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Pedological Heterogeneity of Soils Developed from Lithologies of the Pirambóia, Sanga-do-Cabral, and Guará Geological Formations in Southern Brazil

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ABSTRACT: The source material is one of the factors that most influence soil genesis and the mainly responsible for the nature, composition, and behavior of the soil. Given the geological complexity of the Santa Maria River basin, the objective of this study was to investigate whether the new lithologies described recently may be responsible for a greater variation in soil properties, as well as in the soil taxonomy itself. The study area is located in the municipality of Rosário do Sul, RS, Brazil at 30° 15’ 28” S and 54° 54’ 50” W, with average altitude of 132 m and climate type Cfa. This study was supported by a cartographic base composed of topographic charts, geological maps, satellite images, digital elevation models, and maps of geomorphometric variables, with the support of GPS receivers and GIS. Topolithosequences were defined from soils developed from the Pirambóia, Sanga-do-Cabral, and Guará Formations, and soil profiles were chosen based on types of source materials, variations in relief, and altitude. A classical model of slope compartmentalization was applied for correlation of the geomorphic surfaces with pedogenesis. Soil profiles were described in a general and morphological manner, and soil samples were collected for analysis. The physical and chemical properties determined were particle size, active and potential acidity, organic C content, Ca^{2+}, Mg^{2+}, K^+, and Al^{3+}. The sum of bases, CEC, flocculation activity and degree of flocculation of the clay fraction, and base (V), aluminum (m), and sodium saturation were calculated. Soil properties were evaluated through factor analysis and grouping, which allowed profiles to be grouped based on their variables and identification of which variables were preponderant in distinguishing them. Furthermore, multivariate analysis allowed statistical differentiation of the profiles in the same lithostratigraphic unit and in different relief positions, and also differentiation of soils developed from different source materials and occupying similar positions in the pedo-landscape, through the formation of homogeneous groups of profiles linked by their degree of similarity.

Keywords: lithology, topolithosequence, geomorphic surfaces, soil properties, multivariate analysis.

INTRODUCTION

In geological mapping, the Guará Formation had been interpreted as the Botucatu Formation. Formations that are now individualized as Sanga-do-Cabral and Pirambóia had been interpreted as being composed of sedimentary rocks of the Rosário do Sul Formation, which has recently been elevated to the category of the Rosário do Sul Group by the Geological Survey of Brazil (CPRM, 2006). This new and more complex geological interpretation of the region raises new questions about the supposed uniformity of its soil classes, and it is necessary to investigate whether the lithologies now described are responsible for greater variation in soil properties, both in terms of morphology, the soil physical, chemical, and mineralogical properties, and of the taxonomy itself, according to the Brazilian Soil Classification System (Santos et al., 2013).

Multivariate analysis of the properties of soil profiles in different environments provides important information that can be used to identify and quantify soil variation associated with different pedogenetic processes. This can deepen knowledge regarding the pedogeomorphological relationships of these soils (Carvalho Junior et al., 2008) and taxonomic interpretation of them by means of numerical classification (Pedron et al., 2012). Multivariate statistical methods can potentially be applied in pedological surveys and in the study of soil properties (Webster and Oliver, 1990; Kravchenko et al., 2002), which would make it possible to predict the occurrence of similar pedons and to delimit the mapping units (Demattê and Garcia, 1999; Demattê and Nanni, 2003; Santos et al., 2015a).

The soils under study developed from the same geological formation are assumed to have different morphological, physical, and chemical properties, due to lithological variations in the source material. Thus, the aim of this study was to compare pedons and group similar ones using multivariate statistical techniques, factor analysis, and cluster analysis, based on physical and chemical properties, and identify which properties determine soil discrimination. An additional aim was to detect differences between profiles of the same geological formation in regard to variations in the sedimentary package, and similarities between the profiles of different formations because of morphogenetic processes that were affected by soil position on slopes and variations in hydrological conditions.

MATERIALS AND METHODS

The study area is located in the physiographic region called the *Campanha Gaúcha*, in the Central Depression geomorphological province and geomorphological unit called the Ibicuí River-Black River Depression (Justus et al., 1986), which extends from Rosário do Sul to Santana do Livramento, RS, Brazil (Figure 1a). The municipality of Rosário do Sul is at 30° 15’ 28” S and 54° 54’ 50” W, with an average altitude of 132 m. According to the Köppen classification system (Köppen and Geiger, 1928), the climate is humid subtropical, with hot summers and cold winters (Cfa) and mean annual rainfall between 1,300 and 1,600 mm (PMRS, 2005).

This study was supported by a cartographic base composed of planialtimetric and hydrographic charts in scales of 1:100,000 and 1:50,000 from IBGE; a geological map of the state of Rio Grande do Sul in the scale 1:750,000 (CPRM, 2006); multispectral optical images of the satellites Landsat 5 - Thematic Mapper (5R4G3B) and Rapideye (3R2G1B); digital elevation model (DEM) derived from SRTM (Shuttle Radar Topographic Mission) data; and the database of geomorphometric variables of the TOPODATA project (slope, vertical and horizontal curvature, and slope orientation); with support from the global satellite positioning system and geographic information systems (SIGs), SPRING 5.1.8 and ARCGIS 9.3.

The choice of representative profiles of the predominant soil classes in the study area took into account the different types of source materials, variations in elevation and altitude, rock outcrops, soil color, accessibility (roads), and cuts (gullies) with the aid of geotechnologies

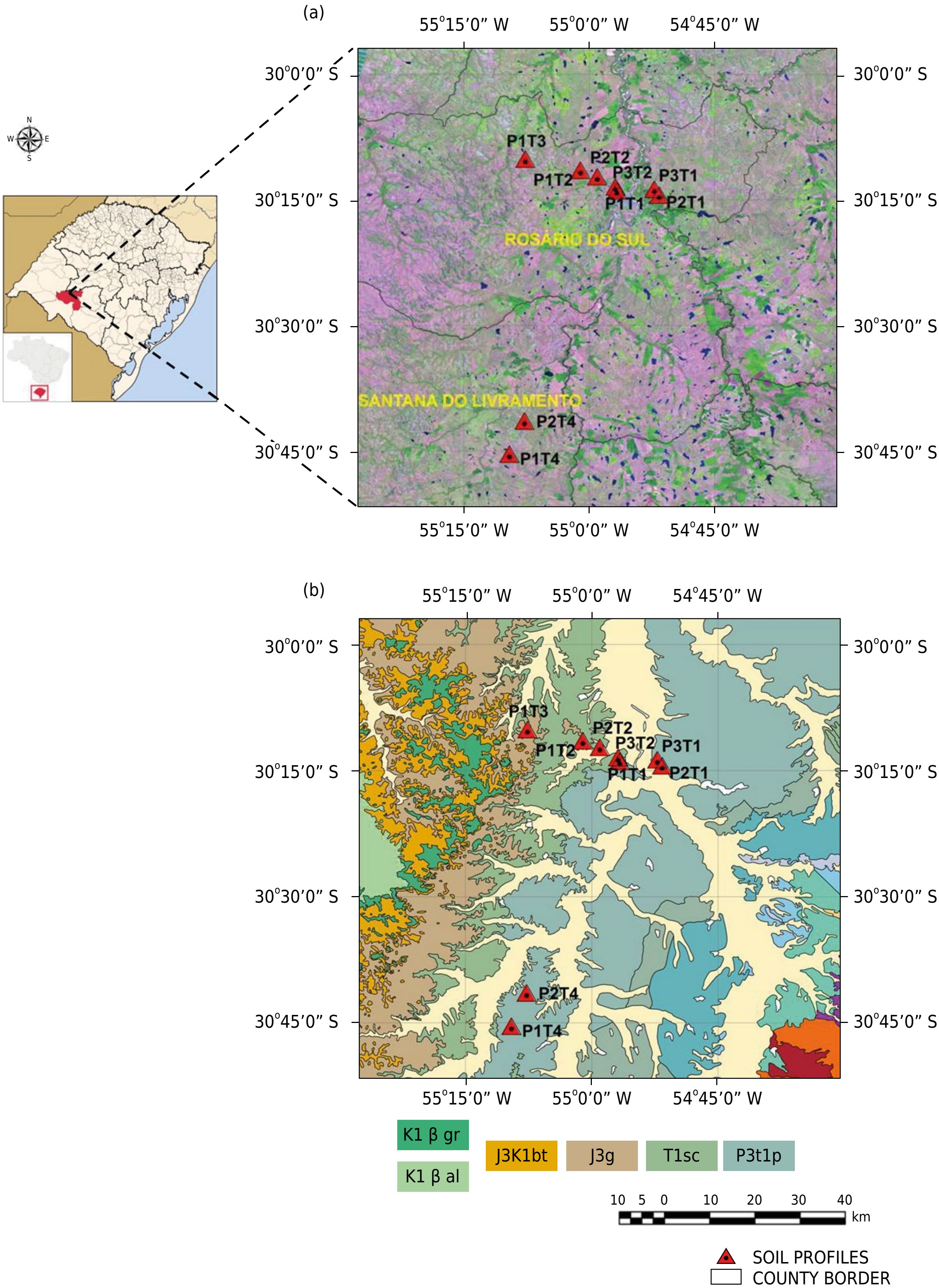

Figure 1. (a) Image chart with the geographical location of the study area and soil profiles - Municipality of Rosário do Sul and Santana do Livramento, RS (Image Landsat 5 Thematic Mapper - Composition 5R4G3B / Datum SAD69 - Scale indicated). (b) Simplified geological map of part of the southwest region of the state of Rio Grande do Sul. Main Formations - P3T1p: Pirambóia Formation; T1sc: Sanga-do-Cabral Formation; J3g: Guará Formation; J3K1bt: Botucatu Formation; K1β: Serra Geral Formation (Scale indicated).

by real-time spatial positioning in a SIG environment over the cartographic base with a GPS navigation receiver. Therefore, a traditional toposequence was not characterized. Rather, we examined the different types of soils formed from distinct lithologies in several segments of the landscape (topolithosequence). The profiles P1T1, P2T1, P3T1, P1T4, and P2T4 belong to the Pirambóia Formation; the profiles P1T2, P2T2, and P3T2, to the Sanga-do-Cabral Formation; and profile P1T3, to the Guará Formation (Figure 1b). The Pirambóia Formation consists of medium to fine sandstone with well-developed lenticular geometry, deposited in an eolic, continental environment with river intercalations. Siltite layers may also occur, interspersed with the sandstones. The Sanga-do-Cabral Formation belongs to the Rosário do Sul Group and is characterized by subarcosic and arcosic sandstones, tabular or elongated lenticular bodies (consisting of breccia and intraformational conglomerate), siltite, and rare argillite, deposited in continental, fluvial interlaced environments that contain fragments of fossilized vertebrates. The Guará Formation is composed of sandstone, fine to conglomeratic, with whitish to reddish colors, occasionally interspersed with centimetric levels of pellets containing dinosaur footprints deposited in a continental desert environment with fluvial, Eolic, and lacustrine deposits (CPRM, 2006).

A general and morphological description of the selected profiles was carried out according to the method described in Schneider et al. (2007) and Santos et al. (2015b). In each subhorizon of the profiles, a soil sample was collected for chemical and physical characterization. The soil samples were air dried, crushed, milled, and sieved in a 2 mm mesh, separating the coarse fractions and the air-dried fine earth (ADFE). Soil particle size distribution and basic chemical analyzes were performed on the ADFE according to methods described in Tedesco et al. (1995) and Claessen (1997). Active acidity (pH in H_2O at a ratio of 1:1 v/v) was determined by potentiometry using a pH-meter. Organic carbon (OC) was determined by the Walkley-Black method through its oxidation with the dichromate anion in acid medium and redox titration with ferrous sulfate solution in the presence of ferroin indicator. The exchangeable K and Na contents were determined using the double-acid extraction method (Mehlich-1) with flame photometer readings. Exchangeable Ca and Mg were extracted with 1 mol L^{-1} KCl and determined in an atomic absorption spectrophotometer. Exchangeable Al was obtained by neutralization titration with 0.0125 mol L^{-1} NaOH after extraction with 1 mol L^{-1} KCl. Potential acidity (H+Al) was obtained with 0.5 mol L^{-1} calcium acetate extractor buffered to pH 7 and titrated with 0.02 mol L^{-1} NaOH. Sum of bases (SB), cation exchange capacity at pH 7 (T), base saturation (V), Al saturation (m), Na saturation (Na%), and activity of the clay fraction (T_{CLAY}) were calculated according to the following expressions: $SB = Ca^{2+} + Mg^{2+} + K^{+} + Na^{+}$; CEC pH7 $(T) = SB + (H+Al)$; $V = (SB/T) \times 100$; $m = [Al/(Al + SB)] \times 100$; $Na\% = (Na/T) \times 100$; and $T_{CLAY} = (T \text{ soil}/\% \text{ clay in the B subhorizon}) \times 100$, respectively. The Fe_2O_3 contents were determined according to the method of sulfuric acid attack of fine earth (SAFE) proposed by Embrapa (1979). The clay fraction was determined using the simplified densimeter method (Bouyoucus, 1962) after dispersion of the soil samples in H_2O - water dispersible clay (WDC) - and with 1 mol L^{-1} NaOH solution or Calgon (sodium hexametaphosphate and anhydrous sodium carbonate) - total clay (C_T). The sand fraction was gravimetrically quantified (weighing) after mechanical sieving and oven drying. Silt was determined by the difference between the mass of total sample and the mass of clay + sand fractions. The silt/clay ratio was calculated by the simple ratio between the values of the two fractions, and the degree of clay flocculation (DF) was determined by the following equation: $DF = 100 \times (C_T\text{-}WDC)/C_T$.

The profiles were taxonomically classified up to the 4th categorical level (subgroups) according to the SiBCS (Santos et al., 2013) and the Soil Taxonomy (Soil Survey Staff, 2014) systems.

Using digital mapping tools from the DEM, hypsometric maps of topographic and three-dimensional (3D) profiles were created to assist in the study of soil-landscape relationships. For correlation of the geomorphic surfaces with pedogenesis, the method proposed by Troeh (1965) was applied.

The physical and chemical properties of the soil profiles were determined by multivariate statistical analysis through use of factor analysis (FA) and cluster analysis (CA) techniques. The data were standardized (mean zero and unit variance) to avoid influence of the units of measurement on the analyses. In cluster analysis, Euclidean distance was used to measure similarity, and the agglomerative method of Ward was adopted for formation of groups. The Statistica 8 program (Statsoft, 2007) was used for analyses.

RESULTS AND DISCUSSION

Pedological characterization and taxonomic classification

The morphological data of the profiles and the analytical results for characterization are shown in tables 1, 2, and 3. A general description of these soils can be found in Santos (2015).

In the P1T1-PVd profile (*Argissolo Vermelho Distrófico espessarênico abrúptico*/Arenic Kanhapludults) in the surface horizon, the OC ranged from 4.2 g kg^{-1} in the A1 to 1.7 g kg^{-1} in the A2. The depth of the solum was 2.88 m, and the thickness of the A horizon was 0.90/0.95 m. The structure exhibited a massive appearance that broke apart into weakly developed blocks. It had a sandy texture to a depth of more than 1.00 m, low CF, and V <65 %. The subsurface horizon was B texture type, presenting soil reaction phase with negative ΔpH. The soil texture in the Bt1, Bt3, and BC horizons was medium and clayey in Bt2, with high CF (100 %) in the Bt3 and BC horizons, indicating high stability of microaggregates. The texture ratio was quite high (TR = 4.8). In addition, the soil exhibited abrupt textural change (ATC) in the transition between the E and Bt1, with low activity clay (Tl) in the Bt and a silt/clay ratio <0.6. The structure of the B horizon ranged from medium moderate and small sub-angular blocks to medium strong sub-angular and angular blocks. There was the presence of clay films at a quantity/degree of low/weak expression in the Bt1 and abundant/strong in the Bt2 and Bt3, represented by depositions similar to argilans + humans or argilans + ferrans. The B horizon exhibited V lower than 50 % and content of Al^{3+} <4 $cmol_c$ kg^{-1}. The Fe content of the SAFE was only 38.3 g kg^{-1} of Fe_2O_3 (hypoferric). The dominant color in the B was dark red.

The P2T1-PBACal profile (*Argissolo Bruno-Acinzentado Alítico abrúptico endorredóxico*/Oxyaquic Hapludults) had a type A moderate surface horizon, with OC content of approximately 7 g kg^{-1}. The thickness of the A horizon was 0.42 m with solum depth of 1.75 m. The structure was small/weak granular and in simple grains in the A1, with massive appearance that fell apart in weak medium sub-angular and angular blocks in the A2. The average clay content in the A was 140 g kg^{-1}, and V was lower than 65 %. It had colors ranging from very dark grayish brown in the A1 to very dark brown in the A2. Lithological discontinuity was identified based on irregular distribution of the sand fractions between the horizons, difference in the value of uniformity, variation in the Zr/Ti ratio, and mineralogical analysis, as well as field observation of a gravel line at the top of the 2BA (Santos, 2015). In subsurface horizons, the texture was clayey in 2BA and medium in 2Bt and 2BC, with high activity clay (Th) in all subhorizons, but with low V (dystrophic) in most of the B horizon (2BA + 2Bt) and 2BC. The TR was 2.1, with an increase in clay for identification of textural B horizon, and the occurrence of ATC. The silt/clay ratio was very low, 0.38 on average. The structure varied in type, size, and degree between subhorizons. The predominant color was dark-brown at the top of the B horizon and brown in 2Bt and 2BC, typical of the suborders of *Argissolos Bruno-Acinzentados*. An allytic character was identified, with high contents of Mg^{2+} and medium contents of Ca^{2+}, despite its dystrophic nature. The Fe_2O_3 content was 21 g kg^{-1} (hypoferric) on average.

The profile P3T1-PAal (*Argissolo Amarelo Alítico plintossólico*/Oxyaquic Hapludults) had an A moderate surface horizon because it included the following properties: thickness = 0.66 m,

Table 1. Morphological characterization of the soil in horizons A and B of the studied profiles

Horizon	Depth	Color (wet)	Structure			Consistency			Transition	
		Munsell	Degree(1)	Size(2)	Type(3)	Dry(4)	Humid(5)	Wet(6)	Topography(7)	Distinctness(8)
	m									
P1T1-PVd: *Argissolo Vermelho Distrófico espessarênico abrúptico* (Arenic Kanhapludults)										
A1	0.00-0.23	7.5YR 3/4	we	sm, md	sub, ang.bl	s.hd	v.fri	n.plas, n.sti	smo	cl
A2	0.23-0.70	7.5YR 3/3	we	sm, md	sub ang.bl	hd	fri	n.plas, n.sti	smo	grad
AE	0.70-0.90/0.95	7.5YR 4/4	we	sm, md	sub.bl	sof	v.fri to lo	n.plas, n.sti	wav	grad
E	0.90/0.95-1.10	7.5YR 4/6	we	sm	sub.bl	sof	lo to v.fri	n.plas to s.plas, n.sti	smo	abrp
Bt1	1.10-1.20	2.5YR 3/4	mod	md, sm	sub.bl	v.hd	v.fri to fri	v.plas, s.sti to sti	smo	cl
Bt2	1.20-1.77	2.5YR 3/6	str	md	ang, sub.bl	v.hd to e.hd	fri	plas, peg to v.sti	smo	cl
Bt3	1.77-2.44	2.5YR 3/6	str	md, lar	ang, sub.bl	e.hd	fri to fir	plas, sti	smo	grad
BC	2.44-2.88	2.5YR 2.5/4	we to mod	md, lar	ang.bl	v.hd	v.fri to fri	s.plas to plas, sti	smo	grad
P2T1-PBACal: *Argissolo Bruno-Acinzentado Alítico abrúptico endorredóxico* (Oxyaquic Hapludults)										
A1	0.00-0.20	10YR 3/2	we	sm	gran, sg	sof	v.fri	n.plas, n.sti	smo	grad
A2	0.20-0.42	10YR 2/2	we	md	sub, ang.bl	s.hd	fri	n.plas, n.sti	smo	cl
2BA	0.42-0.63	7.5YR 3/2	mod	md, sm	sub.bl	hd	fri to fir	plas, peg	smo	grad
2Bt	0.63-1.25/1.40	7.5YR 4/4 e 2.5YR 4/7	mod	lar, md	sub, ang.bl	e.hd	fir	s.plas to plas, s.sti	wav	grad
2BC	1.25/1.40- 1.70/1.80	7.5YR 4/2 e 2.5YR 3/6	we we	lar, md, lar	prism ang, sub.bl	v.hd	fri	s.plas, sti	wav	grad
P3T1-PAal: *Argissolo Amarelo Alítico plíntossólico* (Oxyaquic Hapludults)										
A1	0.00-0.28	10YR 3/3	we	sm, md	ang.bl, sg	sof	v.fri to lo	n.plas, n.sti	smo	grad
A2	0.28-0.50	10YR 3/4	we	md, sm	ang.bl	s.hd to hd	fri	n.plas, n.sti	smo	cl
AB	0.50-0.66	10YR 4/4	we	md, lar	ang.bl	hd	fri	s.plas to plas, sti	smo	grad
BAx	0.66-0.82	10YR 4/6	we to mod	md	sub, ang.bl	hd	fri	v.plas, sti to v.sti	smo	cl
Btf$_1$	0.82-1.15/ 1.25	7.5YR 5/8 e 10YR 5/3	mod mod	lar md	prism ang, sub.bl	hd	fri to fir	plas, v.sti	wav	grad
Btf$_2$	1.15/ 1.25-1.70/ 1.85	10YR 6/1 e 10R 3/6	str str	lar lar, md	prism ang.bl	e.hd	fir	n.plas to s.plas, s.sti to sti	wav	grad
Btf$_3$	1.70/1.85-2.00$^+$	10YR 5/1 e 7.5YR 6/8	str str	lar lar	prism ang.bl	e.hd	v.fir to e.fir	n.plas to s.plas, s.sti	-	-
P1T2-PBACal: *Argissolo Bruno-Acinzentado Alítico abrúptico arênico* (Arenic Hapludults)										
A1	0.00-0.18	10YR 3/3	we	sm	sub.bl, sg	lo	v.fri	n.plas, n.sti	smo	grad
A2	0.18-0.34	10YR 3/2	we	md	sub.bl, sg	sof	v.fri	n.plas, n.sti	smo	cl
A3	0.34-0.51	10YR 3/2.5	we	lar, md	sub.bl	sof	fri	n.plas, s.sti	smo	cl
BAt	0.51-0.65	10YR 3/3	we to mod we to mod	md md, sm	prism ang, sub.bl	hd	fri to fir	v.plas, sti	smo	grad
Bt	0.65-0.96	10YR 3/4 e 2.5YR 3.5/6	mod mod	lar lar, md	prism sub.bl	v.hd	fir	s.plas, s.sti	smo	grad
BC	0.96-1.15	5YR 4/6 e 7.5YR 5/1				hd	fri to fir	s.plas to plas, sti	smo	cl
P2T2-TCk: *Luvissolo Crômico Carbonático solódico* (Mollic Hapludalfs)										
A	0.00-0.35	10YR 3.5/2.5	we	md, lar	sub.bl	sof	fri	plas, s.sti to sti	smo	abrp
Btxn	0.35-0.58	10YR 5/4	mod mod to str	lar, md lar	ang.bl sub.bl	e.hd	e.fir	v.plas, sti	smo	cl
Btkn	0.58-0.80	5YR 5/7	we to mod	md	ang.bl	e.hd	v.fir	s.plas, sti	smo	grad
P3T2-FTd: *Plintossolo Argilúvico Distrófico abrúptico* (Plintic Paleudults)										
A1	0.00-0.22	7.5YR 4/4	we	sm	gran, sg	sof	lo & v.fri	n.plas, s.sti	smo	grad
A2	0.22-0.60	10YR 4/4	we	md	sub, ang.bl e sg	s.hd to hd	fri	n.plas, s.sti	smo	abrp

Continue

Table 1. Morphological characterization of the soil in horizons A and B of the studied profiles

$2Btf_1$	0.60-0.78	5YR 4/5 e 2.5YR 4/6	we to mod	md	sub.bl	s.hd	fri to fir	s.plas, s.sti to sti	smo	grad
$2Btf_2$	0.78-1.20	10R 4/8 e 5YR 4/6	mod mod	lar md ,sm	prism ang.bl	e.hd	fir	n.plas to s.plas, sti	smo	grad
$2Btf_3$	$1.20\text{-}2.00^+$	7.5YR 5/7 e 10R 4/8	mod mod	lar md	prism ang, sub.bl	v.hd	fir	plas, sti	-	-
P1T3-LVe: *Latossolo Vermelho Eutrófico psamítico* (Typic Eutrudox)										
A1	0.00-0.15	5YR 4/6	we	sm	gran, sg	lo	lo, v.fri	n.plas, n.sti	smo	dif
A2	0.15-0.50	5YR 3/4	we we	md sm	sub.bl gran, sg	sof	lo to v.fri	n.plas, n.sti	smo	dif
AB	0.50-0.71	3.5YR 3/4	we	md, sm	sub.bl, sg	sof	v.fri	n.plas, s.sti	smo	grad
B_1	0.71-0.95	2.5YR 4/6	we	md, sm	sub.bl, sg	sof to s.hd	v.fri	n.plas, s.sti	smo	dif
B_2	0.95-1.45	2.5YR 3/5	we mod	md v.sm	sub.bl gran	sof to s.hd	v.fri	n.plas, s.sti	smo	dif
B_3	$1.45\text{-}1.70^+$	2.5YR 3/6	we mod	md v.sm	sub.bl gran	sof to s.hd	v.fri to fri	s.plas, sti	-	-
P1T4-TXp: *Luvissolo Háplico Pálico endorredóxico* (Oxyaquic Hapludalfs)										
A1	0.00-0.11	10YR 3/2	we	sm	gran, sg	sof	lo, v.fri	n.plas, s.sti	smo	grad
A2	0.11-0.38	10YR 4/3.5	we	lar, md	ang.bl	s.hd	fri	n.plas, s.sti to sti	smo	cl
AB	0.38-0.48	10YR 3/4	we	lar, md	ang.bl	s.hd to hd	fri to firm	plas, sti	smo	abrp
BAt	0.48-0.70	10YR 2/2	mod	sm, md	ang, sub.bl	v.hd to e.hd	fri to firm	s.plas, s.sti	smo	grad
Bt	0.70-0.85/0.98	10YR 5/2 e 2.5YR 4/6	mod to str mod	lar, md md	ang.bl prism	e.hd	fir	s.plas to plas, s.sti	wav	cl
BC	0.85/0.98-1.25	7.5YR 4/3 e 2YR 3/6	we	lar, md	ang.bl	v.hd	fri to fir	s.plas, sti	smo	cl
P2T4-PVd: *Argissolo Vermelho Distrófico arênico* (Arenic Kandiudults)										
A1	0.00-0.20	7.5YR 3/3	we	md, sm	gran, sg	sof	lo, v.fri	n.plas, n.sti	smo	grad
A2	0.20-0.55	5YR 3/4	we	md	sub.bl	sof to s.hd	v.fri	n.plas, n.sti	smo	cl
AB	0.55-0.67	5YR 4/6	we	md, sm	sub.bl	sof to s.hd	v.fri	n.plas, s.sti	smo	cl
BAt	0.67-0.77	5YR 3/3	we to mod	md	sub.bl	s.hd	fri	plas, sti	smo	cl
Bt1	0.77-0.98	2.5YR 3/6	mod	md, sm	sub.bl	hd	fir	plas, sti	smo	grad
Bt2	$0.98\text{-}1.75^+$	2.5YR 4/6	mod	md, sm	sub.bl	v.hd	fir	s.plas, s.sti	-	-

(1) we = weak; mod = moderate; str = strong. (2) v. sm = very small; sm = small; md = medium; lar = large. (3) gran = granular; sub.bl = subangular blocks; ang.bl = angular blocks; prism = prismatic; m = massive; sg = simple grain. (4) lo = loose; sof = soft; s. hd = slightly hard; hd = hard; v. hd = very hard; e. hd = extremely hard. (5) lo = loose; v. fri = very friable; fri = friable; fir = firm; v. fir = very firm; e. fir = extremely firm. (6) n. plas = non-plastic; s. plas = slightly plastic; plas = plastic; v. plas = very plastic; n. sti = non-sticky; s. sti = slightly sticky; sti = sticky; v. sti = very sticky. (7) smo = smooth; wav = wavy. (8) cl = clear; grad = gradual; abrp = abrupt; dif = diffuse.

wet color with value and chroma >3, dry color with value ≤5 (brown in the A1 and yellowish-brown in the A2 and AB), OC content of 6 g kg^{-1} in the A1 and 4 g kg^{-1} in the A2 and AB, V <65 %, a structure that appeared to be massive but that broke down into angular blocks and simple grains, and clay contents that increased from 110 g kg^{-1} in the A1 to 200 g kg^{-1} in the AB. The subsurface horizon was characterized as textural B, with TR of 2.2. However, the clay content, in the transition from the AB to BAx was not significant to the point of characterizing ATC. It had low activity clay (Tl), but >20 $cmol_c$ kg^{-1}, and a silt/clay ratio <0.6. The BAx and Btf_2 horizons were of medium texture, while the Btf_1 was clayey and the Btf_3 was medium to clayey, with CF >50 % throughout the B. It had an acid reaction phase and a dystrophic character in most of the B, except in the Btf_3. Because the Al^{3+} was higher than 4 $cmol_c$ kg^{-1}, together with clay activity higher than 20 $cmol_c$ kg^{-1} and the high m, an allytic character was identified in most of the B horizon. The dominant

Table 2. Physical properties of the soil in the A and B horizons of the studied profiles

Horizon	Sand	Silt	Clay	Scattered clay H_2O	Clay flocculation	Silt/clay
	g kg^{-1}				%	
P1T1-PVd: *Argissolo Vermelho Distrófico espessarênico abrúptico* (Arenic Kanhapludults)						
A1	852	68	80	60	25	0.85
A2	834	86	80	50	38	1.08
AE	857	73	70	50	29	1.05
E	837	113	50	30	40	2.26
Bt1	643	87	270	140	48	0.32
Bt2	500	70	430	80	81	0.16
Bt3	611	79	310	0	100	0.26
BC	743	47	210	0	100	0.22
P2T1-PBACal: *Argissolo Bruno-Acinzentado Alítico abrúptico endorredóxico* (Oxyaquic Hapludults)						
A1	797	83	120	20	83	0.69
A2	762	78	160	60	63	0.49
2BA	474	136	390	130	67	0.35
2Bt	598	132	270	100	63	0.49
2BC	713	67	220	60	73	0.31
P3T1-PAal: *Argissolo Amarelo Alítico plíntossólico* (Oxyaquic Hapludults)						
A1	801	89	110	40	64	0.81
A2	609	261	130	90	31	2.01
AB	680	120	200	80	60	0.60
BAx	602	148	250	120	52	0.59
Btf_1	477	163	360	140	61	0.45
Btf_2	505	175	320	140	56	0.55
Btf_3	482	168	350	40	89	0.48
P1T2-PBACal: *Argissolo Bruno-Acinzentado Alítico abrúptico arênico* (Arenic Hapludults)						
A1	845	75	80	40	50	0.93
A2	833	77	90	60	33	0.85
A3	764	96	140	80	43	0.68
BAt	597	93	310	190	39	0.30
Bt	565	65	370	260	30	0.17
BC	681	59	260	200	23	0.23
P2T2-TCk: *Luvissolo Crômico Carbonático solódico* (Mollic Hapludalfs)						
A	620	256	124	70	44	2.06
Btxn	478	308	214	200	7	1.44
Btkn	162	564	274	274	0	2.06
P3T2-FTd: *Plintossolo Argilúvico Distrófico abrúptico* (Plintic Paleudults)						
A1	728	182	90	60	33	2.02
A2	728	182	90	70	22	2.02
$2Btf_1$	502	168	330	200	39	0.51
$2Btf_2$	510	140	350	120	66	0.40
$2Btf_3$	500	150	350	150	57	0.43
P1T3-LVe: *Latossolo Vermelho Eutrófico psamítico* (Typic Eutrudox)						
A1	892	28	80	70	13	0.35
A2	862	38	100	80	20	0.38
AB	888	2	110	100	9	0.02
B_1	845	45	110	100	9	0.41
B_2	825	45	130	130	0	0.35
B_3	778	32	190	150	21	0.17
P1T4-TXp: *Luvissolo Háplico Pálico endorredóxico* (Oxyaquic Hapludalfs)						
A1	749	121	130	70	46	0.93
A2	733	143	124	110	11	1.15
AB	607	119	274	220	20	0.44
BAt	374	172	454	380	16	0.38
Bt	345	241	414	320	23	0.58
BC	580	196	224	200	11	0.87
P2T4-PVd: *Argissolo Vermelho Distrófico arênico* (Arenic Kandiudults)						
A1	823	63	114	80	30	0.55
A2	812	74	114	100	12	0.65
AB	737	89	174	160	8	0.51
BAt	584	82	334	260	22	0.24
Bt1	454	102	444	300	32	0.23
Bt2	481	125	394	240	39	0.32

Table 3. Soil chemical properties in the A and B horizons of the studied profiles

Horizon	$pH(H_2O)$	OC	Ca^{2+}	Mg^{2+}	K^+	Al^{3+}	H+Al	SB	T	V	m	Na	T_{CLAY}	Fe_2O_3
		$g\ kg^{-1}$	$cmol_c\ kg^{-1}$							%			$cmol_c\ kg^{-1}$	$g\ kg^{-1}$
P1T1-PVd: *Argissolo Vermelho Distrófico espessarênico abrúptico* (Arenic Kanhapludults)														
A1	5.53	4.2	0.75	0.58	0.06	0.16	1.21	1.42	2.63	54	10	2	-	-
A2	4.67	1.7	0.37	0.40	0.03	0.58	1.53	0.85	2.38	36	41	3	-	7.96
AE	4.88	1.6	0.17	0.21	0.02	0.60	0.92	0.42	1.34	31	59	3	-	
E	5.07	0.9	0.06	0.16	0.01	0.46	0.61	0.26	0.87	30	64	4	-	-
Bt1	4.71	3.9	0.52	0.42	0.04	1.95	3.03	1.01	4.04	25	66	1	14.96	-
Bt2	4.95	3.7	1.45	1.30	0.05	2.32	3.52	2.83	6.35	45	45	1	14.76	38.31
Bt3	5.11	1.9	0.94	1.27	0.02	2.24	2.68	2.26	4.94	46	50	1	15.93	-
BC	4.93	2.3	0.44	0.81	0.02	1.72	2.10	1.28	3.38	38	57	1	-	-
P2T1-PBACal: *Argissolo Bruno-Acinzentado Alítico abrúptico endorredóxico* (Oxyaquic Hapludults)														
A1	4.76	7.8	0.34	0.89	0.07	1.70	3.04	1.33	4.37	30	56	1	-	-
A2	4.86	7.2	0.40	0.83	0.05	2.61	4.05	1.31	5.36	24	67	1	-	9.02
2BA	4.96	10.0	1.79	2.39	0.06	8.63	9.19	4.27	13.46	32	67	<1	34.50	-
2Bt	5.25	3.9	2.70	3.77	0.06	9.62	8.91	6.55	15.47	42	59	<1	57.20	21.00
2BC	5.44	1.6	3.71	6.27	0.03	5.71	4.71	10.04	14.75	68	36	<1	67.00	-
P3T1-PAal: *Argissolo Amarelo Alítico plíntossólico* (Oxyaquic Hapludults)														
A1	4.96	6.6	0.41	0.98	0.02	0.66	1.48	1.42	2.91	49	32	1	-	-
A2	4.89	4.5	0.23	0.34	0.02	1.62	2.45	0.61	3.06	20	73	1	-	4.10
AB	4.88	4.3	0.45	0.36	0.02	2.46	3.06	0.84	3.90	21	75	1	-	-
BAx	5.01	5.6	0.79	0.48	0.01	3.29	4.26	1.30	5.56	23	72	<1	22.24	-
Btf_1	5.04	4.7	1.04	0.80	0.07	5.55	5.98	1.94	7.92	25	74	1	22.00	-
Btf_2	5.29	2.6	1.63	1.41	0.06	4.56	4.85	3.14	8.00	39	59	1	25.00	30.56
Btf_3	5.34	3.1	3.13	2.46	0.06	2.33	2.92	5.70	8.62	66	29	1	24.60	-
P1T2-PBACal: *Argissolo Bruno-Acinzentado Alítico abrúptico arênico* (Arenic Hapludults)														
A1	4.83	6.4	0.83	0.67	0.19	0.59	1.60	1.72	3.32	52	26	1	-	-
A2	4.61	5.9	0.75	0.42	0.08	1.22	2.75	1.28	4.03	32	49	1	-	4.06
A3	4.69	5.7	0.98	0.42	0.07	1.80	3.27	1.50	4.77	31	55	1	-	-
BAt	4.87	9.2	1.39	0.74	0.06	4.98	6.66	2.24	8.90	25	69	1	28.70	-
Bt	5.06	7.1	0.97	0.73	0.06	6.10	7.06	1.80	8.86	20	77	<1	23.90	21.75
BC	5.02	4.2	0.78	0.56	0.05	6.28	5.77	1.43	7.19	20	81	<1	27.60	-
P2T2-TCk: *Luvissolo Crômico Carbonático solódico* (Mollic Hapludalfs)														
A	5.97	10.6	6.08	1.97	0.04	0.34	2.08	8.26	10.34	80	4	2	-	15.63
Btxn	6.43	5.1	6.00	3.03	0.05	1.25	2.24	10.16	12.41	82	11	9	58.00	-
Btkn	8.81	1.9	14.4	7.03	0.06	0.00	0.00	24.94	24.94	100	0	14	91.00	19.13
P3T2-FTd: *Plintossolo Argilúvico Distrófico abrúptico* (Plintic Paleudults)														
A1	4.93	5.0	0.68	0.55	0.04	0.74	1.54	1.30	2.84	46	36	1	-	-
A2	4.68	3.3	0.54	0.40	0.03	0.79	1.36	0.99	2.35	42	44	1	-	7.77
$2Btf_1$	4.94	4.9	1.27	0.93	0.03	2.77	4.08	2.26	6.34	36	55	1	19.21	-
$2Btf_2$	4.95	4.0	1.32	1.23	0.03	3.02	3.95	2.62	6.57	40	54	1	18.20	27.77
$2Btf_3$	5.17	2.3	1.54	1.73	0.03	2.46	2.86	3.34	6.20	54	42	1	17.30	-
P1T3-LVe: *Latossolo Vermelho Eutrófico psamítico* (Typic Eutrudox)														
A1	5.32	4.4	0.40	0.49	0.07	0.32	0.98	0.98	1.96	50	25	2	-	-
A2	5.12	2.8	0.41	0.36	0.03	0.56	1.29	0.82	2.11	39	41	1	-	7.75
AB	5.16	3.8	0.56	0.38	0.02	0.57	1.18	0.99	2.17	46	36	1	-	-
B_1	5.44	2.0	0.82	0.39	0.02	0.41	0.82	1.25	2.07	61	25	1	18.80	-
B_2	5.39	2.6	1.10	0.59	0.02	0.34	0.83	1.73	2.56	68	17	1	19.60	10.29
B_3	5.33	1.7	1.33	0.79	0.02	0.38	0.89	2.17	3.07	71	15	1	16.15	-
P1T4-TXp: *Luvissolo Háplico Pálico endorredóxico* (Oxyaquic Hapludalfs)														
A1	5.35	12.8	2.29	1.97	0.22	0.07	1.71	4.50	6.21	72	2	1	-	-
A2	5.27	6.4	1.62	1.67	0.16	0.35	1.53	3.49	5.02	70	9	1	-	9.20
AB	4.97	7.7	2.65	2.38	0.15	2.99	4.83	5.24	10.06	52	36	1	-	-
BAt	5.26	10.6	5.88	3.90	0.13	7.29	8.91	9.98	18.89	53	42	<1	41.60	-
Bt	5.60	5.7	12.8	8.03	0.09	8.00	8.15	21.06	29.21	72	28	<1	70.50	37.83
BC	5.78	3.5	12.3	7.49	0.05	3.72	3.52	19.98	23.51	85	16	<1	104.90	-
P2T4-PVd: *Argissolo Vermelho Distrófico arênico* (Arenic Kandiudults)														
A1	5.01	6.5	0.62	0.62	0.04	0.61	1.64	1.30	2.94	44	32	1	-	-
A2	5.14	3.8	0.64	0.55	0.01	0.64	1.46	1.21	2.68	45	34	1	-	9.15
AB	5.10	4.9	1.09	0.89	0.02	0.91	2.10	2.01	4.11	49	31	1	-	-
BAt	5.06	8.2	1.72	1.44	0.02	1.62	3.21	3.21	6.42	50	33	1	19.20	-
Bt1	5.00	7.3	1.96	1.51	0.01	2.23	3.87	3.51	7.37	48	39	<1	16.50	33.43
Bt2	4.96	4.4	1.27	1.35	0.00	2.85	3.36	2.64	6.00	44	52	<1	15.20	-

pH in water at a ratio of 1:1 v/v; OC: organic carbon (Walkley-Black method); K^+ and Na^+ (Mehlich-1 solution); Ca^{2+}, Mg^{2+} and Al^{3+} (1 mol L^{-1} KCl); H+Al (0.5 mol L^{-1} calcium acetate extractor buffered to pH 7); SB: sum of bases; T: cation exchange capacity at pH 7; V: base saturation; m: Al saturation; Na%: Na saturation; and T_{clay}: activity of the clay fraction.

color/hue was 7.5YR or yellower in most of the first 1.00 m of the B horizon, with Fe_2O_3 content around 30 g kg^{-1} (hypoferric). The structure in the upper portion was weak to moderate and of medium size, with sub-angular and angular blocks and fragipan type apparent cementation (BAx). In the underlying horizons (Bt_f), there was a predominance of large size and a strong degree of prismatic structure. There was an intense amount of prominent and distinct mottles and/or plinthite in the Btf_2 and Btf_3 horizons, and reddish color interspersed by glazed gray spots, characterizing the plinthic character in this soil.

In the profile P1T2-PBACal (*Argissolo Bruno -Acinzentado Alítico abrúptico arênico*/Arenic Hapludults), the solum depth was 1.15 m, with a total thickness of 0.51 m in the A horizon. The average OC content in the surface horizon was 6 g kg^{-1} and the V was lower than 65 %. The soil had a dry color with value ≤5, and a wet color with value/chroma ≤3 in all subhorizons of the A horizon. Due to the average sand and clay content, this soil had a sandy texture from the surface to at least 0.50 m deep (arenic). The structure had a weak degree of development, with sub-angular blocks and simple grain type. The dry consistency ranged from loose to soft, and the wet consistency from very friable to friable. The subsurface horizon had high activity clay (Th) in the BAt and BC, and low activity clay (Tl) in the Bt, but had low V in all subhorizons. The TR was 3.2, depicting a high textural gradient, meeting the criterion for textural B. In addition, there was a considerable increase in clay content from the A3 to BAt, indicating ATC. The textural class was medium in the BAt and BC, and clayey in the Bt. All of them had low CF and a silt/clay ratio ≤0.3. It had an acidic reaction phase with high amounts of Al^{3+} and high m, with low Ca^{2+} and Mg^{2+} contents that expressed an allytic character.

In the profile P2T2-TCk (*Luvissolo Crômico Carbonático solódico*/Mollic Hapludalfs) the solum depth was greater than 0.75 m, with the A horizon >0.25 m thick. The OC content was >0.6 %, and the V >65 %. However, the wet color had a value >3; therefore, it was insufficient to characterize the A horizon as chernozemic. The A horizon also had a subangular block type structure of weak degree and medium and large size, soft and friable consistency, and sandy texture, with 124 g kg^{-1} of clay. The Btxn subhorizon had a slightly acidic reaction phase, whereas, in the underlying horizon (Btkn), the pH value was very high (alkaline), but with negative ΔpH. The average clay content in the B was 244 g kg^{-1}, with very low CF, possibly influenced by the high pH and Na content/saturation in the CEC, causing dispersion of the clays. The TR was 1.9, with an increase for textural B; however, in this profile there was no ATC. The B horizon showed high activity clay (Th), and V was higher than 50 % (eutrophic), which is characteristic of soils of this order. The silt/clay ratio in the profile, as a whole, was high, which indicated a low degree of weathering. This can be seen by very high values for Ca^{2+} and Mg^{2+}, due to low base leaching. Although no analysis of the carbonate content was carried out, the soil had a significant presence of calcium carbonate concretions disseminated in the Btkn and Cr horizons, which showed strong effervescence in field tests with 20 % HCl, indicating a probable carbonate character. It showed a solodic character in the B horizon. The wet color of the Btxn horizon was yellowish brown, and in the Btkn it was yellowish red and had a chromic character.

The profile P3T2-FTd (*Plintossolo Argilúvico Distrófico abrúptico*/Plintic Paleudults) had a solum depth >2.00 m and a moderately drained profile. Properties and morphological features indicated lithological discontinuity (Santos, 2015). In the upper horizon, this soil had an average of only 4 g kg^{-1} of OC. The thickness of the A horizon was 0.60 m, with a clay content of 90 g kg^{-1} and a low CF. The structure ranged from simple grains and granular in the A1 to subangular and angular blocks in the A2, but both were of weak degree. The wet soil color in the A horizon had a chrome/value of 4/4 and dry color of 5/4 in the A1 and 6/4 in the A2. The TR was 3.8, indicating an expressive depth gradient, characterized by an ATC in which the clay content at the transition between the diagnostic horizons increased from 90 to 330 g kg^{-1}. As for the textural grouping, the 2Btf1 subhorizon was of medium texture, and the 2Btf2 and 2Btf3 were of medium-clay texture, all with silt/clay ratio ≤0.5, indicating a material with an advanced degree of weathering. The B horizon showed low activity clay, with V lower than 50 % (dystrophic), except for 2Btf3 and Cr. Despite the low pH, the Al^{3+} content was relatively low in this soil and did not have an aluminic or allytic character. Plinthite was disseminated throughout the 2Btf2 and 2Btf3 in the form of red aggregates, interspersed with gray and whitish spots.

The profile P1T3-LVe (*Latossolo Vermelho Eutrófico psamítico*/Typic Eutrudox) was a very deep profile (solum thickness >2.00 m). The surface horizon was moderate type A, not classified as weak A only because of its color. It had an average OC content of only 3.6 g kg^{-1}, was relatively thick, and had a sandy texture with low V. The structure had a massive appearance, crumbling into single grains and sub-angular blocks with a weak degree of development and loose, very friable, non-plastic, and non-sticky consistency. The silt/clay ratio was very low, throughout the profile, showing a high degree of evolution of this material, compatible with soils of this order. The TR was 1.48, with a gradual clay increase at depth and an absence of clay films on ped surfaces. The transition between the horizons was diffuse in most of the profile. Regarding color, the dominant hue in the B was 2.5YR, and the Fe_2O_3 content was low (hypoferric). The textural subcluster was of medium sandy texture with very low silt values and, in this case, with low CF. Although the clay activity was slightly greater than 18 $cmol_c$ kg^{-1} in the first two subhorizons of B, it was less than 17 in the underlying ones. The exchangeable base contents, mainly of Ca^{2+} and Mg^{2+}, were low, possibly due to the chemical poverty of the source material and the intense leaching. Despite that, the soil had a eutrophic character in the subsurface horizons. The amount of OC and Al^{3+} was perceived to be low.

The profile P1T4-TXp (*Luvissolo Háplico Pálico endorredóxico*/Oxyaquic Hapludalfs) had a solum depth of 1.25 m and was from moderately to imperfectly drained. The A horizon had an average OC content of only 9 g kg^{-1}. The thickness of the A horizon was 0.48 m. The V was very high, around 70 % in the A1 and A2, and 52 % in the AB. The clay content in the A1 and A2 was close to 130 g kg^{-1}, increasing to 274 g kg^{-1} in the AB. It had colors ranging from very dark grayish brown in the A1 to brown to dark yellowish brown in the A2 and AB, where, despite the high V in the A, the wet and dry color value and chrome characterized a diagnostic A moderate horizon. The subsurface horizon showed clayey texture in the BAt and Bt and medium in the BC, with high activity clay in all subhorizons. The TR was 2.4, with a significant increase in clay for characterization of the textural B horizon, but there was no occurrence of ATC in the profile. The silt/clay ratio was 0.87 in the BC, and 0.38 and 0.58 in the BAt and Bt respectively, with a very high content of clay dispersed in H_2O. However, in spite of a low CF, it generally had a structure with good development. The predominant color at the top of the B (BAt) was very dark brown, and brown-gray in the Bt, with intense presence of mottles and iron depletion spots in the Bt and BC horizons. This feature was, therefore, very similar to the suborder of the *Argissolo Bruno-Acinzentado*. However, the profile had a eutrophic characteristic, which excluded it from that suborder. It had high contents of Ca^{2+} and Mg^{2+}, but simultaneously high contents of Al^{3+} (7.29 and 8 $cmol_c$ kg^{-1} in the BAt and Bt, respectively), but without showing an aluminum or allytic character. The total Fe_2O_3 content of SAFE was 37.8 g kg^{-1} (hypoferric). The presence of plinthite was registered but was not sufficient for diagnosis of the plinthic B horizon, but rather of a plinthic character. In addition, it showed properties indicative of a planic or redoximorphic character.

The profile P2T4-PVd (*Argissolo Vermelho Distrófico arênico*/Arenic Kandiudults) had an average of only 5 g kg^{-1} of OC in the A horizon and thickness of 0.67 m, with dark-brown (wet) colors in the A1, dark reddish-brown in the A2, and yellowish red in the AB. It had low V, and CF between 8-30 %, which reflects a structure with a weak degree of development. It had sandy texture in the first 0.50 m, and medium texture in the AB. The TR was high (2.9), occurring a significant clay increment; in spite of that, the soil did not exhibit ATC at the transition between the AB and the BAt, where the clay contents were 174 and 334 g kg^{-1}, respectively. The soil texture in the Bt1 and Bt2 horizons was clayey, and medium in the BAt, all with low CF. Presented CEC of clay lower than 20 $cmol_c$ kg^{-1} and an extremely low silt/clay ratio. Clay films were present in quantity and degree of expression abundant and moderate in the Bt1, and common and moderate in the Bt2. The B horizon had pH in H_2O close to 5 and V slightly lower than 50 %. Despite that, there was little increase in S at depth. It did not have an Al character, because the Al^{3+} content was inferior to 4 $cmol_c$ kg^{-1} in all the subhorizons. It was a hypoferric soil, having a dominant hue in the B of 2.5YR, with dark-red and red colors.

Pedogeomorphic relationships

The elevation map with the distribution of the altitude classes (hypsometric levels) in equidistant vertical intervals, the tracing, and the topographic profile maps of the topolithosequences are shown in figure 2. The data of the geomorphometric variables divided into classes are shown in table 4.

The slope is defined as the angle of inclination (zenithal) of the terrain surface relative to the horizontal, i.e., it is the ratio of the difference in elevation or elevation change (vertical distance) to the horizontal distance between two points of an alignment in the same orientation of the local slope. The plane of curvature (horizontal curvature) and the profile of curvature (vertical curvature) represent the shapes of the relief and are important properties in distinguishing geomorphological units. The horizontal curvature refers to the shape of the slope, in a plane, which can be convergent, divergent, or planar, and the vertical curvature refers to the shape of the slope, analyzed in profile, which can be convex, concave, or rectilinear. The slope orientation is defined as the azimuth angle corresponding to the highest slope of the terrain in the downward direction, characterizing the direction of terrain exposure.

According to the altimetric map (Figure 2a) generated from the DEM, the elevation of the region in this segment ranges from approximately 90 to 390 m. The *Campanha Gaúcha* region has an average altitude of around 100 m. In this region where basalt predominates (western portion), the relief is flat to gently rolling. In the areas of sandstone of the Botucatu Formation, the relief reaches altitudes of 200 to 300 m (Santana do Livramento and near Rosario do Sul) and is rolling. In the southwestern part, in the areas of Gondwanian sediments, the relief is gently rolling (Brasil, 1973).

As for slope (Table 4), in general, the predominant relief in the soil profiles was gently rolling, and was rolling only in the area of profiles P2T1-PBACal and P2T4-PVd, with slopes ranging from 8 to 20 % in much of the territorial extension of the study region. Slope is one of the most important topographic properties that control pedogenetic processes, directly affecting the speed of the surface and subsurface water flow and, consequently, water content in the soil and the erosion/deposition potential, among other important processes in soil formation (Gallant and Wilson, 2000).

The horizontal curvature (Table 4) expresses the shape of the slope when observed in horizontal projection, and it can be described as the variation of slope orientation over a given distance, which is reflected in the divergence or convergence character of the flow lines. The horizontal curvature is related to the intensity of the processes of migration and accumulation of water, minerals and organic matter accumulation in the soil, through the concentration of surface runoff. The profiles P1T2-PBACal, P2T2-TCk, P3T2-FTd, and P1T3-LVe exhibited very divergent and divergent horizontal curvature in the profiles P1T1-PVd and P3T1-PAal. The profiles P2T1-PBACal and P2T4-PVd had convergent curvature, and the profile P1T4-TXp had planar. The convergent areas represent the valleys and the divergent areas the interflows, where, according to Sirtoli (2008) in his study, the deepest and most evolved soils generally tend to occupy divergent and planar slopes, and the less developed and shallow soils tend to be distributed in convergences and divergences. Chagas (2006), states that less developed soils occur only under convergent plan conditions, where the occurrence is related to the slope and

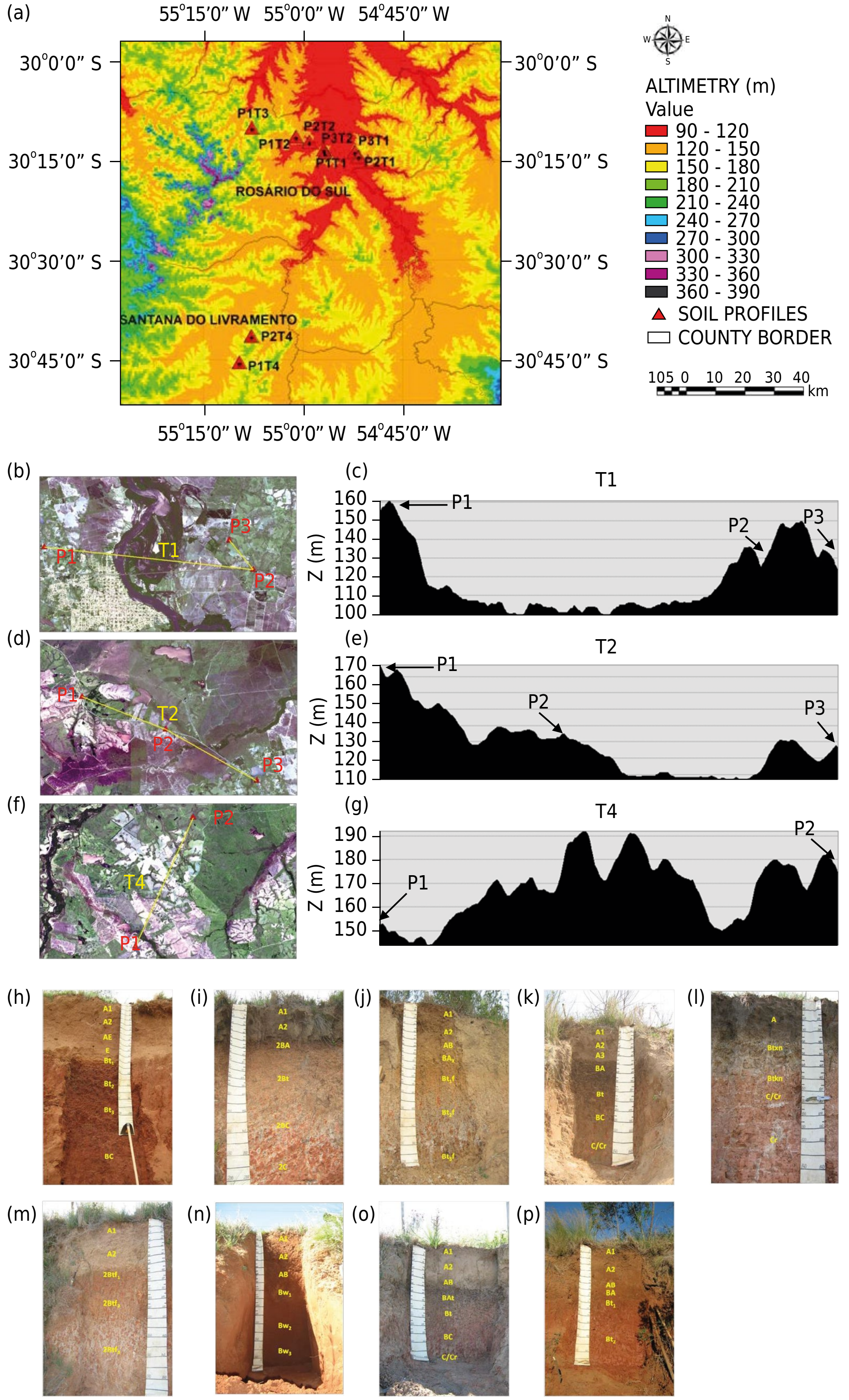

Figure 2. (a) Altimetric map of the region (Datum SAD69 - Scale indicated); T1 (Profiles P1-PVd, P2-PBACal, and P3-PAal), T2 (profiles P1-PBACal, P2-TCk, and P3-FTd), and T4 (profiles P1-TXp and P2-PVd) (RapidEye Image Composition 3R2G1B - without scale); (c), (e), and (g): Topographic profile map of T1, T2, and T4 topolith sequences, constructed from the DEM (without scale); Photographs of soil profiles: (h) P1T1-PVd, (i) P2T1-PBACal, (j) P3T1-PAal, (k) P1T2-PBACal, (l) P2T2-TCk, (m) P3T2-FTd, (n) P1T3-LVe, (o) P1T4-TXp, and (p) P2T4-PVd.

Table 4. Altimetric variables and geomorphometric derivations

Profile	Elevation		Slope class(1)	Curvature		Slope orientation
	GPS	DEM		Horizontal	Vertical	
	m					
P1T1-PVd	140	150	Gently rolling	Divergent	Very convex	N
P2T1-PBACal	125	127	Rolling	Convergent	Rectilinear	E
P3T1-PAal	132	123	Gently rolling	Divergent	Convex	N
P1T2-PBACal	172	177	Gently rolling	Very divergent	Very convex	S
P2T2-TCk	124	127	Gently rolling	Very divergent	Convex	N
P3T2-FTd	115	125	Gently rolling	Very divergent	Very convex	W
P1T3-Lve	177	189	Gently rolling	Very divergent	Convex	S
P1T4-TXp	146	153	Gently rolling	Flat	Rectilinear	SE
P2T4-PVd	165	174	Rolling	Convergent	Very convex	NE

(1) According to relief defined in Embrapa (1999).

the greater convergent flow of water in these areas, a reason that favors morphogenesis, causing these soils to be constantly rejuvenated by erosion.

The vertical curvature (Table 4) expresses the shape of the slope when observed in profile, referring to the convex/concave character, and is expressed in angle difference divided by horizontal distance. Due to its strong relationship with substrate type and relief formation processes, topography compartmentalization studies point to vertical curvature as a variable of high power for identifying homogeneous units, mainly for pedological and geological mapping. This variable is related to the processes of migration and accumulation of matter across the surface, acting indirectly in equilibrium between the processes of pedogenesis/morphogenesis, and it influences local distribution of the water regime and, consequently, the thermal regime (Valeriano, 2008).

The profiles P1T1-PVd, P1T2-PBACal, P3T2-FTd, P1T3-LVe, and P2T4-PVd showed very convex vertical curvature, whereas the profiles P3T1-PAal and P2T2-TCk had convex curvature. The profiles P2T1-PBACal and P1T4-TXp, in contrast, had a rectilinear curvature, not being observed in the slope of the soil profiles sampled, the concave and very concave shape, but only in the adjacent areas.

Convergent water flow is conditioned by the concave pedoform, whereas the linear pedoform is characterized by surface runoff processes (Troeh, 1965). According to Resende et al. (1997), the concave pedoform has greater instability in the higher parts (of removal) and greater stability in the lower areas (of accumulation); that is, soil erosion increases from concave to convex pedoforms, passing through the linear pedoform, which has greater stability. Thus, the concave shape favors concentration of water in the system, while the convex shape favors dispersion and loss of water from the system (Resende et al., 2007). Greater spatial variability of the chemical properties is favored due to the pedogeomorphic conditions in the concave pedoform (Zebarth et al., 2002; Montanari et al., 2005). The differences in the spatial distribution of soil properties in the different pedoforms are associated with variations in soil relief (water flow), and greater variability of erosion is observed in the concave pedoform than in linear areas (Souza et al., 2003). Extreme cases of combinations of curvature of the terrain are represented by the concave-convergent form (maximum concentration and accumulation of runoff) and by the convex-divergent form (maximum dispersion of runoff).

The orientation of the slopes (Table 4) can aid in description of the surface hydrological structure through determination of the flow lines (drainage channels and water dividers), subsidizing modeling of the entire transport process along the slopes (Valeriano, 2008). In addition, the orientation of the slopes is directly related to important aspects, such as evapotranspiration, insolation, and soil water content and, consequently, to soil properties (Moore et al., 1993). The results show that the profiles that have N-oriented slopes in the region are P1T1-PVd, P3T1-PAal, and P2T2-TCk; and that P2T4-PVd is NE-oriented. The S-oriented profiles are P1T2-PBACal and P1T3-LVe, and P1T4-TXp is SE-oriented. The profile P2T1-PBACal, for its part, had an E-oriented slope, and P3T2-FTd is W-oriented. According to Sirtoli (2008), the highest values of solar radiation are generally found on the flat portions of the terrain, facing N/NE, and where there is no significant shading of the relief, and the regions with lower solar radiation are found on slopes with high declivities and facing the S and SW. Solar radiation is a primary source of energy for physical and biological processes and, depending mainly on the exposure (north or south), there is large variation in the energy received, affecting the pedoclimate and, consequently, the soil properties (Resende, 1986).

Statistical analysis

The affinity arrangement of the A and B horizons of the soils (Figure 3) was represented by the dendrogram based on Euclidean distance (coefficients of measurement of similarity), determined by calculations from the correlation matrix between the variables studied, where the formation of distinct groups can be identified.

Analyzing the factorial loads (Table 5), we can see which of the chemical and physical properties of the soil determine differentiation of the horizons between the profiles. The objective was to know which soil properties among those that are important for its characterization are associated (correlated) and that influence the establishment of groupings of similar profiles. Factors 1, 2, and 3 that explained the variability of the basic data of the profiles and the correlation between the variables of the soils studied were described by means of factorial analysis. From the results of analysis of soil factors in horizons A and B (Table 5), it can be verified that the proportion of total soil variation explained by the first three factors for the chemical and physical variables were 91.9 % for horizon A and 89.5 % for horizon B.

In the dendrogram, from the properties of the A horizon (Figure 3a), three distinct groups were formed, taking into account a Euclidean distance of 6.0 between the profiles. Group 1 gathered the profiles P1T4-TXp and P2T2-TCk, with a distance of 5.5. Group 2 was formed by the profiles P1T2-PBACal, P3T1-PAal, and P2T1-PBACal, with a distance of 3.8. And group 3 consisted of the profiles P2T4-PVd, P3T2-FTd, P1T3-LVe, and P1T1-PVd, with distance of 3.2. For the A horizon (Table 5), the variability of factor 1 (51.7 %) is due to active acidity [pH(H_2O)], the organic C, Ca^{2+}, and Mg^{2+} contents, SB, CEC pH7, base and Al saturation, and soil sand fraction, while 26.9 % of the total variation attributed to factor 2 is due to the contents of Al^{3+}, potential acidity (H+Al), and degree of clay flocculation (CF). In contrast, factor 3 explains only 13.3 % of the variation, which was caused by K^+ concentrations in the soil.

In the dendrogram, from the properties of the B horizon (Figure 3b), four different groups were formed. Group 1 was formed by P1T4-TXp and P2T2-TCk, with distance of 6.8. Group 2 consisted only of P1T3-LVe, with a distance of 7.2. Group 3 was represented by P1T2-PBACal and P2T1-PBACal, with a distance of 3.2. Finally, group 4 was formed by profiles P2T4-PVd, P3T2-FTd, P3T1-PAal, and P1T1-PVd, with a distance of 2.8. Within group 4, the profiles that most resemble each other are P3T2-FTd and P3T1-PAal, with Euclidean distance close to 1.2. For the B horizon (Table 5), we can see that 50.7 % of the total soil variation, caused by chemical and physical properties, is represented by factor 1, mainly by active acidity [pH(H_2O)], exchangeable bases (Ca^{2+}, Mg^{2+}, and K^+), SB, CEC pH7, base saturation, clay activity, and sand and silt/clay ratio. Factor 2 accounts for 24.2 % of the variability, with significant changes in the values of Al^{3+} and potential acidity (H+Al), while factor 3 accounts for only 14.6 % of the variation, which is attributed to the contents of Fe and clay in the soil.

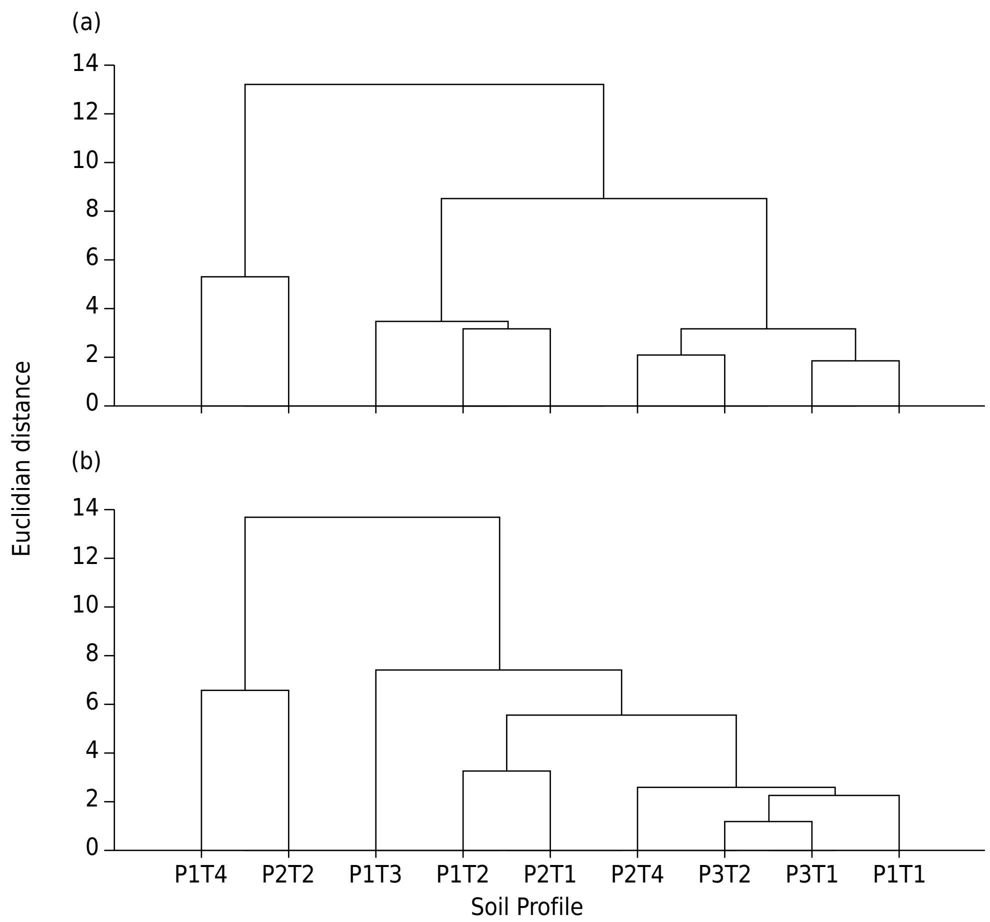

Figure 3. Agglomerative hierarchical grouping between the horizons of the soil profiles by the method of dissimilarity by Euclidean distance: (a) dendrogram by the properties of the A horizon; (b) dendrogram by the properties of the B horizon.

Table 5. Factorial loads of chemical and physical variables in the first three axes in horizons A and B of the soil studied profiles

Variable	Horizon A			Horizon B		
	Factor 1	Factor 2	Factor 3	Factor 1	Factor 2	Factor 3
pH(H_2O)	0.903	-0.272	-0.135	0.768	-0.547	-0.199
OC	0.822	0.444	0.336	-	-	-
Ca^{2+}	0.989	-0.041	-0.039	0.977	-0.115	0.051
Mg^{2+}	0.866	0.131	0.440	0.947	0.170	0.074
K^+	0.153	0.100	0.929	0.764	0.482	0.043
Al^{3+}	-0.340	0.907	0.226	0.207	0.952	0.120
H+Al	0.117	0.896	0.392	0.162	0.949	0.220
SB	0.991	0.005	0.100	0.990	-0.079	0.046
T	0.936	0.262	0.204	0.957	0.252	0.117
V	0.900	-0.377	0.205	0.739	-0.512	-0.285
m	-0.789	0.553	-0.247	-0.575	0.631	0.326
Na%	-	-	-	0.619	-0.654	-0.119
T_{clay}	-	-	-	0.982	0.116	-0.078
Fe_2O_3 (SAFE)	-	-	-	0.012	0.173	0.901
Sand	-0.768	-0.365	-0.003	-0.722	0.202	-0.590
Total clay	0.318	0.508	0.578	0.038	0.341	0.886
Degree of flocculation	0.059	0.930	-0.203	-0.518	0.325	0.457
Silt/clay ratio	-	-	-	0.780	-0.529	-0.039
Horizon thickness	-0.627	-0.581	-0.271	-	-	-
Total variance (%)	51.7	26.9	13.3	50.7	24.2	14.6

SB: sum of bases; T: cation exchange capacity at pH 7; V: base saturation; m: Al saturation; Na%: Na saturation; and T_{clay}: activity of the clay fraction

The statistical classification by cluster analysis (Figure 3b) at first did not differ much from the taxonomic classification, at least at the first categorical level of the SiBCS (orders), even because not all were analyzed or only physical, chemical and morphological properties taken as diagnostic criteria that are considered within the soil classification keys. Thus, group 1 was formed by *Luvissolos*, characterized by higher pH, high Ca^{2+} and Mg^{2+} contents, eutrophic character, and high activity clay (Th) these soils were less weathered and shallower, where there was no ATC. The *Latossolo* formed a single group (group 2) because it was a soil that did not exhibit a textural gradient; it was more weathered/leached and deep, with lower clay and silt content, SB, and CEC of the low clay (Tl) compared to others, but it had low content of Al^{3+} and was eutrophic. Group 3 was formed by the *Argissolos Bruno-Acinzentados*, which stood out with high Al^{3+} content, high T_{Clay}, and low V (allytic character); in addition, ATC occurred in these profiles (abruptical). Group 4 was the most heterogeneous, but, even so, the *Plintossolo Argilúvico* was closer to the *Argissolo Amarelo Plíntico* (smaller Euclidean distance) and, therefore, more similar to it than to the *Argissolos Vermelhos*. In this group, the lower Al^{3+} contents draw attention, together with the Tl that was generally lower than 20 $cmol_c\ kg^{-1}$ and low V, which exhibits a dystrophic character (except for P3T1, which is allytic).

CONCLUSIONS

Taxonomically, the soils of the southwestern region of RS (*Campanha Gaúcha*) varied at both the subgroup and order levels because they had different chemical, physical, and morphological properties, influenced mainly by the type of source material (rock).

Soils developed from the same geological formation have different physical and chemical composition, which can be attributed to variations in the source material due to changes in the depositional environment of the sedimentary package, or to lithologic discontinuity.

Excluding the formation factors, organisms and time, the groupings of soils of different formations, indicate that, their differences are also due to the strong interaction of this source material with the type and intensity of the morphogenetic processes, influenced by the position they occupy in the landscape, conditioned by the relief and flow of water in the profile, since they supposedly were evolved under the same past climate conditions.

Multivariate statistical analysis of factors allowed identification of the soil properties that were determinant in differentiation of the profiles.

Multivariate analysis made it possible to statistically differentiate the profiles within the same lithostratigraphic unit and at different relief positions, as well as differentiate the soils developed from different source materials that occupy similar positions in the pedo-landscape, through formation of homogeneous groups of profiles linked by their degree of similarity.

REFERENCES

Bouyoucus GJ. Hydrometer method improved for making particle size analyses of soils. Agron J. 1962;54:464-5. https://doi.org/10.2134/agronj1962.00021962005400050028x

Brasil. Ministério da Agricultura - Departamento Nacional de Pesquisa Agropecuária - Divisão de Pesquisa Pedológica. Levantamento de Reconhecimento dos solos do Estado do Rio Grande do Sul. Recife: 1973. (Boletim técnico, 30)

Carvalho Junior W, Schaefer CEGR, Chagas CS, Fernandes Filho EI. Análise multivariada de Argissolos da faixa atlântica brasileira. Rev Bras Cienc Solo. 2008;32:2081-90. https://doi.org/10.1590/S0100-06832008000500029

Chagas CS. Mapeamento digital de solos por correlação ambiental e redes neurais em uma bacia hidrográfica no domínio de Mar de Morros [tese]. Viçosa: Universidade Federal de Viçosa MG; 2006.

Claessen MEC, organizador. Manual de métodos de análise de solo. 2a ed. Rio de Janeiro: Centro Nacional de Pesquisa de Solos; 1997.

Companhia de Pesquisa de Recursos Minerais - CPRM. Mapa geológico do estado do Rio Grande do Sul. Escala 1:750.000. Porto Alegre: Serviço Geológico do Brasil; 2006.

Demattê JAM, Garcia GJ. Alteration of soil properties through a weathering sequence as evaluated by spectral reflectance. Soil Sci Soc Am J. 1999;63:327-42. https://doi.org/10.2136/sssaj1999.03615995006300020010x

Demattê JAM, Nanni MR. Weathering sequence of soils developed from basalt as evaluated by laboratory (IRIS), airborne (AVIRIS) and orbital (TM) sensors. Int J Rem Sens. 2003;24:4715-38. https://doi.org/10.1080/0143116031000075116

Empresa Brasileira de Pesquisa Agropecuária - Embrapa. Centro Nacional de Pesquisas de Solos. Manual de métodos de análise de solo. Rio de Janeiro: Embrapa Solos; 1979.

Empresa Brasileira de Pesquisa Agropecuária - Embrapa. Centro Nacional de Pesquisas de Solos. Sistema brasileiro de classificação de solos. Rio de Janeiro: Embrapa Solos; 1999.

Gallant JC, Wilson JP. Primary topographic attributes. In: Wilson JP, Gallant JC, editors. Terrain analysis: principles and applications. New York: John Wiley; 2000. p.51-85.

Justus JO, Machado MLA, Franco MSM. Geomorfologia. In: Instituto Brasileiro de Geografia e Estatística. Levantamento de Recursos Naturais. V. 33: Folha SH.22 Porto Alegre e parte das folhas SH.21 Uruguaiana e SI.22 Lagoa Mirim. Rio de Janeiro; 1986. p.313-404.

Köppen W, Geiger R. Klimate der Erde. Gotha: Verlag Justus Perthes; 1928. Wall-map 150 cm × 200 cm.

Kravchenko AN, Bollero GA, Omonode RA, Bullock DG. Quantitative mapping of soil drainage classes using topographical data and soil electrical conductivity. Soil Sci Soc Am J. 2002;66:235-43. https://doi.org/10.2136/sssaj2002.2350

Montanari R, Marques Júnior J, Pereira GT, Souza ZM. Forma da paisagem como critério para otimização amostral de Latossolos sob cultivo de cana-de-açúcar. Pesq Agropec Bras. 2005;40:69-77.

Moore ID, Gessler PE, Nielsen GA, Peterson GA. Soil attribute prediction using terrain analysis. Soil Sci Soc Am J. 1993;57:443-52. https://doi.org/10.2136/sssaj1993.03615995005700020026x

Pedron FA, Samuel-Rosa A, Dalmolin RSD. Variação das características pedológicas e classificação taxonômica de Argissolos derivados de rochas sedimentares. Rev Bras Cienc Solo. 2012;36:1-9. https://doi.org/10.1590/S0100-06832012000100001

Prefeitura Municipal de Rosário do Sul - PMRS. Perfil geopolítico do município. Secretaria de Planejamento; 2005 [aceso em 8 de maio de 2012]. Disponível em: http://www.prefeituraderosario.com.br/planeja/planeja.htm.

Resende M, Curi N, Resende SB, Corrêa GF. Pedologia: base para distinção de ambientes. 2a ed. Viçosa: Núcleo de Estudo de Planejamento e Uso da Terra; 1997.

Resende M, Curi N, Resende SB, Corrêa GF. Pedologia: base para distinção de ambientes. 5a ed. Lavras: UFLA; 2007.

Resende M. Clima do solo e suas relações com o ambiente agrícola. Inf Agropec. 1986;138:43-59.

Santos PG. Mineralogia, gênese e relações pedogeomórficas de solos desenvolvidos de litologias das formações Pirambóia, Sanga-do-Cabral e Guará na região sudoeste do Estado do Rio Grande do Sul [tese]. Lages: Universidade do Estado de Santa Catarina; 2015.

Santos PG, Bertol I, Miquelluti DJ, Almeida JA, Mafra AL. Agrupamento de pedons de Cambissolos Húmicos com base em atributos físicos e químicos utilizando a estatística multivariada. Rev Bras Cienc Solo. 2015a;39:350-60. https://doi.org/10.1590/01000683rbcs20130415

Santos RD, Santos HG, Ker JC, Anjos LHC, Shimizu SH. Manual de descrição e coleta de solo no campo. 7a ed. Viçosa, MG: Sociedade Brasileira de Ciência do Solo; 2015b.

Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Oliveira JB, Coelho MR, Lumbreras JF, Cunha TJF. Sistema brasileiro de classificação de solos. 3a ed. Rio de Janeiro: Embrapa Solos; 2013.

Schneider P, Giasson E, Klamt E. Morfologia do solo. Guaíba: Agrolivros; 2007.

Sirtoli AE. Mapeamento de solos com auxílio da Geologia, atributos do terreno e índices espectrais integrados por redes neurais artificiais [tese]. Curitiba: Universidade Federal do Paraná; 2008.

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

Souza CK, Marques Júnior J, Martins Filho MV, Pereira GT. Influência do relevo na variação anisotrópica dos atributos químicos e granulométricos de um Latossolo em Jaboticabal, SP. Eng Agríc. 2003;23:486-95.

Statsoft Inc. Statistica - Data analysis software system. Version 8.0 [internet]; 2007 [accessed on Mar 21, 2010]. Available at: http://www.statsoft.com.

Tedesco MJ, Gianello C, Bissani CA, Bohnen H, Volkweiss SJ. Análises de solo, plantas e outros materiais. 2a ed rev e ampl. Porto Alegre: Universidade Federal do Rio Grande do Sul; 1995.

Troeh FR. Landform equations fitted to contour maps. Am J Sci. 1965;263:616-27. https://doi.org/10.2475/ajs.263.7.616

Valeriano MM. Topodata: guia para utilização de dados geomorfológicos locais. São José dos Campos: INPE; 2008.

Webster R, Oliver MA. Statistical methods in soil and land resource survey. Oxford: University Press; 1990.

Zebarth BJ, Rees H, Walsh J, Chow L, Pennock DJ. Soil variation within a hummocky podzolic landscape under intensive potato production. Geoderma. 2002;110:19-33. https://doi.org/10.1016/S0016-7061(02)00213-6