for the formation of genuine spodic horizons (Buurman and Jongmans, 2005; Martinez et al., 2018), in the case of the P4 profile, forming Bs horizons; (iii) acidolysis process leading to degradation of Ultisols clay from Barreiras Formation (P5 profile). This behavior occurs similarly in Coastal Tablelands (Moreau et al., 2006a; Oliveira et al., 2010; Schiavo et al., 2020); and (iv) co-association of the deposition process and podzolization (P6 profile), because of the existence of Post-Barreiras above the Barreiras Formation, being a similar phenomenon in other studies (Dalsgaard and Vad Odgaard, 2001; Waroszewski et al., 2013, 2015).

In general, our results demonstrate that podzolization processes can occur in uniform profiles or with LD. The sandy matrix of Post-Barreiras sediments facilitates this process. Therefore, although some profiles do not fit the criteria for Spodosol (P2 and P3), the podzolization process is possible. However, these findings were only possible by applying a multi-technical approach. Therefore, this indicates the need for adaptation of Brazilian Soil Classification System (Santos et al., 2018) in terms of more concise delimitations of the attributes for defining spodic horizons.
CONCLUSIONS

In the study area, the Post-Barreiras sediments are sandy deposits of late Pleistocene time, and present a more significant variation in sedimentological parameters compared to sediments from the Barreiras Formation. The pre-weathered parent material, predominantly quartz and kaolinite minerals, contribute to soils with low fertility.

Quartzipsamments are present in thick Post-Barreiras sedimentary deposits. In this environment, it also supports podzolization allowing the pedogenesis of Spodosols.

In contact zones (Post-Barreiras/Barreiras Formation) generate characteristics with spodic appearance morphology but without podzolization. However, there are soils with this lithological discontinuity co-associated with podzolization, forming Spodosols.

The Acidolysis process in sediments from the Barreiras Formation allows the pedogenesis of Spodosols.

ACKNOWLEDGMENTS

We thank Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for providing a doctoral scholarship to the first author. The Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), process number: 88882.315083/2019-01. The State University of Santa Cruz (UESC) and friends Alan Azevedo, Glauber Guirra, Hogana Póvoas, and Liliane Góes that helped in the logistics in the fieldworks. We thank Luiz Aníbal for his help in classifying the soils.

AUTHOR CONTRIBUTIONS

Conceptualization: Cristiano Marcelo Pereira de Souza (lead), Ana Maria Souza Santos Moreau (lead), and Liovando Marciano da Costa (supporting).

Methodology: Cristiano Marcelo Pereira de Souza (lead) and Liovando Marciano da Costa (supporting).

Formal analysis: Cristiano Marcelo Pereira de Souza (lead), Carlos César Uchôa de Lima (supporting), Francis Henrique Tenório Firmino (lead), and Marcos Esdras Leite (supporting).

Investigation: Cristiano Marcelo Pereira de Souza (lead) and Ana Maria Souza Santos Moreau (lead).

Writing - original draft: Cristiano Marcelo Pereira de Souza (lead), Francis Henrique Tenório Firmino (lead), and Liovando Marciano da Costa (supporting).

Supervision: Liovando Marciano da Costa (lead), Ana Maria Souza Santos Moreau (supporting), and Carlos César Uchôa de Lima (supporting).

REFERENCES

Abrahão WAP, Costa LM, Mello JWW, Neves JCL. Distribuição de freqüência de tamanho da fração areia e compacidade relativa de solos desenvolvidos de sedimentos do grupo geológico Barreiras. Rev Bras Cienc Solo. 1998;22:1-9. https://doi.org/10.1590/S0100-06831998000100001

Aitken MJ. Thermoluminescence dating. London: Academic Press; 1985.

Anjos LHC, Lucelio MS, Wadt PGS, Lumbereras JF, Pereira MG. Guia de campo da IX Reunião brasileira de classificação e correlação de solos. Brasília, DF: Embrapa; 2013 [cited 2020 Jun 20]. Available from: https://www.infoteca.cnptia.embrapa.br/bitstream/doc/964754/1/24668.pdf
Bigarella JJ. The Barreiras group in northeastern Brazil. An Acad Bras Cienc. 1975;47:365-93. https://doi.org/10.1590/S0001-3765201000300010

Bravard S, Righi D. Geochemical differences in an Oxisol-Spodosol toposequence of Amazonia, Brazil. Geoderma. 1989;44:29-42. https://doi.org/10.1016/0016-7061(89)90004-9

Brito LS, Irmier U, Forte BVG, Xavier TP, Martins RL. Matter turnover in the oligotrophic restinga ecosystem and the importance of the key species Clusia hilariana. Biota Neotrop. 2018;18:e20180552. https://doi.org/10.1590/1676-0611-bn-2018-0552

Busu Junior AA, Pessenda LCR, Mayle FE, Lorente FL, Volkmer-Ribeiro C, Schiavo JA, Pereira MG, Bendassolli JA, Macario KCD, Siqueira GS. Paleovegetation and paleoclimate dynamics during the last 7000 years in the Atlantic forest of Southeastern Brazil based on palynology of a waterlogged sandy soil. Rev Palaeobot Palynol. 2019;264:1-10. https://doi.org/10.1016/j.revpalbo.2019.02.002

Buurman P, Jongmans AG. Podzolisation and soil organic matter dynamics. Geoderma. 2005;125:71-83. https://doi.org/10.1016/j.geoderma.2004.07.006

Buurman P, Vidal-Torrado P. A Comment on “Chemical and Morphological Distinctions between Vertical and Lateral Podzolization at Hubbard Brook” by Bourgaul et al. Soil Sci Soc Am J. 2015;79:1815-7. https://doi.org/10.2136/sssaj2015.05.0191c

Camargo MG. SysGran: um sistema de código aberto para análises granulométricas do sedimento. Braz J Geol. 2006;36:371-8. https://doi.org/10.25249/0375-7536.2006362371378

Carvalho SR, Bôa GSV, Fadigas FS. Concentrações naturais de metais pesados em solos derivados de sedimentos do grupo Barreiras. Cad Geocienc. 2013a;10:97-107. https://doi.org/10.1590/S0006-87052002000200008

Carvalho VS, Ribeiro MR, Souza VS. Caracterização de Espodossolos dos estados da Paraíba e do Pernambuco. Rev Bras Cienc Solo. 2013b;37:1454-63. https://doi.org/10.1590/S0100-06832013000600003

Coelho MR, Martins VM, Otero Pérez XL, Macías Vázquez F, Gomes FH, Cooper M, Vidal-Torrado P. Micromorfologia de horizontes espódicos nas restingas do Estado de São Paulo. Rev Bras Cienc Solo. 2012;36:1380-94. https://doi.org/10.1590/S0100-06832012000500002

Cooper M, Vidal-Torrado P, Lepsch IF. Stratigraphical discontinuities, tropical landscape evolution and soil distribution relationships in a case study in SE-Brazil. Rev Bras Cienc Solo. 2002;26:673-83. https://doi.org/10.1590/S0100-06832002000300012

Cremens DL, Mokma DL. Argillic horizon expression and classification in the soils of two Michigan Hydrosequences. Soil Sci Soc Am J. 1986;50:1002-7. https://doi.org/10.2136/sssaj1986.0361599505000040034x

Cunha AM, Fontes MPF, Lani JL. Mineralogical and chemical attributes of soils from the Brazilian Atlantic Forest domain. Sci Agric. 2019;76:82-92. https://doi.org/10.1590/1678-992x-2017-0109

Dalsgaard K, Vad Odgaard B. Dating sequences of buried horizons of podzols developed in wind-blown sand at Ulfborg, Western Jutland. Quat Int. 2001;78:53-60. https://doi.org/10.1016/S0104-068X(00)00115-4

Demattê JLI, Mazza JA, Demattê JAM. Caracterização e gênese de uma topossessão Latossolo amarelo-podzol originado de material da Formação Barreiras - estado de Alagoas. Sci Agric. 1996;53:20-30. https://doi.org/10.1590/S0103-90161996000100004

Ferreira RO, Costa ODAV, Souza LS, Jacomine PKT. Áreas delagoas intermitentes em tabuleiros costeiros do Recôncavo da Bahia: gênese, caracterização e classificação dos solos. Rev Bras Cienc Solo. 2015;39:1513-23. https://doi.org/10.1590/01000683bcs20150068

Folk RL, Ward WC. Brazos River bar (Texas): a study in the significance of grain size parameters. J Sediment Res. 1957;27:3-26. https://doi.org/10.1306/74D70646-2B21-11D7-8648000102C1865D.

Gandini R, Rossetti DF, Netto RG, Bezerra FHR, Góes AM. Neotectonic evolution of the Brazilian northeastern continental margin based on sedimentary facies and ichnology. Quat Res. 2014;82:462-72. https://doi.org/10.1016/j.yqres.2014.07.003
Gomes FH, Vidal-Torrado P, Macías F, Gherardi B, Perez XLO. Solos sob vegetação de Restinga na ilha do Cardoso (SP). I - caracterização e classificação. Rev Bras Cienc Solo. 2007;31:1563-80. https://doi.org/10.1590/S0100-06832007000600003

Gomes JBV, Araújo Filho JC, Vidal-Torrado P, Cooper M, Silva EA, Curi N. Cemented horizons and hardpans in the coastal tablelands of Northeastern Brazil. Rev Bras Cienc Solo. 2017;41:e0150453. https://doi.org/10.1590/18069657rbcs20150453

Gomes JM, Pereira MG, Piña-Rodrigues FC, Pereira GHA, Gondim FR, Silva EMLR. Aporte de serapilheira e de nutrientes em fragmentos florestais da Mata Atlântica, RJ. Rev Bras Cienc Agrar. 2010;5:383-91. https://doi.org/10.5039/agraria.v5i3a552

González-Pérez M, Vidal Torrado P, Colnago LA, Martin-Neto L, Otero XL, Milori DMBP, Gomes FH. 13C NMR and FTIR spectroscopy characterization of humic acids in Spodosols under tropical rain forest in southeastern Brazil. Geoderma. 2008;146:425-33. https://doi.org/10.1016/j.geoderma.2008.06.018

Guerra MBB, Neto EL, Prianti MTA, Pereira-Filho ER, Schaefer CEGR. Post-fire study of the Brazilian scientific Antarctic station: toxic elements contamination and potential mobility on the surrounding environment. Microc J. 2013;110:21-7. https://doi.org/10.1590/microc.2013.01.007

Horbe AMC, Costa ML. Solos gerados a partir do intemperismo de crostas lateríticas silico-ferruginosas. Acta Amaz. 1997;27:241-56. https://doi.org/10.1590/1809-43921997274256.

IUSS Working Group WRB. World reference base for soil resources 2014, update 2015: International soil classification system for naming soils and creating legends for soil maps. Rome: Food and Agriculture Organization of the United Nations; 2015. (World Soil Resources Reports, 106).

Lopes-Mazzetto JM, Buurman P, Schellekens J, Martinez PHRM, Vidal-Torrado P. Soil morphology related to hydrology and degradation in tropical coastal Podzols (SE Brazil). Catena. 2018;162:1-13. https://doi.org/10.1016/j.catena.2017.11.007

Magnago LFS, Martins SV, Schaefer CEGR, Neri AV. Structure and diversity of restingas along a flood gradient in southeastern Brazil. Acta Bot Bras. 2013;27:801-9. https://doi.org/10.1590/S0102-33062013000400020

Martinez P, Buurman P, Lopes-Mazzetto JM, Giannini PCF, Schellekens J, Vidal-Torrado P. Geomorphological control on podzolisation – an example from a tropical barrier island. Geomorphology. 2018;309:86-97. https://doi.org/10.1016/j.geomorph.2018.02.030

Maynard J. Chemistry of modern soils as a guide to interpreting Precambrian paleosols. J Geol. 1992;100:279-89. https://doi.org/10.1086/629632

Mebius LJ. A rapid method for the determination of organic carbon in soil. Anal Chim Acta. 1960;22:120-4. https://doi.org/10.1016/S0003-2670(00)88254-9

Menezes AR, Fontana A, Anjos LHC. Spodosols in Brazil: distribution, characteristics and diagnostic attributes of spodic horizons. S Afr J Plant Soil. 2018;35:241-50. https://doi.org/10.1080/02571862.2017.1410734

Moreau AMSS, Ker JC, Costa LM, Gomes FH. Caracterização de solos de duas topossequências em Tabuleiros Costeiros do sul da Bahia. Rev Bras Cienc Solo. 2006a;30:1007-19. https://doi.org/10.1590/S0100-06832006000600010

Moreau AMSS, Costa LM, Ker JC, Gomes FH. Gênese de horizonte coeso, fragipã e duripã em solos do Tabuleiro Costeiro do sul da Bahia. Rev Bras Cienc Solo. 2006b;30:1021-30. https://doi.org/10.1590/S0100-06832006000600011

Murray AS, Wintle AG. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. Radiat Meas. 2000;32:57-73. https://doi.org/10.1016/S1350-4487(99)00253-X

Nott J, Young R, Bryant E, Price D. Stratigraphy vs. pedogenesis; problems of their correlation within coastal sedimentary facies. Catena. 1994;23:199-212. https://doi.org/10.1016/0341-8162(94)90068-X

Novaes Filho JP, Couto EG, Rodrigues LCM, Chig LA, Johnson MS. Indicativos de descontinuidade litológica de regolitos derivados de granitos em uma microlaca sob floresta Amazônica, em Juruaena - MT. Rev Bras Cienc Solo. 2012;36:317-24. https://doi.org/10.1590/S0100-06832012000200001
Ochoa FL, Góes AM, Rossetti DF, Sawakuchi AO, Cassini LV, Coutinho JMV. Discriminação dos depósitos cenozoicos da parte emersa da Bacia Paraíba (NE, Brasil) por meio de minerais pesados e granulometria. Braz J Geol. 2013;43:555-70. https://doi.org/10.5327/Z2317-48892013000300010

Oliveira AP, Ker JC, Silva IR, Fontes MPF, Oliveira AP, Neves ATG. Spodosols pedogenesis under Barreiras formation and sandbank environments in the south of Bahia. Rev Bras Cienc Solo. 2010;34:847-60. https://doi.org/10.1590/S0100-06832010000300026

Phillips JD. Development of texture contrast soils by a combination of bioturbation and translocation. Catena. 2007;70:92-104. https://doi.org/10.1016/j.catena.2006.08.002

Phillips JD, Lorz C. Origins and implications of soil layering. Earth-Sci Rev. 2008;89:144-55. https://doi.org/10.1016/j.earscirev.2008.04.003

Rêgo LGS, Silva JJA, Souza CMM, Portela J, Moura INBM, Silva ACR, Miranda NO. Pedogenesis in the Barreiras formation under climates of Rio Grande do Norte, Brazil. J Agric Sci. 2019;11:19-29. https://doi.org/10.5539/jas.v11n16p19

Rossetti DF, Bezerra FHR, Dominguez JML. Late Oligocene-Miocene transgressions along the equatorial and eastern margins of Brazil. Earth-Sci Rev. 2013;123:87-112. https://doi.org/10.1016/j.earscirev.2013.04.005

Rossetti DF, Bezerra FHR, Góes AM, Valeriano MM, Andrades-Filho CO, Mittani JCR, Tatumi SH, Brito-Neves BB. Late Quaternary sedimentation in the Paraíba Basin, Northeastern Brazil: Landform, sea level and tectonics in Eastern South America passive margin. Palaeogeogr Palaeoclim Palaeoecol. 2011;300:191-204. https://doi.org/10.1016/j.palaeo.2010.12.026

Ruiz HA. Incremento da exatidão da análise granulométrica do solo por meio da coleta da suspensão (silte+argila). Rev Bras Cienc Solo. 2005;29:297-300. https://doi.org/10.1590/S0100-06832005000200015

Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Lumberras JF, Coelho MR, Almeida JA, Araújo Filho JC, Oliveira JB, Cunha TJF. Sistema brasileiro de classificação de solos. 5. ed. rev. ampl. Brasília, DF: Embrapa; 2018.

Santos RD, Lemos RC, Santos HG, Ker JC, Anjos LHC. Manual de descrição e coleta de solo no campo. Viçosa, MG: Sociedade Brasileira de Ciência do Solo; 2015.

Schaetzl RJ. Lithologic discontinuities in some soils on drumlins: theory, detection, and application. Soil Sci. 1998;163:570-90. https://doi.org/10.1097/00010694-199807000-00006

Schiavo JA, Pessenda LCR, Buso Júnior AA, Calegari MR, Fornari M, Secretti ML, Pereira MG, Mayle FE. Genesis and variation spatial of Podzol in depressions of the Barreiras Formation, northeastern Espírito Santo State, Brazil, and its implications for Quaternary climate change. J S Am Earth Sci. 2020;98:102435. https://doi.org/10.1016/j.jsames.2019.102435

Silva GAD, Camêlo DDL, Corrêa MM, Souza Júnior VS, Ribeiro Filho MR, Araújo Filho JC. Pedogenesis on Coastal Tablelands area with low range altimetry in Paraíba state. Rev Caatinga. 2019;32:458-71. https://doi.org/10.1590/1983-21252019v32n219rc

Silva MSL, Klamt E, Cavalcanti AC, Kroth PL. Adensamento subsuperficial em solos do semi-árido: processos geológicos e/ou pedogenéticos. Rev Bras Eng Agric Amb. 2002;6:314-20. https://doi.org/10.1590/S1415-43662002000200021

Soil Survey Staff. Keys to soil taxonomy. 12th ed. Washington, DC: United States Department of Agriculture, Natural Resources Conservation Service; 2014.

Souza CMP, Costa LM, Moreau AMSS, Gomes RL. Sedimentological parameters and dating of post-barreiras sediments from region the coastline. Mercator. 2016a;15:127-39. https://doi.org/10.4215/RM2016.1503.0008

Souza CMP, Costa LM, Gomes RL, Moreau AMSS. Análise das áreas de ocorrência e características morfológicas de sedimentos Pós-Barreiras na região sul da Bahia. Rev Bras Geog Fisi. 2016b;9:1543-57. https://doi.org/10.26848/rgbf.v9.5.p1559-1573

Swift RS. Organic matter characterization. In: Sparks DL, Page AL, Helmke PA, editors. Methods of soil analysis. Chemical methods. Part 3. Madison: Soil Science Society of America; 1996. p. 1011-69.
Tadini AM, Hajjoul H, Nicolodelli G, Mounier S, Montes CR, Milori DMBP. Characterization of organic matter in Spodosol Amazonian by fluorescence spectroscopy. IJGE. 2017;11:399-402. https://doi.org/10.5281/zenodo.1129784

Tatumi SH, Silva LP, Pires EL, Rossetti DF, Góes AM, Munita CS. Datação de Sedimentos Pós-Barreiras no norte do Brasil: implicações paleogeográficas. Rev Bras Geocienc. 2008;38:514-24. https://doi.org/10.25249/0375-7536.2008383514524

Teixeira PC, Donagemma GK, Fontana A, Teixeira WG. Manual de métodos de análise de solo. 3. ed. rev. ampl. Brasília, DF: Embrapa; 2017.

Tricart J, Silva TC. Estudos de geomorfologia da Bahia e Sergipe. Salvador: Fundação para o Desenvolvimento da Ciência na Bahia; 1968.

Tyson RV. Abundance of organic matter in sediments: TOC, hydrodynamic equivalence, dilution and flux effects. In: Tyson RV, editor. Sedimentary organic matter. Dordrecht: Springer; 1995. p. 81-118.

Vidal G. A palynological preparation method. Palynology. 1988;12:215-20. https://doi.org/10.1080/01916122.1988.9989345

Vilas Boas GS, Sampaio FJ, Pereira A. The Barreiras Group in the Northeastern coast of the state of Bahia, Brazil: depositional mechanisms and processes. An Acad Bras Cienc. 2001;73:417-27. https://doi.org/10.1590/S0001-37652001000300010

Waroszewski J, Kalinski K, Malkiewicz M, Mazurek R, Kozlowski G, Kabala C. Pleistocene–Holocene cover-beds on granite regolith as parent material for Podzols - An example from the Sudeten Mountains. Catena. 2013;104:161-73. https://doi.org/10.1016/j.catena.2012.11.006

Waroszewski J, Malkiewicz M, Mazurek R, Labaz B, Jezierski P, Kabala C. Lithological discontinuities in Podzols developed from sandstone cover beds in the Stolowe Mountains (Poland). Catena. 2015;126:11-9. https://doi.org/10.1016/j.catena.2014.10.034

Wilding LP, Drees L. Spatial variability and pedology. In: Wilding LP, Smec NE, Hall GF, editors. Pedogenesis and soil taxonomy. New York: Elsevier; 1983. p. 83-116.