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Genesis of sandstone-derived soils in the Cerrado of the Piauí State, Brazil

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Diego Ferreira de Souza[1]; Ronny Sobreira Barbosa[1]; Yuri Jacques Agra Bezerra da Silva[1]; Márcio Cleto Soares de Moura[2]; Romário Porto de Oliveira[1]; Vanessa Martins[3*]

[1]Universidade Federal do Piauí (UFPI), Bom Jesus, PI, Brasil
Programa de Pós-Graduação em Ciências Agrárias.
E-mail: agrodiegoufpi@hotmail.com, ronny.barbosa@ufpi.edu.br, yuri_jacques@hotmail.com, rportoo55@hotmail.com
[2]Universidade Federal do Piauí (UFPI), Teresina, PI, Brasil
Centro de Ciências da Natureza (CCN). E-mail: marcio@ufpi.edu.br
[3]Universidade Federal do Piauí (UFPI), Bom Jesus, PI, Brasil
Colégio Técnico de Bom Jesus (CTBJ). E-mail: nessaufla@yahoo.com.br
[*]Corresponding author

ABSTRACT

This study characterized the morphological, physical and chemical attributes of sandstone-derived soils at the Cerrado of the Piauí State, Brazil, in order to identify evolutionary standards. The study was carried out with five representative soil profiles identified as P1-RY (Typical Flavic Psychotic Neosol - Aquents), P2-PA (Typical Dystrophic Yellow Argisol - Alfisol), P3-RL (Fragmentary Litholic Distrophic Neosol - Psammenit), P4-RQ (Typical Ortic Quartzenetic Neosol - Orthents) and P5-PV (Typical Dystrophic Red Argisol - Ultisol). Soil samples were submitted laboratory analysis described morphologically. In general, the soils presented high sand content, low pH, low content of exchangeable bases and low cation exchange capacity (CEC). Organic matter governed the CEC in most cases, suggesting dependence of organic matter in the supply of charges. These soils showed a low degree of weathering, but with iron of high crystallinity. Thus, the relief and the parent material are the major important soil-forming factors at the Cerrado of the Piauí State. Moreover, these soils are young, with the soils from the Piauí Formation being more evolved. However, the sandstones from the Canindé Group apparently are providing lithological secondary minerals for the soil.

Keywords: sand-loam soils, tropical soils, weathering indexes.

Gênese de solos derivados de arenitos no Cerrado Piauiense, Brasil

RESUMO

Objetivou-se com este trabalho caracterizar atributos morfológicos, físicos e químicos de solos formados a partir de arenitos no Cerrado Piauiense, na tentativa de encontrar padrões evolutivos. O estudo foi realizado em cinco perfis de solos representativos identificados como P1-RY (Neossolo Flúvico Psamítico típico - Aquents), P2-PA (Argissolo Amarelo Distrófico típico - Alfisol), P3-RL (Neossolo Litólico Distrófico fragmentário - Psamments), P4-RQ

(Neossolo Quartzarênico Órtico típico - Orthents) e P5-PV (Argissolo Vermelho Distrófico Típico - Ultisol). As amostras dos solos foram submetidas à descrição morfológica e análises laboratoriais. Em geral, os solos desta região apresentaram altos teores da fração areia, baixo pH, baixo conteúdo de bases trocáveis e baixa capacidade de troca catiônica (CTC). A matéria orgânica governou a CTC na maioria dos horizontes, sugerindo uma dependência da matéria orgânica no fornecimento de cargas. Estes solos mostraram baixo grau de intemperismo, mas com ferro de alta cristalinidade. Assim, é possível afirmar que o relevo e o material de origem são os fatores de formação do solo que possuem maior influência nos atributos dos solos do Cerrado Piauiense, Brasil. Além disso, estes solos são jovens, sendo os mais evoluídos aqueles originados da Formação Piauí. Contudo, os arenitos do grupo Canindé aparentemente estão fornecendo minerais secundários diretamente da rocha ao solo.

Palavras-chave: índices de intemperismo, solos franco-arenosos, solos tropicais.

1. INTRODUCTION

The Cerrado biome is home to the main thrust of Brazilian agricultural expansion. Its climate and soil characteristics are very diverse. The soils of the Brazilian Cerrado evolve from rocks that go back from Pre-Cambrian to Cenozoic (Pfaltzgraff, 2010). The relief exhibits a very large range of morphological features distributed at different altitudes, constituting well-defined units, among which stand out plateaus, depressions, and plains. Soils consist of representative units of more than a dozen classes and are mostly dystrophic and acid (Pfaltzgraff, 2010).

In the state of Piauí, this biome occupies approximately 11.5 million hectares and is world-renowned for its economic importance as a reflection of its imminent agricultural expansion (Pragana *et al.*, 2012). There is also noticeable soil variability at different levels when compared with the Cerrado of other Brazilian regions. This variability, which occurs in response to the interaction between the soil formation factors, suggests major challenges for a conscious agricultural production.

The particularities of each site must be considered to facilitate the use of natural resources in agricultural activities. According to Buol *et al.* (2011), soil genesis and classification can permit better and more concise recommendations for soil use. Since weathering is directly related to the soil genesis, Kehrig (1949) reported that using weathering indexes such as Ki and Kr is a great option to explore soil genesis, considering the lack of more accurate information provided by x-ray diffractometry.

In the Cerrado of Piauí, most farmers consider general information about the soils for the adoption of management systems. Most of them assume that the soil belongs to the order of the Oxisols, with not only the same weathering level but also characteristics of soils from other places (i.e. soils in the south and southeast regions). This inevitably causes errors since not every soil in this region has the same level of weathering and homogeneity due to the landscape often observed in the Cerrado of Piauí State. Negative reflections of these deductions are amplified due to the sedimentary nature of the parent material of these soils, in addition to the climate intensity to which they are submitted each year, which demand more and more soil performance.

To correct this, the first steps involve soil characterization, recognizing that the evolution of each one soil is inherently tied to its formation environment. Thus, this study characterized the morphological, physical and chemical attributes of sandstone-derived soils at the Cerrado of the Piauí State in order to identify evolutionary standards.

2. MATERIAL AND METHODS

2.1. Study area

This research was carried out using five representative soils of the Upper Middle Gurguéia micro-region, at the Cerrado of the Piauí State, Brazil (Figure 1). The regional relief is craggy, with a warm and humid tropical climate, classified as Aw according to the Köppen classification. Historical data from the last 44 years, 1973 to 2017, show that the mean values of minimum and maximum temperatures are 20.3 and 33.6°C, respectively, and the mean annual precipitation is 939 mm (Inmet and Bdmet, 2017).

In order to represent as much as possible the environments of the study area, the sampling sites were chosen based on its geodiversity map (Pfaltzgraff, 2010). At each site, a trench was opened to expose the profiles of the studied soils, a procedure described by Santos *et al.* (2015) in areas under native Cerrado. Soil horizons were collected and identified according to Santos *et al.* (2015).

The study was carried out in five representative soil profiles identified as P1-RY (Typical Flavic Psychotic Neosol - Aquents), P2-PA (Typical Dystrophic Yellow Argisol – Alfisol), P3-RL (Fragmentary Litholic Distrophic Neosol - Psamments), P4-RQ (Typical Ortic Quartzenetic Neosol - Orthents) and P5-PV (Typical Dystrophic Red Argisol - Ultisol).

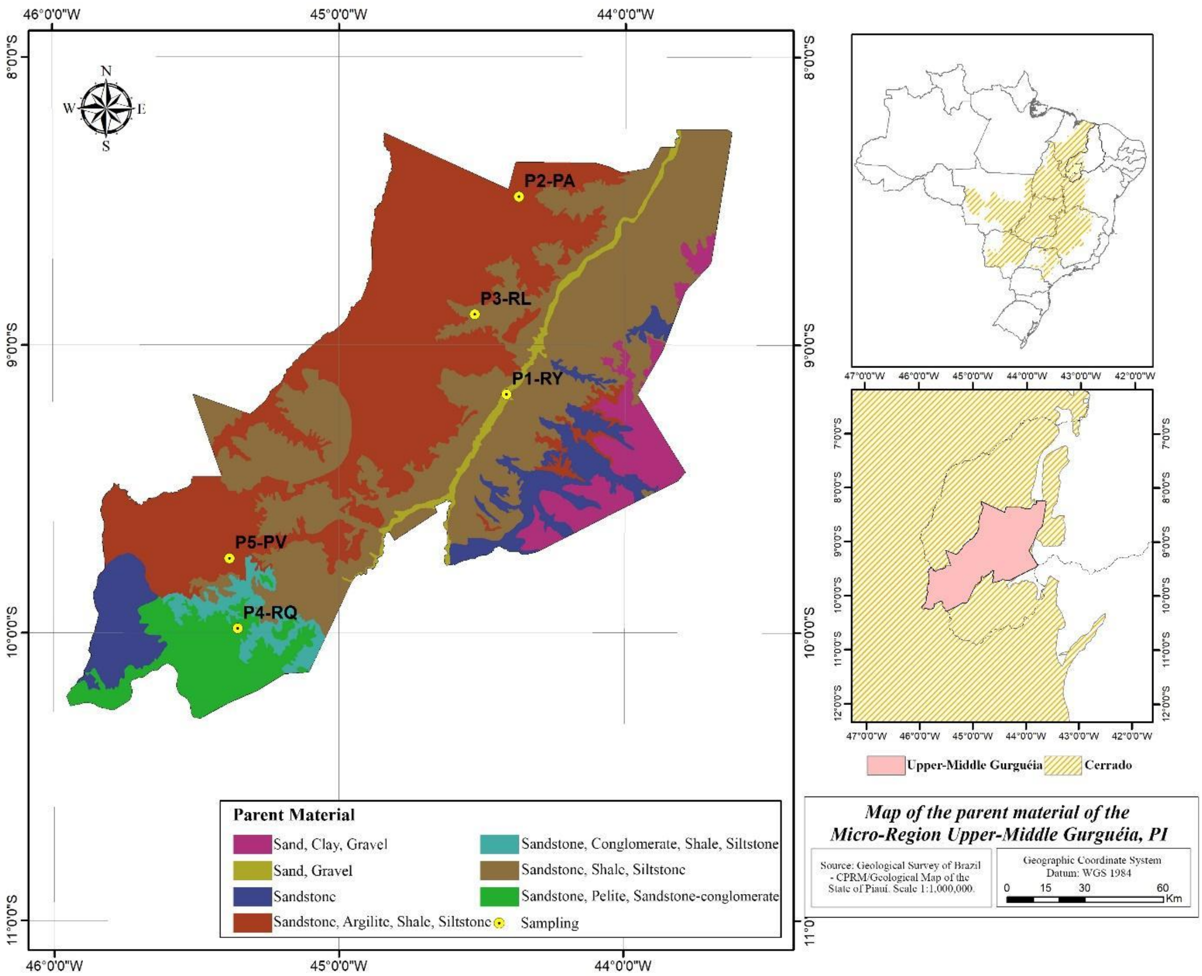

Figure 1. Study area location with indication of the sampling sites (profiles) on the parent material map.

The P1-RY is located at the flood plain and was developed under unconsolidated sediments (sand and gravel) of Cenozoic origin (Pfaltzgraff, 2010). The P2-PA and P5-PV were derived from sandstone (Piauí Formation, Balsas Group) of Paleozoic origin. The P2-PA is located at the crest, whereas the soil P5-PV is on the shoulder (Pfaltzgraff, 2010).

The P3-RL was also derived from sandstone (Piauí Formation, Canindé Group), but it is positioned at the side slope (Pfaltzgraff, 2010). The P4-RQ is located at the toe slope and was derived from sandstone (Mesozoic origin, Urucuia Complex) (Pfaltzgraff, 2010).

2.2. Physical and chemical analyzes

The samples from each horizon or layer were air-dried and subsequently declotted, homogenized, sieved in a stainless steel sieve with a 2.00 mm mesh, and used for the physical and chemical analyses. The particle size distribution was performed using 0.1 mol L^{-1} NaOH solution as a dispersant under slow stirring and the clay content was determined by the pipette method (Teixeira *et al.*, 2017). The clay dispersed in water (CDW) and the degree of flocculation were obtained according to Teixeira *et al.* (2017).

The pH in water and KCl, potential acidity (H+Al), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), and aluminum (Al^{3+}) were obtained using the methodologies proposed by Raij *et al.* (2001). The P and organic carbon (C_{org}) contents were analyzed using the methodology recommended by Teixeira *et al.* (2017). The values equivalent to the sum of bases (SB), cation exchange capacity (CEC), base saturation (V), and aluminum saturation (m) were obtained by calculations proposed by Teixeira *et al.* (2017).

2.3. Sulfuric attack, weathering indexes and crystallinity of iron oxides

Topsoil samples of all profiles were used for analyses of sulfuric attack and crystallinity of iron oxides. Only the samples of the subsurface diagnostic horizons of the P2-PA (Bt1) and P5-PV (Bt) were used for that. In the total sulfuric attack, the samples were treated with H_2SO_4 to extract the total contents of iron (Fe_2O_3) and aluminum (Al_2O_3) oxides, followed by alkaline dissolution for silicon (SiO_2) and titanium (TiO_2) oxides according to Teixera *et al.* (2017). These values were used to calculate the weathering indexes Ki and Kr as suggested by Kehrig (1949).

The free iron oxides (Fe_d) were extracted with citrate-dithionite-bicarbonate (Mehra and Jackson, 1960) and the poorly crystallized iron (Fe_o) was extracted with acid ammonium oxalate according to the methodology described by Camargo *et al.* (2009) adapted from Schwertmann (1973).

3. RESULTS AND DISCUSSION

3.1. Soil Morphology

The soil P1-RY presented the horizons A-2C1-3C2-4C3-5C4-6C5-7C6-8C7-9C8 formed by lithological discontinuity along a 2.0 m depth (Table 1). These layers show heterogeneity, among others, in the texture and color of the material that makes up the solid phase of the soil, denoting no or little relation to each other. This discontinuity is caused by the deposition of sediments in the Holocene period that occurs yearly during the wet season, which provides water presence on the surface. Darker shades in these layers are indicative of an erratic organic matter distribution (Demattê *et al.*, 2011). Silva *et al.* (2017) studied profiles of a landscape in the Brazilian Cerrado and also found in the flood plain a profile with color variability.

The P2-PA and P5-PV soil profiles showed the diagnostic horizon know as Bt, coherent with the Argissolos (Ultisol) class (Santos et al., 2018) (Table 1). The P2-PA has a yellowish hue (5Y), whereas the soil P5-PV has reddish hue (10R to 2.5YR), which probably reflects differences related to the goethite and hematite contents. Both P2-PA and P5-PV have differences along their depths, being P2-PA more developed. Apparently, the P5-PV evolved through soil-erosion processes often observed in soils located at the slopes of the landscape (Buol et al., 2011).

Table 1. Morphological description of the profiles studied.

Horizon	Depth (m)	Color (moisture)	Structure[a]	Consistency			Transition[b]
				Dry	Moisture	Wet[c]	
P1–RY							
A	0-0.15	5YR 4/3	S; Sm; e SubBlo	Slightly hard	Friable	Npl / St	Grad e Fla
2C1	0.15-0.35	5YR 6/6	Sg; T e Granu	Slightly hard	Friable	Npl / St	Grad e Fla
3C2	0.35-0.45	7.5YR 7/6	Sg; T e Granu	Slightly hard	Friable	Npl / St	Abr e Fla
4C3	0.45-0.80	7.5YR 7/6	Sg; T e Granu	Slightly hard	Friable	Spl / St	Grad e Fla
5C4	0.80-1.10	5YR 5/4	S; grande e SubBlo	Slightly hard	Friable	Spl / St	Abr e Fla
6C5	1.10-1.30	5YR 5/	Mo; Sm; e SubBlo	Slightly hard	Friable	Spl / Stk	Abr e Rip
7C6	1.30-1.40	5YR 5/4	Mo; T e SubBlo	Slightly hard	Friable	Spl / Stk	Grad e Fla
8C7	1.40-1.60	7.5YR 6/8	Sg; T e SubBlo	Slightly hard	Friable	Spl / St	Grad e Fla
9C8	1.60-2.00+	7.5YR 6/8	Sg; T e SubBlo	Slightly hard	Friable	Spl / St	-
P2–PA							
A	0-0.20	5Y 2.5/2	Mo; T e SubBlo	Slightly hard	Friable	Npl / Stk	Cle
AB	0.20-0.35	5Y 5/2	Mo; Sm; e SubBlo	Slightly hard	Friable	Npl / St	Grad
BA	0.35-0.60	5Y 7/4	Mo; Sm; e SubBlo	Slightly hard	Friable	Npl / St	Dif
Bt1	0.60-1.10	5Y 7/6	Mo; Sm; e Granu	Slightly hard	Friable	Spl / St	Dif
Bt2	1.10-2.10+	5Y 7/6	Mo; Sm; e Granu	Slightly hard	Friable	Spl / St	-
P3–RL							
A	0-0.10	7.5YR 3/1	W; Sm; e Granu	Slightly hard	Friable	Spl / St	Abr e Des
CR	0.10-0.40	7.5YR 3/1	W; Sm; e Granu	Slightly hard	Firm	Spl / St	-
P4–RQ							
A1	0-0.20	5YR 4/4	W; Sm; e SubBlo	Soft	Very friable	Npl / NStk	Dif e Fla
A2	0.20-0.55	5YR 5/6	W; Sm; e SubBlo	Soft	Very friable	Npl / NStk	Grad e Fla
C1	0.55-1.13	5YR 6/8	W; Sm; e SubBlo	Soft	Very friable	Npl / NStk	Cle e Fla
C2	1.13-2.00+	5YR 6/8	W; Sm; e SubBlo	Soft	Very friable	Npl / NStk	-
P5–PV							
A	0-0.20	2.5YR 3/6	S; Med e SubBlo	Slightly hard	Friable	Spl / St	Fla e Cle
BA	0-20-0.30	2.5YR 4/6	S; Med e SubBlo	Hard	Firm	Spl / St	Fla e Cle
Bt	0.30-0.85	10R 4/8	S; Med e SubBlo	Hard	Firm	Spl / St	Fla e Cle
BC	0.85-1.10	10R 4/8	S; Med e SubBlo	Hard	Extremely firm	Spl / St	Fla e Cle
CR	1.10-1.30	10R3/6	S; grande e SubBlo	Too Hard	Extremely firm	Spl / St	-

[a]S, Strong; W, Weak; Mo, Moderate; Sg, Simple grains; T, Tiny; Sm, Small; Med, Medium; SubBlo, Subangular Blocks; Granu, Granular. [b]Grad, Gradual; Dif, Diffuse; Abr, Abrupt; Cle, Clear; Fla, Flat, Rip, Rippled; Dis, Discontinuous. [c]St, Slightly tacky; Stk, Sticky; NStk, Not Sticky; Spl, Slightly plastic; Npl, Not plastic.

In P3-RL, an A horizon was found on a Cr layer, with lithic contact less than 50 cm deep (Table 1). This profile is located in a landscape position typically erosional, which prevents the formation of deeper soils. The A horizon had a dominance of very dark gray color (7.5YR 3/1) with a weak structure. The Cr layer consists of angular and subangular rock boulders, accounting for more than 90% of the volume of its mass, with the remaining part filled with a weathered material (A horizon). The current climate condition may promote higher advances in soil formation in the long term. Other factors, such as organisms and relief, do not give conditions to potentiate the use of these soils for food production.

The soil P4-RQ presented sequence of horizons A1-A2-C1-C2 with a depth higher than 2.0 m (Table 1). This profile is located in the foothill position on the slope. All horizons have colors predominantly with a hue of 5YR. Because of the high sand content, it presented weak aggregates with structure in subangular blocks and the humid and wet consistency were very friable and not sticky, respectively. Due to the poor performance of the pedogenetic processes of soil formation, the characteristics of this profile are closely related to the parent material, predominantly composed of sandstone.

3.2. Physical Attributes

The soil P1-RY presented an erratic distribution of clay, silt, and sand content. This lack of uniformity may result from the variation in the sedimentary nature of the parent material (Table 2). Due to the formation by sedimentation of fluvial nature, the occurrence of irregularity in the granulometric contents along the profile is a characteristic of this soil class (Buol *et al.*, 2011). The observed sand contents were higher than 741 g kg^{-1}, occurring in most horizons and composed of a higher proportion of fine sand.

Table 2. Physical characterization of the horizons of the studied profiles.

Horizon	Depth (m)	VCS[a]	CS	MS	FS	VFS	TS	Clay (H_2O)	Clay (NaOH)	Silt	Flocculation	Textural class[b]
		g kg^{-1}									%	
P1–RY												
A	0-0.15	13	14	52	410	252	741	51	204	55	75	SCL
2C1	0.15-0.35	0	1	57	671	236	965	25	25	10	0	FSA
3C2	0.35-0.45	0	1	135	728	90	954	25	25	21	0	FS
4C3	0.45-0.80	1	3	35	511	312	862	25	100	38	75	LFS
5C4	0.80-1.10	6	24	49	135	259	810	25	153	37	84	LFS
6C5	1.10-1.30	30	216	375	195	98	914	25	75	11	67	FSA
7C6	1.30-1.40	5	47	105	271	296	724	25	101	15	75	SCL
8C7	1.40-1.60	0	3	12	477	436	928	25	50	22	50	FS
9C8	$1.60\text{-}2.00^{+}$	1	21	327	424	177	950	25	25	25	0	FS
P2–PA												
A	0-0.20	4	43	278	480	79	884	25	101	15	75	LFS
AB	0.20-0.35	2	36	241	492	108	879	25	100	21	75	LFS
BA	0.35-0.60	1	31	223	478	67	800	0	176	25	100	FSL
Bt1	0.60-1.10	2	36	223	398	99	758	0	226	16	100	SCL
Bt2	1.10-2.10	1	36	213	373	90	713	0	251	35	100	SCL
P3–RL												
A	0-0.10	15	41	179	366	140	741	126	202	58	38	SCL
CR	0.10-0.40	18	48	210	313	163	752	100	190	58	38	SCL
P4–RQ												
A1	0-0.20	5	2	88	453	398	946	0	25	29	100	FSA
A2	0.20-0.55	1	2	109	437	361	910	0	75	15	100	FSA
C1	0.55-1.13	1	1	105	422	398	927	0	50	23	100	FSA
C2	$1.13\text{-}2.00^{+}$	0	1	97	404	398	900	25	75	25	67	FSA
P5–PV												
A	0-0.10	5	18	203	468	135	829	75	125	45	40	LS
BA	0.10-0.20	4	20	196	322	82	624	0	201	175	100	SCL
Bt	0.20-0.85	5	18	180	307	84	594	0	251	155	100	SCL
BC	0.85-1.10	6	18	177	312	109	622	0	226	152	100	SCL
CR	1.10-1.30	4	21	209	338	91	663	25	175	161	86	SCL

[a]VCS, Very coarse sand; CS, Coarse sand; MS, Medium sand; FS, Fine sand; VFS, Very fine sand. [b]SCL, Sand clay loam; FSL, Fine sand loam; LFS, Loamy fine sand; FSA, Fine sand; LS, Loamy sand.

The P2-PA and P5-PV soil profiles showed highest clay concentration at the B horizons than A horizons, with texture ratio B/A more than 1.8 (P2-PA = 2.4, P5-PV = 2.0), but with a predominance of sand (Table 2). The soil P2-PA varied from 101 to 251 g kg^{-1} between A and Bt2 horizons, whereas the soil P5-PV presented a variation in clay content between 125 and

251 g kg^{-1}, the both in accordance with the criteria to classify it as a B textural, as observed by Santos *et al.* (2018).

Besides the difference of their position on the landscape, the soils P2-PA and P5-PV also had differences related to their parent material (i.e., sandstone). These differences may be responsible for granulometric variation and morphologic attributes showed in Table 1. However, both P2-PA and P5-PV showed flocculation equal to 100% at the Bt horizon that reflect the importance of the oxide content in the function of these soils.

In P4-RQ, the predominance of sand was significant in all horizons, with values ranging from 900 to 946 g kg^{-1}, while the clay content was between 25 and 75 g kg^{-1}. The parent material of this profile is characterized by sandstone and Cretaceous conglomerates, with a predominance of sandy sediments of continental, lacustrine, fluvial or wind deposition (Pfaltzgraff, 2010), which provided a higher amount of the sand fraction in this profile due to the little pedogenetic alteration.

3.3. Chemical Attributes

The values of pH in water of all profiles were higher in relation to the pH values in KCl, indicating a predominance of a negative net load for all the studied profiles (Table 3). All profiles, except for some layers in P1-RY, had low pH values, probably due to the low amount of exchangeable bases in these soils. The distribution of pH values presented a low variation in the horizons of each profile, except for P1-RY, presenting a pH in KCl with values between 4.3 and 5.6. The chemical characteristics of each layer of P1-RY are closely related to the parent material characteristic of this soil class, which is formed by sediment transport and deposition.

A low variation in the pH values was also observed in the soil P2-PA, with slightly lower values in the surface horizons. The lower values in the surface are possibly associated with the masking of the positive surface charge and creation of a negative charge due to the presence of organic matter. In addition, the increase of pH in the subsurface horizons of soils may be associated with the presence of iron oxides and the adsorption of H^+ ions at the soil colloids (Buol *et al.*, 2011). The pH values in KCl show a similar tendency in the profile, but with a unit lower than that of the pH in water, indicating a predominance of acid cations (Al^{3+} and H^+) at exchange sites (Tawornpruek *et al.*, 2006).

The contents of P are similar for most of the profile horizons, except for P1-RY and the A horizons of P3-RL, P4-RQ, and P5-PV. The soil P1-RY presented the highest values of the sum of exchangeable bases (K^+, Ca^{2+}, and Mg^{2+}), being predominantly composed of Ca^{2+} and Mg^{2+}. However, the lowest values of the sum of exchangeable bases were observed in P4-RQ and P5-PV, which is related to an intense leaching of basic cations and favored by climate conditions and soil characteristics. In P2-PA, the value of SB varied from 0.6 to 0.7 $cmol_c\ kg^{-1}$, with the highest values in the subsurface horizons. The increase of SB in depth in this profile is possibly related to a higher clay content, which increases its adsorption potential by cations. The contents of Ca^{2+} were higher in comparison to Mg^{2+} in all horizons and its values increased in depth, as observed in SB values. The contents of K^+ were low in all horizons, with values close to zero.

The dystrophic character was observed in most of the studied profiles, except for P1-RY, which showed a base saturation higher than 50% in the A horizon and in some of its layers. The low base saturation values observed in P2-PA, P3-RL, P4-RQ, and P5-PV reflect the low natural fertility of these soils. Regarding the C_{org} distribution, P1-RY presented an erratic distribution, while the other profiles showed higher values in the surface horizons, with decreases in depth. The same results were observed for the contents of Al^{3+} + H^+, which presented higher values in the surface horizons. According to Inda Junior *et al.* (2007), the formation of organometallic complexes with Al^{3+} increases the resistance of organic matter and minimizes the losses of Al^{3+}.

Table 3. Chemical characterization of the studied profiles.

Horizon	pH H_2O	pH KCl	ΔpH	P mg kg^{-1}	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	SB	V (%)	m	C_{org} g kg^{-1}	H+Al	CEC
					cmol$_c$ kg^{-1}								cmol$_c$ kg^{-1}	
P1–RY														
A	6.1	5.1	-1.0	31.1	0.6	3.9	1.7	0.2	6.2	70	3	1.7	2.6	8.8
2C1	6.2	4.5	-1.7	19.7	0.1	0.7	0.3	0.2	1.1	44	15	0.6	1.4	2.5
3C3	5.7	4.3	-1.4	9.6	0.1	0.5	0.2	0.1	0.8	44	11	0.1	1.0	1.8
4C3	6.1	4.4	-1.7	29.1	0.2	1.2	0.7	0.1	2.1	57	5	1.2	1.6	3.7
5C4	6.9	5.6	-1.3	9.5	0.4	3.7	3.9	0.1	8.0	92	1	2.9	0.7	8.7
6C5	7.2	5.2	-2.0	13.1	0.1	0.8	1.2	0.1	2.1	81	5	0.1	0.5	2.6
7C6	6.2	5.0	-1.2	5.5	0.2	1.1	2.0	0.1	3.3	79	3	0.6	0.9	4.2
8C7	6.7	5.0	-1.7	4.0	0.1	0.7	1.0	0.1	1.8	82	5	0.1	0.4	2.2
9C8	6.6	5.1	-1.5	3.2	0.1	0.4	0.1	0.2	0.6	55	25	0.1	0.6	1.1
P2–PA														
A	4.6	3.6	-1.0	1.7	0.1	0.4	0.1	0.1	0.6	15	14	5.2	3.5	3.9
AB	4.7	3.8	-0.9	1.7	0.1	0.4	0.1	0.6	0.6	23	50	2.3	2.2	2.6
BA	4.9	3.8	-1.1	1.7	0.1	0.4	0.1	0.5	0.6	28	45	2.3	1.7	2.1
Bt1	4.9	3.9	-1.0	1.7	0.1	0.5	0.1	0.5	0.7	33	42	1.7	1.6	2.1
Bt2	5.1	4.0	-1.1	1.7	0.1	0.5	0.1	0.3	0.7	39	30	0.6	1.3	1.8
P3–RL														
A	4.2	3.5	-0.7	4.0	0.1	0.1	0.1	1.1	0.3	7	79	10.5	4.1	4.4
CR	4.9	3.9	-1.0	1.4	0.1	0.2	0.2	0.2	0.5	31	29	4.2	1.3	1.6
P4–RQ														
A1	5.3	3.9	-1.4	2.0	0.1	0.1	0.1	0.5	0.3	17	63	2.9	1.7	1.8
A2	5.6	4.2	-1.4	1.7	0.1	0.1	0.1	0.4	0.3	18	57	1.2	1.7	1.7
C1	5.0	4.0	-1.0	1.7	0.1	0.1	0.1	0.4	0.3	17	57	1.2	1.8	1.8
C2	5.0	4.0	-1.0	1.7	0.1	0.1	0.1	0.4	0.3	19	57	0.1	1.6	1.6
P5–PV														
A	4.1	3.4	-0.8	3.0	0.1	0.1	0.1	0.8	0.3	9	73	7.6	3.1	3.3
BA	4.4	3.5	-0.8	1.7	0.1	0.1	0.1	0.9	0.3	20	75	1.2	1.5	1.5
Bi	3.6	3.3	-0.3	1.7	0.1	0.1	0.1	1.1	0.3	13	79	1.2	2.3	2.3
BC	3.6	3.2	-0.4	1.7	0.1	0.1	0.1	1.0	0.3	14	77	1.2	2.2	2.2
CR	3.8	3.2	-0.6	1.7	0.1	0.1	0.1	0.8	0.3	33	73	1.2	0.9	0.9

The highest CEC values were 8.8 and 8.7 cmol$_c$ kg^{-1} for the A horizon and layer 5C4 in P1-RY, respectively. Other studied soils showed CEC decrease with depth, as well as C_{org} content. This scenario can be related to the low clay content in these soils, as well as the probable predominance of minerals containing a small amount of permanent charge such as kaolinite, which provide high dependence of organic matter in the CEC. Tawornpruek *et al.* (2006) also observed a relationship between CEC variations in depth with soil organic carbon content.

3.4. Sulfuric attack, weathering indexes and crystallinity of iron oxides

In the clay fraction of the studied soils, the SiO_2 was the oxide of highest concentration (3.2 to 8.9%), followed by Al_2O_3 (1.5 to 8.5%), Fe_2O_3 (0.4 to 3.2%) and TiO_3 (0.2 to 0.9%) (Table 4). This behavior suggests a majority presence of phyllosilicates in this fraction (Buol *et al.*, 2011). The soils P2-PA and P5-PV presented the highest mean SiO_2 content, which is reflection of the content of the clay fraction in these soils. The behavior observed for Al_2O_3, and Fe_2O_3 suggests high content of aluminum octahedrons and iron oxides such as goethite and hematite, respectively.

Table 4. Oxides rates by sulfuric attack, weathering indices and crystalline and amorphous Fe.

Horizon	SiO_2	Al_2O_3	TiO_3	Fe_2O_3	Ki	Kr	Fe_d	Fe_o	Fe_o/F_d
	%						g kg^{-1}		
					P1 – RY				
A	6.4	3.3	0.5	1.4	3.3	2.6	0.9	0.5	0.6
					P2 – PA				
A	6.1	4.2	0.6	3.0	2.5	1.7	1.9	0.3	0.2
Bt1	8.9	8.5	0.9	3.2	1.8	1.4	1.5	0.2	0.1
					P3 – RL				
A	7.7	6.7	0.3	0.9	2.0	1.8	1.0	0.2	0.2
					P4 – RQ				
A1	3.2	1.5	0.2	0.4	3.6	3.1	0.6	0.2	0.3
					P5 – PV				
A	9.8	6.7	0.4	1.7	2.5	2.1	1.8	0.1	0.1
Bt	8.7	8.0	0.5	1.6	1.8	1.6	1.0	0.1	0.1

The P1-RY and P4-RQ soil profiles presented the highest Ki values (Table 4). The P2-PA, P3-RL and P5-PV showed Ki values between 1.6 and 2.5 (Table 4). According Kehrig (1949), as kaolinite has a Ki value of 2.0, soils with a Ki value near 2.0 are kaolinitcs. Whereas values much higher than 2.0 are considered slightly weathered and values much smaller than 2.0 are considered strongly weathered. Thus, it is possible to affirm that the soils derived from sandstone in the Cerrado of the Piauí State are newly evolved, and soils derived from sandstones of the Piauí Formation (P2-PA, P3-RL and P5-PV) are more evolved.

While the Ki value of the soil P3-RL suggests a majority presence of kaolinite, this is a soil with many characteristics of a newly evolved soil, such as a deep horizon and the absence of the subsurface diagnostic horizons (Table 1). In addition, many of the Neossolos (Psamments) characteristics are provided directly from parent material, with smaller expression of the chemical weathering and neogenesis (Buol *et al.*, 2011). This suggests that part of these came directly from sandstones of the Canindé Group, given that is possible to notice the presence of kaolinite in sandstone (Shelton, 1964).

All soils presented Kr values higher than 0.75 (Table 4), suggesting that all of them have more kaolinite than oxides (Kehrig, 1949). The soils P2-PA, P3-RL and P5-PV showed Fe_d expressively higher than other soils, which also suggests higher content of iron oxides such as hematite, goethite, lepidocrocite or maghemite (Buol *et al.*, 2011). The Fe_d values of the P3-RL reinforce the thesis that its mineralogical compound might be partially provided by parent material. Wu and Caetano-Chang (1992) reported that sandstone can provide lithological iron oxides improving cementation of sandstone. The Feo values are low for these soils (0.1 to 0.5), indicating a low occurrence of ferrihydrite and Fe from organic compounds in these soils (Buol *et al.*, 2011). The Fe_o/Fe_d ratio, except for P1-RY that have influence of fluvial sediments, show that studied soils have high content of crystalline iron oxyhydroxides, given that their values are close to 0 (0.1 to 0.3) (Buol *et al.*, 2011). This is a reflection of the pedogenical or lithological environment conditions with good drainage and aeration during the formation of these iron oxides, different from the soil P1-PY, which is influenced by river flooding annually.

4. CONCLUSIONS

The relief and the parent material are the most important soil-forming factors of Cerrado of the Piauí State, Brazil. The relief is determinant in the thickness and horizon depth. In addition, river flooding has strong influences in soil on the floodplain, providing distinct characteristics. Sandstone is responsible for some pedogenetic standards in these soils, including the high sand content, as well as the low content of bases saturation and clay, which make the soils for this region extremely dependent on organic matter when it comes to soil charges. The soils from this region are young according to the weathering indexes. However, the sandstones from Canindé Group apparently are providing lithological secondary minerals for the soil.

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