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Magnetic Susceptibility of Soil to Differentiate Soil Environments in Southern Brazil

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ABSTRACT: The interest in new techniques to support digital soil mapping (DSM) is increasing. Numerous studies pointed out that the measure of magnetic susceptibility (MS) can be extremely useful in the identification of properties related with factors and processes of soil formation, applied to soil mapping. This study addressed the effectiveness of magnetic soil susceptibility to identify and facilitate the distinction of different pedogenic environments of a representative hillslope in the highland Planalto Médio in the state of Rio Grande do Sul (RS), Brazil. In a 350-ha area in the municipality of Santo Augusto, RS, a representative transect was selected, trenches opened for soil characterization and 29 grid points marked at regular distances of 50 m, where soil samples were collected (layers 0.00-0.05, 0.05-0.15, 0.15-0.30, and 0.30-0.60 m) to analyze soil properties. Data from the transect samples were subjected to descriptive statistics. Limits of the pedogenetic environments along the slope were identified by the Split Moving Window (SMW) Boundary Analysis. The combined use of soil magnetic susceptibility and the SMW technique was effective in identifying different pedogenetic environments in the study area.

Keywords: pedometrics, geomorphology, detailed mapping.

INTRODUCTION

Magnetic susceptibility (MS) is a measure that indicates to which degree a material is magnetizable, and is directly related to the compounds of this material (Dearing, 1999). Magnetic susceptibility measurements are used in studies of archaeology (Muniz, 2014), paleomagnetism (Jiang et al., 2015), as well as in the identification and description of pedogenetic environments of different locations, for example in China (Liu et al., 2013), Europe (Torrent et al., 2010; Jordanova et al., 2013), and in the different regions of Brazil: Northeast (Santos et al., 2011), North (Oliveira et al., 2015), Southeast (Camargo et al., 2014; Siqueira et al., 2015), and South (Inda Junior et al., 2014).

In tropical soils, MS has been used to indicate the relationship between landscape and iron oxides, considered indicators of the factors and processes of soil formation (Camargo et al., 2014; Matias et al., 2014, 2015). For being directly related with iron oxides, MS is a covariate of soil mineralogical properties and consequently of different pedogenetic environments, here called landscape compartments (relief). According to Ab'Saber (1969), geomorphological studies validate the compartmentalization of landscapes as a method to understand events that explain relief evolution and global and local transformations of the landscape itself.

Studies on the magnetic variability of Oxisols at locations with a total iron content between 4 and 13 % associated the variation in MS to magnetite derived from the source material and to ferromagnetic maghemite and ferrihydrite formed in different pedogenetic environments (Camargo et al., 2014). Along this same line, Marques Jr. et al. (2014) analyzed a sandy Haplustalf with low total iron content (<4 %) and could accurately reproduce the spatial distribution of soil physical and chemical properties using MS. In both studies, MS was used to construct detailed maps (scale <1:10,000) in the southeastern region of Brazil.

The properties of taxonomically similar soil landscapes located in different landscape compartments can vary greatly. According to Matias et al. (2013) and Camargo et al. (2014), MS was efficient to define different pedogenetic environments in apparently homogeneous areas in southeastern Brazil. Magnetic susceptibility was also effective in landscape compartmentalization and identification of different pedogenic environments of Entisols and Ultisols in the Northeast of Brazil (Santos et al., 2011). Different mathematical approaches with magnetic data were used to characterize the variability of soils and their properties. Some authors applied geostatistics to determine the perimeter of pedogenetically different environments (Camargo et al., 2014; Marques Jr et al., 2014). The "Split Moving Window" (SMW) boundary analysis has been used in cases of landscape compartmentalization and to identify pedogenetic limits in a single direction (Matias et al., 2014; Siqueira et al., 2015).

Numerous studies showed potential applications of the MS technique in soil science studies to stratify the landscape in more homogeneous compartments, serving as an important variable for digital soil mapping (DSM) on a detailed scale. According to Dalmolin and Ten Caten (2015), the potential for the application of new technologies to improve the quality of DSM-generated information is huge. Furthermore, along with morphometry, proximal soil sensing and others, this technique renewed the interest in soil science (Hartemink, 2015). In the region of the Planalto Médio, Rio Grande do Sul (RS), no detailed information on soils and little information from semidetailed surveys is available, covering less than 1 % of the area of this region.

Thus, in an attempt to generate data that can be used in pedotransfer functions in future DSM studies, and considering the potential of magnetic soil susceptibility, we established the following hypothesis: the landscape compartments, representing different pedogenetic environments, can be identified by the SMW technique based on MS data. This study tested the effectiveness of magnetic susceptibility of the soil to identify and facilitate the distinction of different pedogenetic environments in a representative hillslope of the Planalto Médio of Rio Grande do Sul.

MATERIALS AND METHODS

Location and description of the study area and sample design

The study was conducted in an experimental area of 350 ha located in the region of Planalto Médio of Rio Grande do Sul (Figure 1), which is part of the Serra Geral Formation, where basalt, andesite basalt, rhyodacite, and rhyolite spills are predominant. According to the Köppen classification system, the regional climate is Cfa - subtropical. The soils in the area were classified (Santos et al., 2013) as *Latossolo Vermelho-Amarelo Distrófico típico*; *Nitossolo Vermelho Eutrófico latossólico*; *Latossolo Vermelho Distrófico típico*; and *Latossolo Vermelho Eutrófico típico* and as Haplic Ferralsol (Dystric, Clayic); Rhodic Eutric Nitisol (Ochric); Rhodic Ferralsol (Dystric, Clayic); Rhodic Ferralsol (Eutric, Clayic) respectively, by the WRB system (IUSS Working Group WRB, 2014).

A transect was outlined with sampling points repeated along the flanks from the top downhill along the direction of the slightest slope (landscape spike). Twenty-nine grid points were marked in the transect at regular 50-m distances, resulting in a total of 87 sampling points and their replications. All points were georeferenced and trenches were dug at each of them for soil sampling in the layers 0.00-0.05, 0.05-0.15, 0.15-0.30, and 0.30-0.60 m, as proposed by the consortium GlobalSoilMap.net (2011). For a better

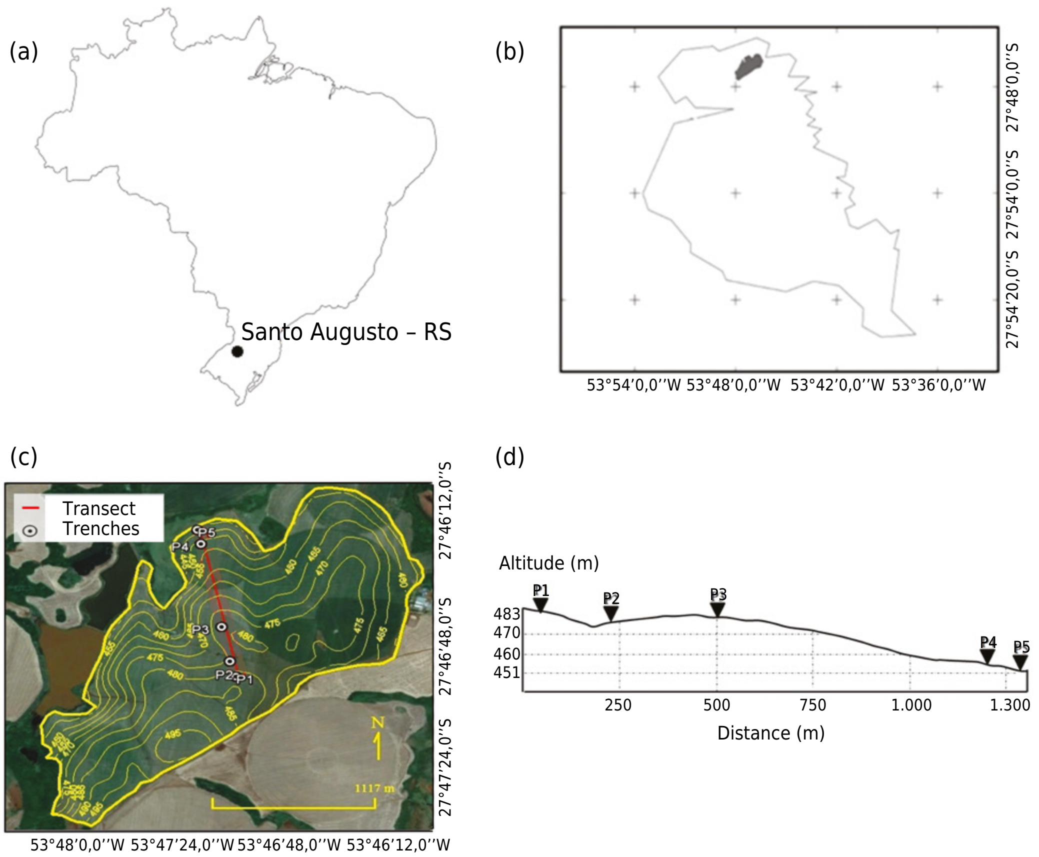

Figure 1. Location of the municipality of Santo Augusto (a); Location of the experimental area in Santo Augusto (b); experimental area with altitude contours and transect with studied profiles (c); elevation profile based on the transect with profile location (d). P1: Haplic Ferralsol (Dystric, Clayic); P2: Haplic Ferralsol (Dystric, Clayic); P3: Rhodic Eutric Nitisol (Ochric); P4: Rhodic Ferralsol (Dystric, Clayic); P5: Rhodic Ferralsol (Eutric, Clayic).

description of the area, five soil profiles were described and sampled (Santos et al., 2013) at locations along the hillslope.

Laboratory tests

The samples were dried (air-dried fine soil - ADFS) and particle- size distribution analyzed as proposed by Donagema et al. (2011). The soil organic carbon content (SOC) was determined by wet combustion with external heating, according to Yeomans and Bremner (1988). In the samples of the representative profiles of the area, particle-size distribution was determined and chemical analysis carried out as described by Donagema et al. (2011).

The free iron-oxide contents were extracted with dithionite-citrate-bicarbonate (DCB) solution (Mehra and Jackson, 1960). The levels of low-crystallinity oxides were determined by extraction with ammonium (acid) oxalate solution (pH 3.0) in the dark, as proposed by McKeague and Day (1966). Total iron contents were determined by high-temperature digestion (at ±170 °C) with sulfuric acid at a concentration of 1:1 (Donagema et al., 2011). After preparing the samples from the surface (Ap) and subsurface (Bw1) horizons of each profile, the clay and fine sand fractions were mineralogically analyzed with a Philips PW 3710 diffractometer, equipped with a Cu tube anode. In the clay fraction samples, the Fe oxides were concentrated (procedure of Norrish and Taylor (1961) modified by Kämpf and Schwertmann (1983) and the iron extracted (Mehra and Jackson, 1960).

Magnetic susceptibility was determined in 10 g ADFS from the sampling points and in the fractions clay, fine sand and ADFS from the profiles. For this, a Bartington Instruments Ltd MS2 magnetic susceptibility meter was linked to a MS2B dual frequency sensor, and read at low frequency (0.47 kHz) (Dearing, 1999).

Statistical analysis

The MS data from 87 samples collected in the transect and the lateral replications were analyzed by descriptive statistics, calculating the mean, minimum and maximum values, variance, standard deviation (SD), and coefficient of variation (CV). The means of MS in different layers and compartments were compared by the Tukey test at 5 % probability, calculated with the statistical package R (R Core Team, 2015). With the data from the soil profiles, MS of the clay fraction and the goethite, hematite and maghemite contents were correlated, by building regression models.

All data from the 87 sampling points of the properties sand, silt, clay, and organic carbon contents and MS were subjected to Split Moving Window (SMW) autocorrelogram analysis (Siqueira et al., 2015), to confirm the landscape compartments (Matias et al., 2015; Siqueira et al., 2015). This evaluation is based on statistical calculations of dissimilarity between the sequences of sample points collected along the transect. In this analysis, a series of “n” points is selected and called window. This window is shifted, point by point, from the beginning to the end of the transect. At each window position, the selected points are divided into two parts, and the means between them are calculated and compared. Comparisons are performed using the t statistic and the results expressed in a distance graph. The window size is determined by autocorrelation analysis of the properties. Aside from the window size, the application of the Mullion index (van den Berg, 1988) also indicates the pre-set distance between two windows.

In this study, windows from seven observations were used and the Mullion index from one; these parameters were chosen by testing and validation of field observations. The peaks expressed in the chart indicate the boundaries between the different compartments and pedogenetic environments.

RESULTS AND DISCUSSION

The sand, silt and clay contents (Table 1) are distributed in the profiles along the hillslope with a slight increase in clay contents in the deeper layers of all profiles. Variations in soil properties are mainly expressions of the relief that affects water flows in the soil surface and subsurface (Anjos et al., 1998).

The silt/clay ratio varied from 0.3 to 0.4 in the surface layer and from 0.1 to 0.2 in the Bw horizon of the five profiles. Soil organic carbon (SOC) was highest in the surface horizons, decreasing in the deeper layers, as expected. The SOC levels were lowest in P5, located below the altimetric level of the other profiles.

Table 1. Soil morphological, physical and chemical properties of the five studied profiles

Depth	Horizont	Sand	Silt	Clay	S/C	SOC	Fe_s	Fe_d	Fe_o	Fe_o/Fe_d	Fe_d/Fe_s
m		———	g kg^{-1}	———		———	———	g kg^{-1}	———		
					P1 - Haplic Ferralsol (Dystric, Clayic)						
0.00-0.19	Ap	56	277	667	0.4	23.6	83.8	35.7	6.7	0.19	0.43
0.19-0.35	A1	43	281	676	0.4	15.9	77.7	58.8	7.9	0.14	0.76
0.35-0.60	AB	27	249	724	0.3	11.6	94.1	67.7	6.6	0.10	0.72
0.60-0.85	BA	25	205	769	0.3	8.6	74.5	43.2	8.1	0.19	0.58
0.85-1.36	Bw1	21	175	804	0.2	6.1	77.6	71.9	8.4	0.12	0.93
1.36-1.70+	Bw2	21	176	803	0.2	5.2	103.2	46.8	6.5	0.14	0.45
					P2 - Haplic Ferralsol (Dystric, Clayic)						
0.00-0.30	Ap	143	256	601	0.4	21.5	158.6	59.8	6.0	0.10	0.38
0.30-0.60	BA	98	244	658	0.4	11.9	141.8	70.5	7.0	0.10	0.50
0.60-0.90+	Bw1	112	186	702	0.3	7.2	142.2	52.7	8.6	0.16	0.37
					P3 - Rhodic Eutric Nitisol (Ochric)						
0.00-0.12	Ap	73	254	673	0.3	20.7	127.7	38.1	6.3	0.17	0.30
0.12-0.47	B	48	190	763	0.2	10.3	115.9	65.9	6.5	0.10	0.57
0.47-0.82	Bw1	46	155	799	0.2	8.1	121.9	75.3	7.5	0.10	0.62
0.82-1.25	Bw2	39	124	837	0.1	6.5	107.7	74.5	7.2	0.10	0.69
1.25-1.70+	Bw3	40	143	817	0.2	3.60	111.4	46.8	7.7	0.16	0.42
					P4 - Rhodic Ferralsol (Dystric, Clayic)						
0.00-0.23	Ap	54	279	667	0.4	23.3	117.9	60.8	5.3	0.09	0.52
0.23-0.42	A1	31	231	737	0.3	12.8	113.9	71.3	4.5	0.06	0.63
0.42-0.64	BA	32	177	791	0.2	10.7	110.7	75.9	4.9	0.07	0.69
0.64-1.10	Bw1	27	167	806	0.2	7.7	103.4	77.8	6.4	0.08	0.75
1.10-1.70+	Bw2	27	186	788	0.2	4.5	96.4	65.9	6.9	0.10	0.68
					P5 - Rhodic Ferralsol (Eutric, Clayic)						
0.00-0.24	Ap	119	341	540	0.6	16.8	164.1	39.2	6.4	0.16	0.24
0.24-0.38	A1	77	312	611	0.5	14.5	150.3	38.3	7.0	0.18	0.25
0.38-0.63	AB	93	247	660	0.4	11.4	138.1	67.5	7.2	0.11	0.49
0.63-0.96	Bw1	60	172	768	0.2	11.8	124.4	44.8	5.7	0.13	0.36
0.96-1.34	Bw2	52	189	758	0.2	10.9	120.6	66.6	4.8	0.07	0.55
1.34-1.70+	Bw3	60	170	770	0.2	10.7	116.6	69.7	5.7	0.08	0.59

S/C: silt/clay ratio; SOC: soil organic carbon; Fe_s: iron extracted with sulfuric acid; Fe_d: iron extracted with dithionite. citrate and sodium bicarbonate; Fe_o: iron extracted with ammonium acid oxalate; Fe_o/Fe_d: ratio of oxalate - to dithionite-extracted iron.

The Fe content extracted with sulfuric acid (Fe_s) from the soils ranged from 164.1 g kg^{-1} at the top to 74.5 g kg^{-1} at the slope bottom. In profile 1, the Fe_o/Fe_d ratio varied from 0.06 in profile 4 to 0.19 in profile 1. The variation in the Fe_o/Fe_d ratio along the landscape showed that the most suitable environment for crystallization formation is at the insertion point of profile 4, as confirmed by XRD (Table 2 and Figure 2). The better crystallized these pedogenetic iron oxides, the more intense was the influence of pedogenic processes in this environment. The high Fe_d/Fe_s ratio indicates the occurrence of highly weathered soils, with values similar to those found by Inda Junior and Kämpf (2003) in B horizons of soils in different regions of Brazil, and by Dalmolin et al. (2006) in Oxisols of the Planalto of Rio Grande do Sul.

The diffractograms (with concentration of iron oxides) of the horizons Ap and Bw1 of all soil profiles are in the figure 2.

The soils of the studied area developed from volcanic rock with a high weathering degree and are found in topographic positions that favor the predominance of hematite (Kämpf and Schwertmann, 1983; Fernandes et al., 2004).

The characteristics of iron oxide and hydroxide structures (goethite, hematite and maghemite) (Table 2) indicate that the iron oxyhydroxides were better represented at lower altitudes; goethite was predominant in profile 3, hematite in profile 4 and maghemite in profile 5. The results showed that in the environment of profile 3 the conditions favor pedogenesis of goethite, while in the environment of profiles 4 and 5, conditions are conducive to pedogenesis of hematite and maghemite. Highest goethite and hematite levels were observed in the surface, and higher maghemite levels in the subsurface horizons. This behavior may be associated with different SOC levels, as stated by Dalmolin et al. (2006).

The diffractograms of the iron-free clay fraction (Figure 3) identified very marked reflections at 0.715 nm, 0.448 nm and 0.357 nm, corresponding to the clay mineral kaolinite and weaker reflections of gibbsite and quartz at 0.485 nm and 0.334 nm, respectively. The kaolinite contents in the soil decreased from the hilltop to the valley

Table 2. Structural characteristics of iron oxides and hydroxides (goethite, hematite and maghemite) in the clay fraction of the Ap and Bw1 horizons of the five studied profiles

Profile	Horizon	Goethite			Hematite			Maghemite		
		WHH	Area	%	WHH	Area	%	WHH	Area	%
		°2θ	cts×°2θ		°2θ	cts×°2θ		°2θ	cts×°2θ	
P1	Ap	0.09	0.54	0.5	0.27	23.96	73.2	0.31	8.59	26.3
	Bw1	0.09	0.12	0.2	0.16	17.81	68.6	0.27	8.13	31.3
P2	Ap	0.39	13.09	13.0	0.27	22.47	75.0	0.24	3.32	10.9
	Bw1	0.31	5.55	7.4	0.14	15.51	68.0	0.31	5.57	24.5
P3	Ap	0.47	16.29	15.4	0.31	22.96	72.0	0.31	4.15	13.0
	Bw1	0.63	8.19	11.3	0.31	14.41	65.5	0.24	5.09	23.2
P4	Ap	0.09	0.42	0.5	0.31	23.71	87.7	0.12	3.18	11.7
	Bw1	0.47	4.32	3.0	0.31	34.83	83.0	0.31	5.92	14.0
P5	Ap	0.47	14.94	8.0	0.31	43.78	78.8	0.47	7.30	13.0
	Bw1	0.19	10.15	14.0	0.27	15.91	72.0	0.47	3.12	14.0

WHH: Width to half height. P1: Haplic Ferralsol (Dystric, Clayic); P2: Haplic Ferralsol (Dystric, Clayic); P3: Rhodic Eutric Nitisol (Ochric); P4: Rhodic Ferralsol (Dystric, Clayic); P5: Rhodic Ferralsol (Eutric, Clayic).

bottom, with predominance of poorly crystallized kaolinite in the environment of profiles 4 and 5. This behavior was most likely influenced by the landscape position that induces different redox conditions, and a better environment for iron oxide crystallization (Siqueira et al., 2015). In this environment (profile 4) the iron content extracted with sulfuric acid reached 164.1 g kg^{-1}, consequently hampering kaolinite crystallization.

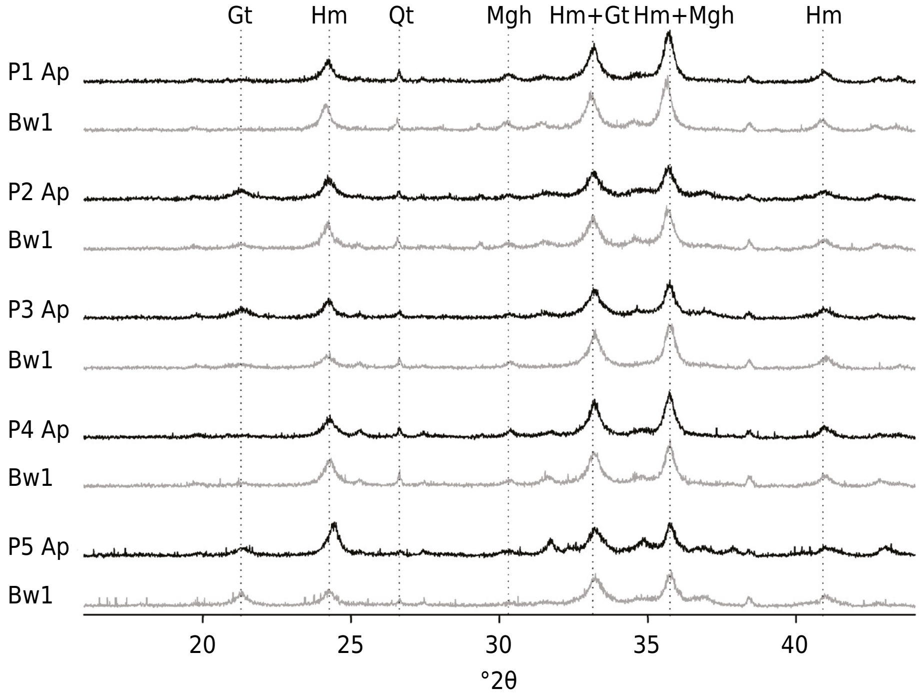

Figure 2. X ray diffractograms of powder samples of the iron oxide concentration, showing the variation in the position of the reflections of goethite (Gt), hematite (Hm), quartz (Qt), and maghemite (Mgh) in the Ap and Bw1 horizons of the five studied profiles. P1: Haplic Ferralsol (Dystric, Clayic); P2: Haplic Ferralsol (Dystric, Clayic); P3: Rhodic Eutric Nitisol (Ochric); P4: Rhodic Ferralsol (Dystric, Clayic); P5: Rhodic Ferralsol (Eutric, Clayic).

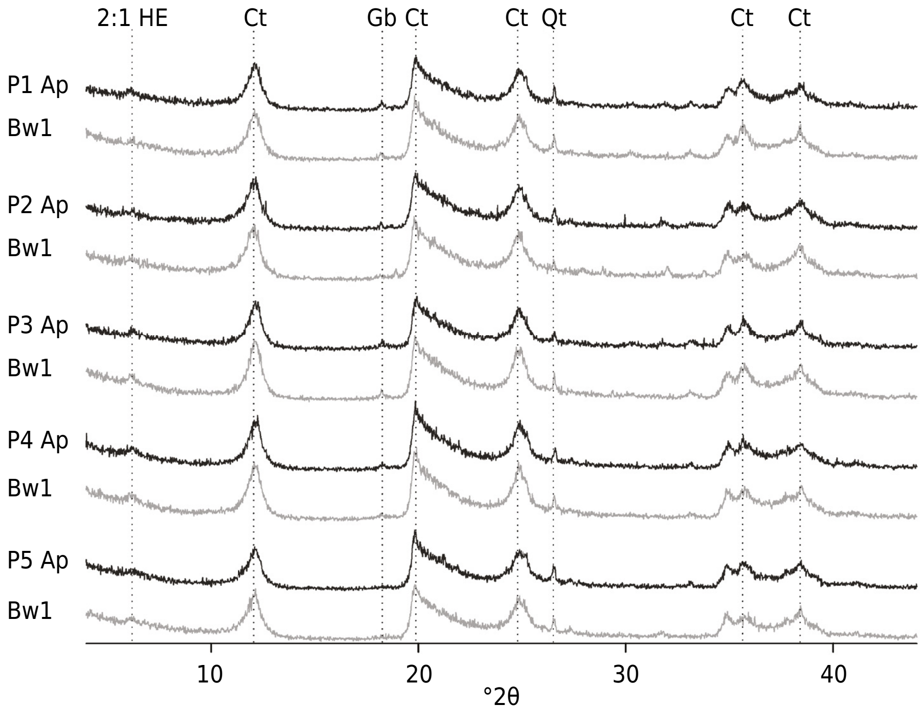

Figure 3. X ray diffractograms patterns of powder of iron-free samples, showing the variation in the position of reflections of kaolinite (Ct), gibbsite (Gb), quartz (Qt) and 2: 1 HE in the Ap and Bw1 horizons of the five profiles. P1: Haplic Ferralsol (Dystric, Clayic); P2: Haplic Ferralsol (Dystric, Clayic); P3: Rhodic Eutric Nitisol (Ochric); P4: Rhodic Ferralsol (Dystric, Clayic); P5: Rhodic Ferralsol (Eutric, Clayic).

Correlations of MS measured in the clay fraction with goethite (0.52; p<0.01), hematite (0.36; p<0.01) and maghemite contents (0.38; p<0.01) were found (data not shown in the table). Although goethite and hematite are antiferromagnetic minerals with low magnetism, they are present in the formation of other ferromagnetic minerals contained in the clay fraction, e.g., ferromagnetic maghemite and ferrihydrite (Barrón et al., 2000; Michel et al., 2010). According to Bahia et al. (2015), the estimation of soil minerals by MS in basaltic soil is ideally improved by the construction of calibration curves after selective dissolution, to reduce possible interferences of lithogenic minerals such as magnetite.

The MS values were highest in the clay fraction of profile 1 (Figure 4), where the maghemite levels were highest (Table 2). This is in line with Fontes et al. (2000), who emphasized that magnetism is most evident in clayey soils. Among the ferromagnetic minerals, magnetite is most easily found in coarser soil fractions, such as sand and silt, and maghemite in finer fractions, such as clay. The MS values of the clay fraction in the soil profiles indicated a decrease in deeper layers throughout the profiles (Figure 4). This behavior may indicate different water flows according to the landscape position, carrying minerals with magnetic expression contained mainly in the clay fraction, e.g., magnetic maghemite and ferrihydrite, which influence MS. Another explanation is based on the age of soils in the landscape. Older soils are associated with more intense pedogenesis, favoring the formation of pedogenic minerals with magnetic expression. The magnetic susceptibility of profile 1 confirms that this environment is the oldest, since the values are homogeneous in the deeper layers, unlike in profile 5.

In the profiles 2 and 5, the MS values were lowest in the clay and ADFS fraction, due to the poor drainage of these profiles, impairing the formation of ferromagnetic minerals such as ferromagnetic maghemite and ferrihydrite in the soils (Souza Jr et al., 2010). The variation in MS among the profiles in the clay fraction was directly related with the Fe_s content (Table 1), in agreement with the findings of Matias et al. (2013) and Bahia et al. (2015).

The MS variations in fine sand were similar to those in the clay fraction, but with higher relative quantities, mainly in profile 3 (Figure 4), on the mid-slope, with medium declivity, which is conducive to the transport of minerals in the clay fraction and higher mineral deposition in the sand fraction. According to Fontes et al. (2000), higher MS values in the sand fraction indicate the presence of ferromagnetic lithogenic minerals, probably magnetite. In profile 2 and 4, MS was lowest in the sand fraction, which may be associated with the position of these profiles in the mid-slope of the transect, a position that favors the loss of fine fractions (clay and

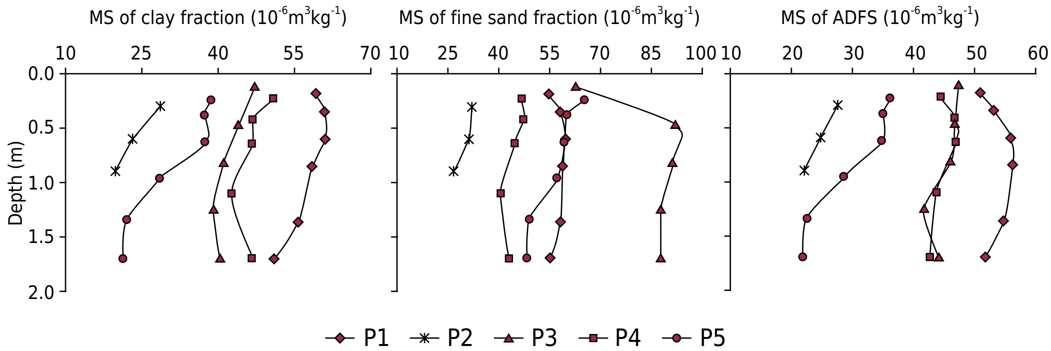

Figure 4. Magnetic susceptibility (MS) of the clay, fine sand and air-dried fine soil (ADFS) measured at low frequency for each layer and profile (P). P1: Haplic Ferralsol (Dystric, Clayic); P2: Haplic Ferralsol (Dystric, Clayic); P3: Rhodic Eutric Nitisol (Ochric); P4: Rhodic Ferralsol (Dystric, Clayic); P5: Rhodic Ferralsol (Eutric, Clayic).

silt) and sand accumulation, which may be related to the presence of (diamagnetic) quartz (Dearing, 1999).

The systematic analysis of the SMW autocorrelogram (Figure 5) was sensitive in relation to the limits of the different segments along the transect. The reflections were most marked in the 0.30-0.60 m layer, comprising the most stable pedogenetic soil horizons, but some peaks in the surface layer coincided with the peaks of the deepest layer. Findings of Matias et al. (2014), based on the same MS analysis procedure, indicated more pronounced peaks in the 0.30-0.80 m layer.

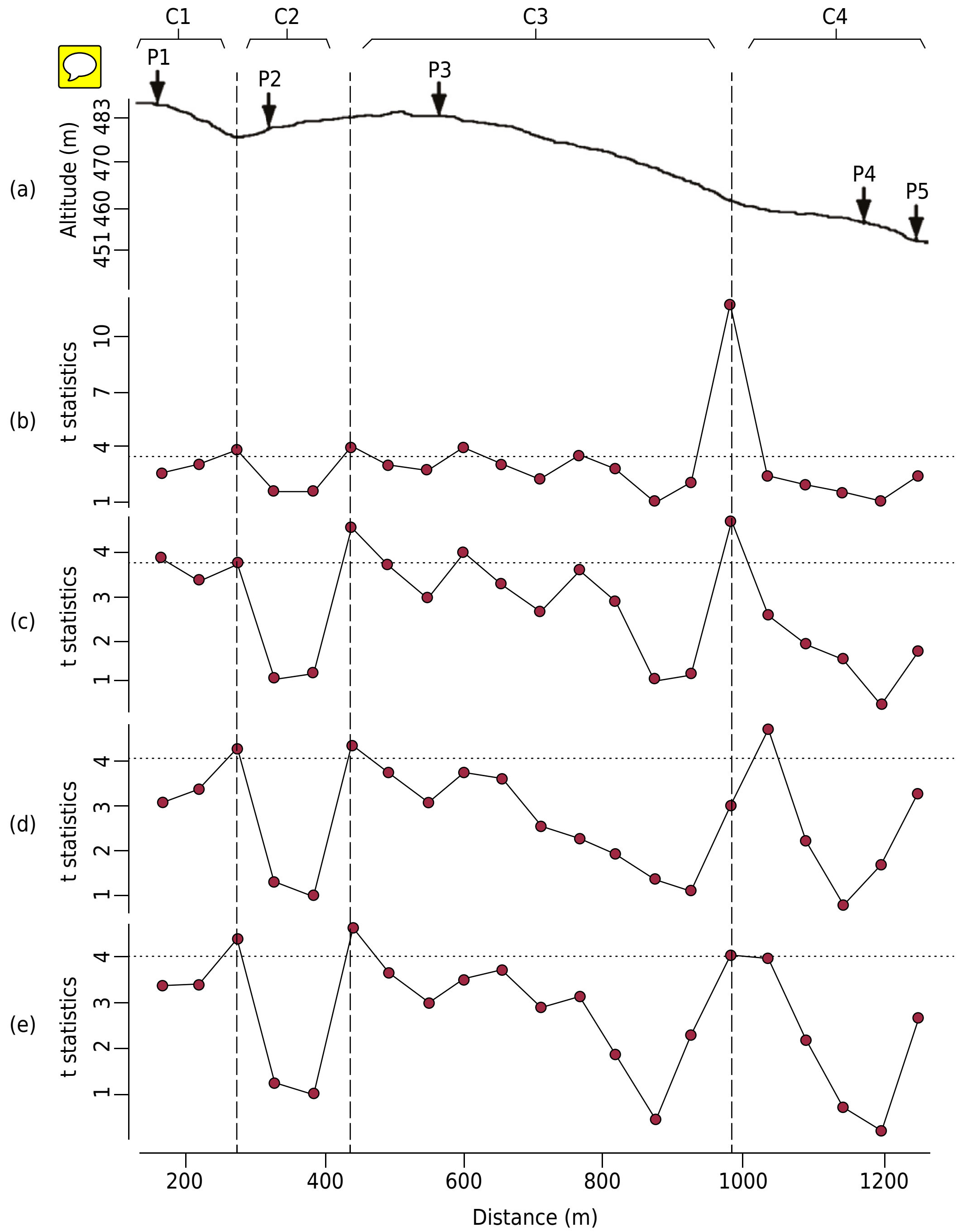

Figure 5. Elevation profile of the transect (a) and the results of the "Split Moving Window" (SMW) analysis and correlation between the t-statistic values for magnetic susceptibility in the layers 0.00-0.05 m (b), 0.05-0.15 m (c), 0.15-0.30 m (d), and 0.30-0.60 m (e) along the transect with points spaced 50 m apart. The peaks above the dotted line (...) indicate significance and the dashed line (---) indicates the peaks of magnetic susceptibility. C: Landscape compartment. P1: Haplic Ferralsol (Dystric, Clayic); P2: Haplic Ferralsol (Dystric, Clayic); P3: Rhodic Eutric Nitisol (Ochric); P4: Rhodic Ferralsol (Dystric, Clayic); P5: Rhodic Ferralsol (Eutric, Clayic).

The identification of the limits of landscape compartments was validated by the peaks of the SMW analysis. Three peaks were found in all layers (at 280 m, 430 m and 985 m below the top of the landscape), delimiting four compartments (Figure 5). These results agree with those of Siqueira et al. (2015), who used SMW analysis to separate landscape compartments in places considered homogeneous for having the same soil type. In their studies, Campos et al. (2012) found that soils in different taxonomic classes can have similar properties if they belong to the same landscape compartment, which may contribute to increase the errors in the mapping units.

The MS values ranged from 19.3 (C2) to 47.7 10^{-6} m^3 kg^{-1} (C3) (Table 3), very close to the results of Bahia et al. (2015) for soils derived from basalt (10-45 10^{-6} m^3 kg^{-1}). The coefficients of variation (CV 20.38-23.22 %) were highest in C2, in agreement with results of Montanari et al. (2005), who reported greater variability of soil properties in concave topography.

In the construction of detailed mapping protocols based on mathematical models such as SMW, geostatistics or cluster analysis, the “internal error” of the defined mapping units can be reduced, since the soil factors and formation processes are more homogeneous within than among the compartments.

The protocol of landscape compartmentalization using SMW of MS is considered an effective indicator of soil environments, representing a contribution to the mapping of specific management areas, detailed soil surveys and the understanding of the variability of soil properties (Campos et al., 2007; Cortez et al., 2011; Barrios et al., 2012). The results of this study will be useful in future research using predictive models of soil properties and extrapolation to neighboring areas by DSM.

Table 3. Descriptive statistics magnetic susceptibility in the four compartments

Depth	Landscape compartment	Mean	Minimum	Maximum	SD	CV
m		10^{-6} m^3 kg^{-1}				%
0.00-0.05	C1	30.7 b	24.0	34.9	4.0	12.99
	C2	23.7 c	19.9	29.2	4.8	20.38
	C3	41.5 a	31.9	46.5	4.8	11.57
	C4	40.1 a	34.9	42.9	2.7	6.78
0.05-0.15	C1	31.1 b	24.4	35.0	4.3	13.80
	C2	23.9 c	19.4	29.8	5.3	22.20
	C3	42.9 a	34.2	47.7	4.2	9.74
	C4	42.2 a	36.2	46.0	3.3	7.71
0.15-0.30	C1	31.6 b	24.6	36.1	4.4	13.84
	C2	23.6 c	19.3	29.6	5.3	22.57
	C3	42.9 a	34.0	47.2	4.1	9.51
	C4	42.0 a	33.8	45.9	3.6	8.68
0.30-0.60	C1	31.8 b	24.7	36.2	4.4	13.88
	C2	23.9 c	19.7	30.2	5.6	23.22
	C3	43.0 a	33.9	47.3	4.2	9.67
	C4	41.5 a	31.6	45.9	4.5	10.72

SD: standard deviation; CV: coefficient of variation. Means followed by the same letter in a row do not differ by the Tukey test at 5 % probability.

CONCLUSIONS

The mineralogical description of the soil profiles showed that the variations in iron oxide forms and contents are related to the profile position in the hillslope.

The limits indicated by SMW analysis based on MS values were effective to outline representative compartments of pedogenetic environments on a hillslope without geological transition, on the Planalto Médio of Rio Grande do Sul.

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