Revista Brasileira de Ciência do Solo

Division - Soil in Space and Time | Commission – Soil Survey and Classification

Andic properties in soils with histic horizon “O” in the highlands of Southern Brazil

Jaime Barros dos Santos Junior[(1)*] **and Jaime Antonio de Almeida**[(2)]

[(1)] Universidade Federal do Pará, *Campus* Universitário de Altamira, Faculdade de Engenharia Florestal, Altamira, Pará, Brasil.
[(2)] Universidade do Estado de Santa Catarina, Centro de Ciências Agroveterinárias, Departamento de Solos, Lages, Santa Catarina, Brasil.

ABSTRACT: Soils with andic properties are characterized by a low apparent density, variable charges, large amounts of allophanes, imogolite, ferrihydrite, and/or organo-metallic complexes with Al, and present high phosphate retention. Soils derived from non-pyroclastic materials rich in silicates, formed under a cold and humid climate, a large amount of organic carbon, acid weathering, andic properties can manifest when a large amount of Al is present in the form of organo-metallic complexes. This study aimed to evaluate the characteristics and geographical expression of soils with such properties in areas of altitude in the extreme south of Brazil, on the escarpment edges of the Serra Geral Formation, under a cold and humid climate. The sampling points were selected based on environmental characteristics such as geomorphology, geology, the coloration of the superficial horizon of the soil, and position in the landscape, covering a linear distance of approximately 185 km at the escarpment edge between the states of Santa Catarina and Rio Grande do Sul. Soil samples were described and collected from ten soils with histic horizon O, three soils with humic horizon, and one soil with histic horizon H. The undisturbed soil samples were collected using volumetric metallic cylinder to determine the soil bulk density. Organic matter, pH(H_2O), P retention, and selective dissolutions of Al, Fe, and Si analyses were performed. The *Cambissolos Hísticos* and *Organossolos Fólicos* showed andic properties, while the *Cambissolos Húmicos* and *Organossolo Háplico* did not meet one or more criteria, as required by the Brazilian Soil Classification System and the World Reference Base for Soil Resources. The horizons with andic properties were classified as aluandic, based on the predominance of Al associated with organic complexes. The cold climate and high cloudiness of the highest altitude areas in the extreme south of Brazil, occurring in a narrow strip of the escarpment of the Serra Geral Formation in the states of Santa Catarina and Rio Grande do Sul, allow the formation of a constantly humid environment. This environment favors the acid weathering of the source material, accumulation of organic matter in the soil, and its stabilization by the formation of organo-metallic complexes, mainly Al-humus. The combination of these factors gives the soils with histic horizons O a low bulk density, high phosphate retention, and $Al_o + ½Fe_o \geq 2$ % values, meeting the criteria required for andic properties.

Keywords: pedology, pedogenesis, organic matter, organo-metallic complexes.

*** Corresponding author:**
E-mail: jaime@ufpa.br

Received: September 30, 2020
Approved: January 25, 2021

How to cite: Santos Junior JB, Almeida JA. Andic properties in soils with histic horizon “O” in the highlands of Southern Brazil. Rev Bras Cienc Solo. 2021;45:e0200152.
https://doi.org/10.36783/18069657rbcs20200152

Editors: José Miguel Reichert, Pablo Vidal Torrado, and Marcos Gervasio Pereira.

INTRODUCTION

Soils with andic properties are characterized by low bulk density, variable charges, large amounts of allophanes, imogolite, ferrihydrite, and/or organo-metallic complexes with Al, in addition to high phosphate retention (Soil Survey Staff, 2014; IUSS Working Group WRB, 2015). The presence of short-range-order minerals and/or organo-metallic complexes in soils with andic properties generally results from part of the moderate weathering sequence of pyroclastic materials (IUSS Working Group WRB, 2015). However, andic properties can also manifest in soils with large amounts of Al in the form of organo-metallic complexes and non-pyroclastic materials rich in silicates in cold and humid climates, with a large amount of organic carbon (IUSS Working Group WRB, 2015) formed under weathering in acidic conditions (Driessen et al., 2001).

There is growing evidence of soils' occurrence with andic properties formed on non-pyroclastic material, indicating that their characteristics are mostly due to organo-metallic complexes instead of short-range-order minerals (Caner et al., 2000). The rapid weathering of volcanic glass can result in the accumulation of stable organo-metallic complexes or the formation of short-range-order minerals, such as allophanes and imogolite, additionally forming ferrihydrite. However, the weathering of other materials rich in silicates in a humid climate also leads to the formation of stable organo-mineral complexes (Garcia-Rodeja et al., 1987; IUSS Working Group WRB, 2015).

The genesis of the andic properties depends essentially on the rapid weathering of the porous, permeable, and fine-grained mineral material in the presence of organic matter. The ions released in the hydrolysis of primary minerals, especially Fe^{2+} and Al^{3+}, can form stable complexes with organic substances. However, the iron quickly oxidizes, and not all ions form complexes, allowing their precipitation as ferrihydrite. The concentration of silica in the soil solution increases if most or all the aluminum is stabilized in the complexes with organic substances. Part of this silica is leached, while another part precipitates as opaline silica. If a considerable proportion of released aluminum is not complexed, it can co-precipitate with silicon to form allophanes of varying composition, often in association with imogolite (Driessen et al., 2001).

When most or all of the aluminum is complexed with organic compounds, the silica concentration in the soil solution increases (Driessen et al., 2001); and while part of the silica is lixiviated, another part precipitates as opaline silica. If not, all aluminum is bound in complexes, the rest can co-precipitate with silicon to form minerals of low structural order, such as allophanes and imogolites. The formation of Al-humus complexes and the formation of allophanic associations are competitive. While allophanes and imogolites are stable under moderately acidic to neutral conditions, Al-humus complexes prevail in more acidic environments.

With excess aluminum available under such acidic conditions, it can combine with silicon to form 2:1 and 2:1:1 phyllosilicate clay minerals, which are often found in association with Al humus complexes (Ndayiragije and Delvaux, 2003). The occurrence of 2:1 and 2:1 of hydroxy-Al interlayer silicates in Andosols has often been associated with the presence of Al-humus complexes in non-allophanic Andosols (Shoji et al., 1993). The incorporation of Al in the organic complexes and / or in the intermediate Al layers of 2:1 clay minerals can induce an anti-antibiotic effect and inhibit the formation of allophane and imogolite (Shoji et al., 1993), as observed by Dahlgren et al. (1993) and Ndayiragije and Delvaux (2003). The abundance of organo-metallic associations resulting from pedogenetic processes, presenting high physical and biological stability, low mobility, and high accumulation of organic matter, constitutes an original characteristic of soils with non-allophanic andic properties (Aran et al., 2001).

In Brazil, the possibility of the contribution of allophanes in the manifestation of properties that would resemble andic soils in an altitude environment in areas of effusive rocks in the southern region of the country is briefly discussed by Bennema and Camargo (1964). Fasolo et al. (1980) also mention soils with potential andic properties in the state of Santa Catarina. However, these soils had no such properties (Ker, 1988; Ker and Resende, 1990). Volkoff et al. (1984) studied humus and mineralogy of altitude field soils in the states of Minas Gerais, Paraná, and Santa Catarina, focusing on the mobility of fulvic and humic acids, and found that the humus in these environments is similar to the humus of andic soils, of which properties were attributed to organo-metallic complexes, mainly with Al.

Studies of the soils from Trindade Island, in Brazil, indicate the presence of volcanic glass, amorphous materials, and low bulk density and high pH values in NaF, suggesting the presence of andic properties (Clemente, 2006; Clemente et al., 2009; Sá, 2010; Machado, 2016; Machado et al., 2017). The presence of soils with andic properties in this location was later confirmed by Mateus et al. (2020). Furthermore, soils with andic properties in Brazil were described for the first time, by Dümig et al. (2008), in the municipality of São Francisco de Paula, Rio Grande do Sul. This was the first confirmation of andic soils in South America outside the areas of recent volcanism in the Andes. This occurrence is mentioned in the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015).

There is an expressive area of soils that resemble those studied by Dümig et al. (2008) along the escarpment edge of the Serra Geral Formation in southern Brazil. The cold and humid climate of this environment favors the high accumulation of organic matter in the soil, which, associated with the acid weathering of the source material, rich in silicates, can generate andic properties on soils in a much more extensive area than that studied by Dümig et al. (2008). However, this phenomenon can be restricted to a stretch on the escarpment edges, where the climate conditions favor the formation of histic horizons.

The general objective of this study was to evaluate the presence, characteristics, and extent of the occurrence of andic properties in soils with significant carbon content, formed on the escarpment edges of the Serra Geral Formation, in the southern plateau of the state of Santa Catarina (SC) and northeast plateau of the state of Rio Grande do Sul (RS).

MATERIALS AND METHODS

Study area

The study area includes the Serra Geral Formation's escarpment edge in the southern plateau of Santa Catarina, and the extreme northeast plateau of Rio Grande do Sul (Figure 1). The studied environment is predominated by undulating relief areas, with smoothly wavy and flat parts, which contrast sharply with adjacent rugged reliefs that characterize the entire escarpment of the Serra Geral Formation in the extreme south of Brazil. Such areas are mainly in the municipalities of São Francisco de Paula, Cambará do Sul, and São José dos Ausentes, in RS, and Bom Jardim da Serra, Urubici, and Urupema, in SC.

The Serra Geral Formation of the Lower Cretaceous is the record of a fissure extensive volcanic event that covered approximately 75 % of the Paraná Sedimentary Basin (Stewart et al., 1996; Milani et al., 1998; Nardy et al., 2002). This event was caused by the rupture of Gondwana, which formed after the Pan-African/Brazilian orogenic cycle and remained stable in its southern portion for approximately 400 million years, giving rise to the South Atlantic Ocean (Peate, 1997; Roisenberg and Viero, 2000; Orlandi Filho et al., 2009).

The escarpment of the Serra Geral Formation extends diagonally across southern Brazil, with an abrupt east face, slowly declining to the west towards the Paraná and Uruguay rivers. Close to the border between the states of Santa Catarina and Rio Grande do Sul, the Serra Geral Formation rises and approaches the coast, bending in the north-northeast

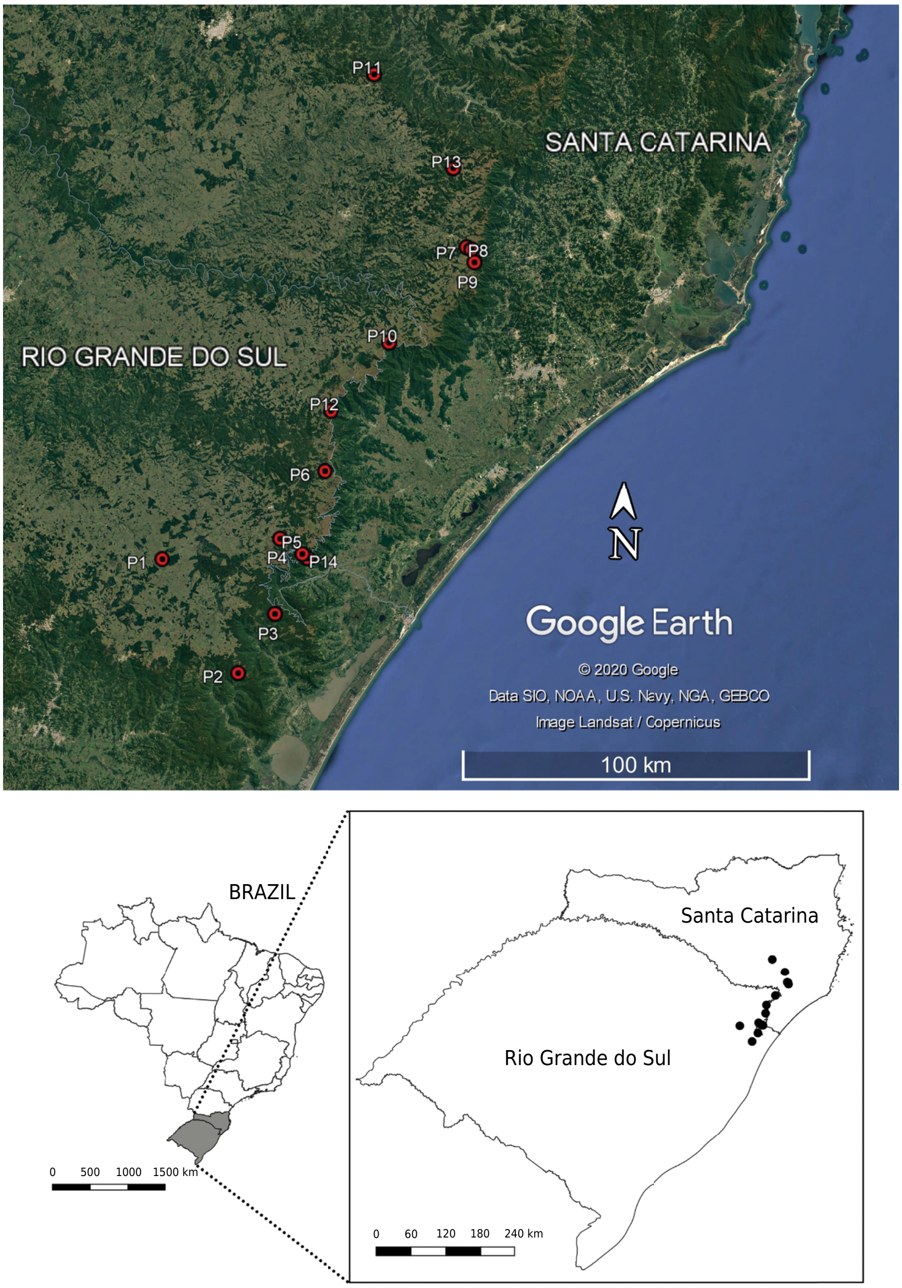

Figure 1. Soil profiles with andic properties in southern Brazil.

(NEE) direction for approximately 230 km following the coastline (Besser et al., 2015). It consists of a series of rocks originating from basaltic spills, interspersed with andesitic spills, and the most recent spills of more acidic characteristics, resulting in the formation of more siliceous rocks, such as rhyodacite, dacites, and rhyolites (Bellieni et al., 1986).

The region’s climate, according to the Köppen classification system, is Cfb, wet temperate (C), with well-distributed rains throughout the year (f), and an average temperature of the hottest month below 22 °C (b) (Mota, 1951; Kuinchtner and Buriol, 2001; Potter et al., 2004). There is a high water condensation in the highest portions of the escarpment, with daily fog formation near the top of the slopes and at the edges of the escarpments. These fogs can last up to weeks (Falkenberg, 2003).

Soil characterization

The sampling points were selected based on environmental characteristics such as geomorphology, geology, coloring of the superficial horizon of the soil, and position in the landscape, covering a stretch at the escarpment edge of the Serra Geral Formation, to the east from the municipality of São Francisco de Paula (RS) to Urupema (SC), in a linear distance of approximately 185 km (Figure 1 and Table 1).

Soil samples were described and collected from ten soils profiles with diagnostic histic horizon O (P2, P3, P4, P6, P8, P9, P10 P11, P12, and P13), three soils profiles with diagnostic humic horizon A (P1, P5, and P7), and one soil profile with histic horizon H (P14). The diagnostic histic horizon O is formed from deposited organic materials under free drainage conditions, without stagnant water, and occurring closer to the escarpment edge. The diagnostic humic horizon A occur a little further from the escarpment. The histic horizon H formed from organic materials deposited under excess water conditions in a small depression surrounded by soils with the histic horizon O. In 14 soil profiles were evaluated the possible presence of andic properties in this environment.

The basic characterization of all soil profiles, including the analysis of the main physical and chemical properties, are in tables 2 and 3. Details of these soils can be found in Santos Junior (2017).

Soil classification

The determination of superficial and subsurface diagnostic horizons was carried out according to the criteria defined in the 5th edition of the Brazilian Soil Classification System – *SiBCS* (Santos et al., 2018). The most acidic spills originated the rhyodacite and constituted the dominant source material of the soils in the studied area. The studied soils were classified according to the criteria established by the SiBCS (Santos et al., 2018) and the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015).

The diagnostic criteria used to identify andic properties in the WRB system (IUSS Working Group WRB, 2015), which were recently adopted by the SiBCS (Santos et al., 2018), as suggested by Santos Junior (2017), are (a) soil density ≤0.9 kg dm^{-3}; (b) phosphate retention ≥85 %; and (c) Al_o + ½ Fe_o ≥2 %. The nature of the andic properties was

Table 1. Lithology and position in the landscape of soils in the highlands in southern Brazil

Pedon	Lithology	Hillside positions	Slope	Altitude	Escarpment distance[(1)]
			%	m	
P1	rhyodacite	upper third	6.5	989	26484
P2	rhyodacite	upper third	12.0	919	1635
P3	rhyodacite	middle third	10.5	978	1036
P4	rhyodacite	middle third	25.0	1003	1605
P5	rhyodacite	upper third	10.0	1023	4391
P6	rhyodacite	upper third	20.0	1130	1765
P7	basalt	upper third	8.0	1423	2104
P8	andesit/ basalt	middle third	32.0	1372	631
P9	rhyodacite	middle third	27.5	1445	213
P10	rhyodacite	lower third	12.0	1330	169
P11	rhyodacite	upper third	35.0	1676	0
P12	rhyodacite	upper third	35.0	1213	662
P13	rhyodacite	upper third	60.0	1713	201
P14	rhyodacite	lower third	5.0	1003	354

(1) Distance from the *pedon* to the nearest escarpment edge.

defined based on the criteria of Poulenard and Herbillon (2000), described in the WRB IUSS Working Group (2015): a) silandic = Sio ≥0.6 % or Alp/Alo <0.5 (predominance allophane, imogolite, and similar minerals); b) aluandic = Sio <0.6 % and Alp/Alo ≥0.5 (predominance of Al complexed by organic acids); and c) alusilandic = Sio ≥0.6 % and <0.9 % and Alp / Alo ≥0.3 and <0.5 (transition condition considered a particular case of silandic property).

Laboratory analyses and other determinations

The soil samples were oven-dried at 40 °C, ground, and sieved to separate the fractions with a diameter smaller than 2.0 mm. Undisturbed soil samples were collected from the studied horizons using volumetric metallic cylinders to determine the soil bulk density (BD).

Organic carbon (C_{org}), pH(H_2O), selective dissolution of Al, Fe, and Si, and P retention were analyzed using the air-dried fine earth fraction (ADFE). Hydrogen potential was measured using a combined electrode immersed in soil:water suspension in the proportion of 1:2.5, while C_{org} was quantified via muffle-drying by incineration, both according to methodologies described by Teixeira et al. (2017). The contents of Al, Fe, and Si in the soil were determined through selective dissolutions, being extracted by ammonium acid oxalate solution (Al_o, Fe_o, and Si_o), according to McKeague and Day (1966), described by Teixeira et al. (2017), and sodium pyrophosphate (Al_p), according to Bascomb (1968), described by Teixeira et al. (2017), using an optical emission spectrometer with ICP-OES plasma. Phosphorus retention was determined according to the methodology described by Van Reeuwijk (2002), adapted from Blakemore et al. (1987).

RESULTS

The lithologies, location of the soils in relation to the hillside, slope, altitude, and distance to the edge of the escarpment are shown in table 1. Except P7 and P8, which were developed on basalt and andesite / basalt, respectively, the other studied soils are on rhyodacites. Three *pedons* are below 1000 m altitude (P1, P2, and P3), two *pedons* (P11 and P13) are above 1500 m, and the others are within this range of altitudes. The *pedons* P1, P5, P7, and P14 are in places with a slope less than or equal to 10 % and have the greatest distances to the Serra Geral Formation's escarpment edge.

The physical and morphological properties of the 14 soil profiles surveyed are shown in table 2. According to the soil depth classes established by Santos et al. (2018), these soils can be classified as shallow (P13 and P14), fairly deep (P4, P10, and P12), and deep (P1, P2, P3, P5, P6, P7, P8, P9, and P11). The superficial horizons have a dark color and low BD ranging from 0.44 to 0.83 Mg m^{-3} (Table 4). The subsurface horizons are predominantly clayey with 100 % flocculation degree and at least incipient structure development, and with considerable variations in consistency: from slightly hard to extremely hard, very friable to firm, non-plastic to plastic, and non-sticky to sticky.

Table 3 shows the chemical properties of the soils. They are chemically poor soils, with low nutrient reserves, from strong to extremely acidic, according to the definitions of the soil reaction classes (Santos et al., 2018), with very low base saturation, containing high levels of extractable aluminum and consequently with high aluminum saturation. The pH(H_2O) of the soil samples varied between 4.1 and 5.3 and the pH(KCl) varied between 3.4 and 4.7, however, in most horizons the pH(H_2O) was below 5.0. and the pH(KCl) varied between 3.4 and 4.7. Extremely low P assimilable and C_{org} of surface horizons relatively high.

Table 4 shows the values of BD, P retention, melanic index, and the results of the selective dissolution of Al_o, Fe_o, Si_o, Al_p, in addition to Al_o + 0.5Fe_o and the Al_p / Al_o ratio of the superficial genetic horizons (O, A, and H) of the surveyed soils. These items are

Table 2. Physical and morphological properties of soils in the highlands in southern Brazil

Pedon	Horizon(1)	Layer	Color (Munsell)		Sand	Silt	Clay	Silt / Clay	Textural class	Structure	Consistence		Plasticity	Stickness
			dry	wet							Dry	Moist		
		m			—— g kg^{-1} ——									
P1	A1	0.00-0.07	10 YR 3/2	10 YR 2/1	64	451	485	0.93	SiCl	2Ff Gra	Ha	VFr	NPl	SSt
	A2	0.07-0.23	10 YR 3/2	10 YR 2/1	107	393	500	0.79	Cl	2Ff Gra	Ha	VFr	NPl	SSt
	AB	0.23-0.38	10 YR 4/2	10 YR 2/2	117	362	521	0.69	Cl	1MF SBk	Ha	Fr	Pl	SSt
	BA	0.38-0.65	2.5 Y 5/3	2.5 Y 3/3	108	342	550	0.62	Cl	1MF SBk	VHa	Fr	SPl	SSt
	Bi	0.65-0.90	10 YR 5/4	10 YR 4/3	94	363	543	0.67	Cl	1M SBk	Ha	Fr	MPl	St
	2BC/Cr	0.90-1.02	10 YR 6/4	10 YR 4/4	81	440	479	0.92	SiCl	1C SBk	VHa	Fr	SPl	SSt
	2C1	1.02-1.25	10 YR 6/4	10 YR 5/6	72	462	466	0.99	SiCl	Ma	VHa	Fi	SPl	SSt
P2	O	0.27-0.00	10 YR 4/1	10 YR 2/1	37	656	307	2.14	SiCL	2Ff Gra	EHa	Fr	SPl	NSt
	A	0.00-0.10	10 YR 3/1	10 YR 2/1	36	509	455	1.12	SiCl	1MF SBk/ 2F Gra	EHa	Fi	NPl	NSt
	AB	0.10-0.25	10 YR 3/2	10 YR 2/2	77	465	458	1.02	SiCl	1MF SBk/ 2M Gra	Ha	Fi	NPl	NSt
	BA	0.25-0.38	10 YR 5/3	10 YR 3/3	82	389	529	0.74	Cl	1MF SBk	Ha / VHa	Fr / Fi	SPl	SSt
	Bi1	0.38-0.68	10 YR 6/4	10 YR 4/4	75	411	514	0.80	SiCl	1CM SBk	VHa	Fr / Fi	SPl	SSt
	Bi2	0.68-0.83	10 YR 6/4	10 YR 4/4	93	401	506	0.79	Cl	1CM SBk	Ha	Fr / Fi	SPl	SSt
	C/Cr	0.83-0.97	10 YR 7/4	10 YR 5/4	221	371	408	0.91	Cl	Ma	Ha	Fr / Fi	SPl	SSt
P3	O	0.41-0.24	10 YR 2/1	10 YR 2/1	61	657	282	2.33	SiL	1MSBk/ ABk/2FGra	EHa	Fr / Fi	NPl	NSt
	AO	0.24-0.00	10 YR 2/1	10 YR 2/1	164	382	454	0.84	Cl	1M SBk/ 2F Gra	VHa	Fi	NPl	NSt
	2A	0.00-0.10	10 YR 3/1	10 YR 2/1	143	294	563	0.52	Cl	1MF SBk/ 2F Gra	Ha	Fr / Fi	SPl	NSt
	2BA	0.10-0.20	10 YR 3/1	10 YR 3/2	167	284	549	0.52	Cl	12MF SBk	Ha	Fr / Fi	SPl	SSt
	2Bi1	0.20-0.60	10 YR 5/4	10 YR 4/4	126	516	358	1.44	SiClL	12M SBk	Ha	Fr / Fi	Pl	SSt
	2Bi2	0.60-1.00	10 YR 6/3	10 YR 4/3	116	295	589	0.50	Cl	1M SBk	VHa	Fr / Fi	Pl	SSt
	2Cr	1.00-1.15	10 YR 7/3	10 YR 5/3	122	542	336	1.61	SiClL	1M SBk	SHa	Fr	Pl	SSt
P4	O1	0.00-0.14	10 YR 2/1	10 YR 2/1	221	533	246	2.17	SiL	2MF Gra/ 1M SBk	VHa	Fr / Fi	NPl	NSt
	O2	0.14-0.29	10 YR 2/1	10 YR 2/1	177	582	241	2.41	SiL	1MC SBk	Ha	Fr / Fi	NPl	NSt
	Cr/R	0.29-0.55	10 YR 7/3	10 YR 5/4	76	565	359	1.57	SiClL	Ma	SHa	Fr	NPl	NSt
P5	A1	0.00-0.13	10 YR 3/1	10 YR 2/1	205	286	509	0.56	Cl	2MF Gra	Ha / VHa	Fr	NPl	NSt
	A2	0.13-0.48	10 YR 2/1	10 YR 2/1	134	307	559	0.55	Cl	1MF SBk	Ha	Fr / Fi	SPl	SSt
	AB	0.48-0.62	10 YR 3/1	10 YR 2/1	149	255	596	0.43	VCl	12F SBk/ 2MF Gra	Ha	Fr / Fi	SPl	SSt
	2BA1	0.62-0.77	10 YR 4/2	10 YR 3/2	143	280	577	0.49	Cl	12MF SBk	VHa	Fi	Pl	SSt
	2BA2	0.77-0.92	10 YR 4/4	10 YR 3/3	133	277	590	0.47	Cl	12MF SBk	Ha	Fi	SPl	SSt
	2Bi	0.92-1.10	10 YR 5/4	10 YR 4/3	84	370	546	0.68	Cl	1M SBk	Ha / VHa	Fr / Fi	SPl	SSt
	2BC	1.10-1.35	10 YR 6/3	10 YR 4/3	165	271	564	0.48	Cl	Ma	Ha	Fr	SPl	SSt
	2C	1.35-1.60	10 YR 5/4	10 YR 4/4	138	237	625	0.38	VCl	Ma	Ha	Fr / Fi	Pl	SSt
P6	O1	0.00-0.13	10 YR 2/1	10 YR 2/1	80	573	347	1.65	SiClL	1F SBk	SHa	Fr	NPl	NSt
	O2	0.13-0.34	10 YR 2/1	10 YR 2/1	131	497	372	1.34	SiClL	1MF SBk	EHa	Fr / Fi	NPl	NSt
	AO	0.34-0.47	10 YR 2/1	10 YR 2/1	147	319	534	0.60	Cl	1F SBk/ 2M Gra	VHa	Fr / Fi	NPl	NSt
	A	0.47-0.55	2.5 Y 2.5/1	2.5 Y 2.5/1	177	260	563	0.46	Cl	1F SBk/ 2F Gra	SHa	Fr / Fi	NPl	NSt
	AB	0.55-0.65	2.5 Y 3/2	2.5 Y 2.5/1	149	242	609	0.40	VCl	12MF SBk	So / SHa	Fr	NPl	NSt
	Bi	0.65-1.03	10 YR 3/4	10 YR 5/3	124	291	585	0.50	Cl	1MF SBk	Ha / VHa	Fr / Fi	SPl	SSt

Continue

Continuation

P7	O	0.12-0.00	10 YR 2/1	10 YR 2/1	188	218	594	0.37	Cl	1Ff Gra	VHa	Fr	NPl	NSt
	A	0.00-0.09	10 YR 3/2	10 YR 2/2	286	151	563	0.27	Cl	1MF SBk/ 1Ff Gra	Ha / VHa	Fr / Fi	SPl	SSt
	AB	0.09-0.17	10 YR 3/2	10 YR 3/2	325	117	558	0.21	Cl	1MF SBk	VHa	Fr / Fi	NPl	NSt
	2BA	0.17-0.30	10 YR 3/4	10 YR 3/3	181	203	616	0.33	VCl	2CM SBk	Ha	Fr / Fi	SPl	SSt
	2Bi1	0.30-0.51	7.5 YR 5/4	5 YR 4/3	115	351	534	0.66	Cl	23CM SBk	SHa	Fi	SPl	St
	2Bi2	0.51-0.70	7.5 YR 5/4	7.5 YR 4/4	118	353	529	0.67	Cl	2MF SBk	SHa	Fi	SPl	SSt
	2BC	0.70-0.84	7.5 YR 5/4	7.5 YR 4/4	99	408	493	0.83	SiCl	2MF SBk	SHa / Ha	Fi	SPl	SSt
	2C	0.84-1.20	7.5 YR 6/4	7.5 YR 3/4	91	417	492	0.85	SiCl	2MF SBk	Ha	Fi	SPl	SSt
P8	O1	0.33-0.20	10 YR 2/1	10 YR 2/1	290	457	253	1.81	L	2CM Gra	SHa	Fi	NPl	SSt
	O2	0.20-0.00	10 YR 2/1	10 YR 2/1	546	202	252	0.80	SaClL	21CM SBk ABk	SHa	Fi	SPl	NSt
	A	0.00-0.08	10 YR 2/1	10 YR 2/1	424	243	333	0.73	SaClL	12M SBk ABk	SHa	Fr / Fi	SPl	SSt
	2BA	0.08-0.20	10 YR 4/4.5	10 YR 4/3	345	239	416	0.57	Cl	1M SBk ABk	SHa	Fr / Fi	Pl	SSt
	2Bi1	0.20-0.50	10 YR 4/4.5	10 YR 4/4	186	292	522	0.56	Cl	1C SBk	Sha	Fi	Pl	St
	2Bi2	0.50-0.86	10 YR 5/4	10 YR 4/4	184	258	558	0.46	Cl	Ma/1C SBk	Ha	Fi	SPl	St
	2BC	0.86-1.07^{+}	10 YR 5/4	10 YR 4/6	211	375	414	0.91	Cl	Ma	Ha	Fi	SPl	St
P9	O1	0.00-0.21	10 YR 2/1	10 YR 2/1	282	468	250	1.87	L	3MF Gra	Ha / EHa	Fr	SPl	SSt
	O2	0.21-0.60	10 YR 2/1	10 YR 2/1	700	139	161	0.86	SaL	3MF Gra/ 3F ABk	EHa	Fr / Fi	SPl	SSt
	A	0.60-0.75	10 YR 2/1	10 YR 2/1	347	374	279	1.34	ClL	3M ABk/ 23M SBk	EHa	Fr / Fi	SPl	SSt
	2AB	0.75 0.86	10 YR 4/3	10 YR 4/4	241	206	553	0.37	Cl	2MF Gra	EHa	Fr	Pl	St
	2Bi	0.86-1.27	7.5 YR 4/6	7.5 YR 5/6	242	210	548	0.38	Cl	1CM SBk	VHa	Fi	Pl	St/VSt
P10	O1	0.00-0.10	10 YR 2/1	10 YR 2/1	56	809	135	5.99	SiL	1F SBk/ 1MF Gra	VHa	Fr	NPl	NSt
	O2	0.10-0.30	10 YR 2/1	10 YR 2/1	310	371	319	1.16	ClL	12M ABk	Ha	Fi	SPl	SSt
	2Bi	0.30-0.48	5 YR 4/2	5 YR 3/2	242	259	499	0.52	Cl	1M ABk	Ha	Fi	SPl	SSt
	2Cr	0.48-0.90	5 YR 4/4	5 YR 3/4	351	235	414	0.57	Cl	Ma	VHa	Fr	NPl	SSt
P11	O1	0.00-0.10	10 YR 2/1	10 YR 2/1	64	757	179	4.23	SiL	1Ff Gra	So	VFr	NPl	NSt
	O2	0.10-0.33	10 YR 2/1	10 YR 2/1	131	716	153	4.68	SiL	1M SBk/ 1MF Gra	VHa	VFr	NPl	NSt
	O3	0.33-0.68	10 YR 2/1	10 YR 2/1	33	802	165	4.86	SiL	1M SBk/ 1MF Gra	Ha	VFr	NPl	NSt
	O/Cr	0.68-0.75	10 YR 6/6	10 YR 4/6	320	298	382	0.78	ClL	Ma	SHa	Fr	NPl	NSt
	Cr	0.75-1.30	10 YR 7/4	10 YR 3/4	394	273	333	0.82	ClL	Ma	SHa	Fr	NPl	NSt
P12	O1	0.00-0.13	10 YR 2/1	10 YR 2/1	123	708	169	4.19	SiL	1F SBk/ 1MF Gra	SHa	VFr	NPl	NSt
	O2	0.13-0.30	10 YR 2/1	10 YR 2/2	124	634	242	2.62	SiL	1M SBk/ 1MF Gra	VHa	Fr	NPl	NSt
	A	0.30-0.50	10 YR 2/1	10 YR 2/1	174	465	361	1.29	SiClL	1MF SBk	VHa	Fr	NPl	NSt
	Cr/R	0.50-0.80	10 YR 5/4	10 YR 3/4	220	342	438	0.78	Cl	1MF SBk	Ha	Fr	NPl	NSt

Continue

Continuation

P13	O1	0.00-0.10	10 YR 2/1	10 YR 2/1	38	844	118	7.15	Si	1Ff SBk/ 1F Gra	SHa	Fr	NPl	NSt
	O2	0.10-0.38	10 YR 2/1	10 YR 2/1	58	834	108	7.72	Si	1Ff SBk/ 1F Gra	SHa	Fr	NPl	NSt
P14	H1	0.00-0.20	10 YR 2/1	10 YR 2/1	89	373	538	0.69	Cl	Ma	Ha	Fr	SPl	SSt
	H2	0.20-0.50	10 YR 2/1	10 YR 2/1	223	298	479	0.62	Cl	Ma	Ha	Fr	SPl	SSt

[(1)] According to the *Manual de descrição e coleta de solo no campo* (Santos et al., 2013). Sand, silt, and clay were determined by Pipette method. Bulk density was determined by volumetric ring method. SiCl: silty clay; Cl: clay; SiClL: silty clay loam; SiL: silt loam; VCl: very clay; L: loam; SaClL: sandy clay loam; SaL: sandy loam; ClL: clay loam; Si: silt; 1: weak; 2: moderade; 3: strong; F: fine; f: very fine; M: medium; C: coarse; Gra: granular; SBk: subangular blocky; ABk: angular blocky; Ma: massive; So: soft; SHa: slightly hard; Ha: hard; VHa: very hard; EHa: extremely hard; VFr: very friable; Fr: friable; Fi: firm; NPl: non-plastic; SPl: sligthly plastic; Pl: plastic; VSt: very sticky; SSt: sligthly sticky; St: sticky; NSt: non-sticky.

part of the criteria for andic properties according to IUSS Working Group WRB (2015). There was a great variation in BD with very low values as in O1 and O2 of P4 with 0.44 and 0.54 kg dm^{-3}, respectively, up to higher values as in horizons A1 and A2 of P1 with 0.75 and 0.83 kg dm^{-3}, respectively. However, all surface horizons met the requirement of BD ≤0.9 Mg m^{-3}, required for andic properties. The other horizons were not analyzed to verify all the criteria because they no longer met this BD requirement, making it impossible to frame these horizons as soils with andic properties.

The requirements for Alo + 0.5Feo ≥2 % did not meet the horizons of P1, P5, P7, and P14. For the retention of P ≥85 %, the horizons A1 and A2 of P1, A1 of P5, O and A of P7, and H1 and H2 of P14 did not achieve the requirement. All surface horizons of the studied soils showed Si_o values <0.6 % and Alp / Alo ratio ≥0.5, so the soils with andic properties were classified as aluandic, with a predominance of Al forming complexes with organic acids (IUSS Working Group WRB, 2015).

The soil classification is presented in table 5. The soils classified by the SiBCS criteria (Santos et al., 2018) can be grouped as follows: *Cambissolos Húmicos* (P1, P5, and P7); *Cambissolos Hísticos* (P2, P3, P6, P8, and P10); *Organossolos Fólicos* (P4, P5, P11, P12, and P13); and *Organossolos Háplicos* (P14). As for the WRB criteria (IUSS Working Group WRB, 2015) it has: Cambic Umbrisol (P1, P5, and P7); Aluandic Andosol (P2, P3, P4, P6, P8, P10, P11, and P12); Folic Histosol (P9 and P13) and Leptic Umbrisol (P14). Soils with superficial diagnostic horizons O histic (Figure 2) has andic properties in its superficial genetic horizons.

DISCUSSION

The studied soils presented structures with moderate to strong degree of development with a yellowish color in the subsurface horizons, were clayey, acidic, with low natural fertility, and had superficial horizons (O, H, and A) of dark coloration with relatively high C_{org} values, low BD, and high P retention (Tables 2, 3, and 4).

The large variability of the morphological, physical, and chemical characteristics of soils with andic properties is evident when analyzing studies from different parts of the world (Bech-Borras et al., 1977; Shoji and Saigusa, 1977; Quantin et al., 1985; Wada, 1985; Garcia-Rodeja et al., 1987; Bäumler and Zech, 1994; Arnalds et al., 1995; Johnson-Maynard et al., 1997; Caner et al., 2000; Takahashi and Shoji, 2002; Armas-Espinel et al., 2003; Ndayiragije and Delvaux, 2003; Pigna and Violante, 2003; Delvaux et al., 2004; Ndayiragije and Delvaux, 2004; Pinheiro et al., 2004; Bäumler et al., 2005; Lowe and Palmer, 2005; Buytaert et al., 2006; Msanya et al., 2007; Acevedo-Sandoval et al., 2008; Dümig et al., 2008; Auxtero and Madeira, 2009; Novák et al., 2010; Jakab et al., 2011; Jiomeneck et al., 2011; Kubotera et al., 2013, 2015). However, some characteristics are commonly shared between these soils.

Table 3. Chemical properties of soils in the highlands in southern Brazil

Pedon	Horizon[(1)]	pH		Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	EB	Al^{3+}	H^{+}	T	V	m	P[(2)]	C_{org}	N
		H_2O	KCl													
				$cmol_c\ kg^{-1}$								%		$mg\ kg^{-1}$	$g\ kg^{-1}$	
P1	A1	4.6	3.8	2.2	2.5	0.65	0.04	5.4	2.8	17.2	25.4	21	34	7	56.7	3.3
	A2	4.7	3.8	1.1	1.3	0.35	0.03	2.8	4.8	15.0	22.6	12	63	5	42.3	2.8
	AB	4.4	3.8	0.7	0.6	0.11	0.02	1.4	4.3	10.8	16.5	8	75	1	22.5	1.6
	BA	4.6	3.9	0.0	1.0	0.07	0.02	1.2	5.0	8.6	14.8	8	81	1	14.2	1.1
	Bi	4.7	3.8	0.0	1.0	0.05	0.02	1.1	4.9	5.4	11.4	10	82	<1	6.3	0.7
	2BC/Cr	4.8	3.9	0.0	1.0	0.05	0.02	1.1	4.3	7.5	10.0	11	56	<1	4.2	0.5
	2C1	4.9	3.9	0.7	0.0	0.03	0.01	0.7	4.2	4.2	9.1	8	86	1	2.6	0.4
P2	O	4.6	3.9	1.5	1.5	0.29	0.09	3.4	4.7	29.4	39.5	9	58	2	89.9	5.0
	A	4.8	4.0	1.3	1.2	0.15	0.08	2.7	4.5	21.2	28.4	10	62	1	53.8	2.7
	AB	5.2	4.0	1.0	1.0	0.07	0.05	2.1	4.3	13.6	20.0	10	67	1	31.5	1.9
	BA	4.9	4.0	0.8	1.0	0.08	0.04	1.9	3.9	11.5	17.3	11	67	<1	19.9	1.1
	Bi1	5.0	4.0	0.6	0.7	0.07	0.03	1.4	3.9	6.0	11.3	12	74	<1	8.2	1.0
	Bi2	5.0	4.0	1.0	0.0	0.07	0.03	1.1	5.0	4.4	10.5	10	82	<1	5.8	0.9
	C/Cr	5.0	4.0	1.0	0.0	0.06	0.03	1.1	4.7	4.6	10.4	11	81	<1	5.3	0.6
P3	O	4.4	3.7	0.0	1.1	0.18	0.18	1.5	7.5	39.4	48.4	3	83	3	96.6	6.1
	AO	4.5	3.9	0.0	1.1	0.06	0.11	1.3	6.7	26.9	34.9	4	84	1	54.5	3.6
	2A	4.8	3.9	1.0	0.0	0.04	0.08	1.1	5.7	17.1	23.9	5	84	1	28.2	1.9
	2BA	4.8	3.9	0.9	0.0	0.05	0.07	1.0	5.2	11.0	17.2	6	84	1	17.6	1.1
	2Bi1	5.0	3.9	0.9	0.0	0.04	0.06	1.0	5.9	7.1	14.0	7	86	1	9.2	1.2
	2Bi2	4.9	3.9	0.0	1.1	0.04	0.06	1.2	5.1	7.6	13.9	9	81	1	9.1	1.1
	2Cr	5.0	4.0	0.7	0.0	0.03	0.12	0.8	7.3	7.3	15.4	5	90	2	8.1	0.6
P4	O1	4.4	3.4	0.9	1.0	0.26	0.13	2.3	8.5	58.0	68.8	3	79	4	179.4	9.3
	O2	4.4	3.7	0.8	1.0	0.13	0.10	2.0	9.8	47.3	59.1	3	83	2	118.4	6.9
	Cr/R	4.7	4.1	1.0	0.0	0.07	0.07	1.1	3.3	9.6	14.0	8	75	2	17.2	1.5
P5	A1	4.7	3.9	0.7	0.9	0.25	0.11	2.0	5.6	20.9	28.5	7	74	6	58.9	3.8
	A2	4.5	3.9	0.0	1.1	0.09	0.04	1.2	5.5	19.6	26.3	5	82	2	46.8	1.1
	AB	4.6	3.9	1.0	0.0	0.04	0.03	1.1	5.6	13.2	19.9	6	84	1	24.9	1.7
	2BA1	4.9	3.9	0.9	0.0	0.03	0.03	1.0	5.4	10.9	17.3	6	84	<1	16.3	1.3
	2BA2	4.8	3.9	0.8	0.0	0.04	0.03	0.9	5.1	7.5	13.5	7	85	<1	11.1	1.1
	2Bi	4.8	3.9	0.7	0.0	0.04	0.02	0.8	4.7	6.3	11.8	7	85	1	7.7	0.9
	2BC	4.8	3.9	0.7	0.0	0.04	0.02	0.8	4.7	5.6	11.1	7	85	1	5.4	0.7
	2C	4.9	3.9	0.8	0.0	0.03	0.02	0.8	5.1	4.8	10.1	7	86	1	5.6	0.6
P6	O1	4.6	3.7	0.4	0.0	0.25	0.14	0.8	8.0	46.0	54.8	1	91	7	118.3	8.7
	O2	4.6	3.8	0.2	0.0	0.11	0.10	0.4	10.2	46.7	57.3	1	96	1	123.1	7.4
	AO	4.6	3.9	0.2	0.0	0.05	0.10	0.3	9.0	34.3	43.6	1	97	1	62.5	3.2
	A	4.6	3.9	0.1	0.0	0.03	0.03	0.2	7.9	23.7	31.8	1	98	<1	48.5	2.5
	AB	4.6	3.9	0.1	0.0	0.02	0.02	0.1	7.7	12.6	20.4	0	99	<1	24.6	1.7
	Bi	4.7	3.9	0.2	0.0	0.02	0.02	0.2	7.7	9.0	16.9	1	97	<1	15.0	1.1
P7	O	4.2	3.8	1.7	2.0	0.32	0.14	4.2	4.8	27.9	36.9	11	53	5	81.2	5.1
	A	4.4	3.9	0.7	1.0	0.09	0.05	1.8	3.0	15.0	19.8	9	62	1	39.6	1.1
	AB	4.4	4.0	0.6	1.0	0.05	0.03	1.7	2.3	11.3	15.3	11	58	<1	22.2	1.7
	2BA	4.1	3.9	0.8	0.8	0.04	0.03	1.7	3.0	9.6	14.3	12	64	1	12.3	1.0
	2Bi1	4.8	4.1	0.0	1.0	0.04	0.03	1.1	1.0	6.9	9.0	12	48	<1	5.2	0.6
	2Bi2	4.8	4.1	0.9	0.0	0.04	0.03	1.0	1.1	6.8	8.9	11	52	<1	3.6	0.5
	2BC	4.8	4.0	0.8	0.0	0.06	0.04	0.9	2.2	6.3	9.4	10	71	1	2.8	0.4
	2C	4.7	3.9	0.0	0.0	0.06	0.04	0.1	2.4	6.6	9.1	1	96	1	2.5	0.4

Continue

Continuation

P8	O1	4.8	4.2	3.3	1.7	0.58	0.19	5.8	4.4	37.0	47.2	12	43	5	121.4	7.6
	O2	4.8	4.3	0.7	0.6	0.17	0.08	1.5	3.7	36.6	41.8	4	71	5	105.8	6.0
	A	5.0	4.5	0.7	0.0	0.06	0.04	0.8	1.9	15.1	17.8	4	70	2	38.8	2.5
	2BA	5.3	4.6	0.7	0.0	0.03	0.04	0.8	1.2	7.8	9.8	8	60	2	17.5	1.6
	2Bi1	5.2	4.4	0.7	0.0	0.03	0.04	0.8	2.2	5.7	8.7	9	73	<1	10.7	1.1
	2Bi2	5.1	4.3	0.5	0.0	0.02	0.04	0.6	2.3	4.5	7.4	8	79	<1	6.6	0.8
	2BC	5.2	4.2	0.7	0.0	0.04	0.06	0.8	4.3	3.7	8.8	9	84	1	4.0	0.6
P9	O1	4.3	3.5	0.9	0.8	0.51	0.20	2.4	14.7	100.2	117.3	2	86	3	259.7	18.5
	O2	4.5	3.7	0.5	0.5	0.11	0.07	0.7	10.6	88.7	100.0	1	94	<1	206.6	11.1
	A	4.7	3.8	0.2	0.2	0.03	0.01	0.2	7.4	31.9	39.5	1	97	1	61.4	2.7
	2AB	4.7	3.8	0.2	0.2	0.03	0.01	0.2	7.0	20.2	27.4	1	97	1	31.9	1.7
	2Bi	4.8	3.8	0.2	0.2	0.04	0.01	0.2	5.7	6.9	12.8	2	97	1	8.6	0.9
P10	O1	4.4	3.7	2.1	3.8	1.03	0.20	7.1	2.4	51.8	61.3	12	25	39	274.3	17.9
	O2	4.5	3.8	0.2	1.4	0.13	0.05	1.8	10.9	33.2	45.9	4	86	4	111.1	5.8
	2Bi	4.6	4.0	0.0	1.1	0.04	0.03	1.2	8.2	10.0	19.4	6	87	1	21.1	1.8
	2Cr	4.8	4.1	0.1	0.9	0.05	0.02	1.1	6.5	3.7	11.3	10	86	3	7.5	0.8
P11	O1	5.2	3.9	0.4	1.7	0.46	0.19	2.7	8.1	37.5	48.3	6	75	23	22.3	15.6
	O2	5.0	4.0	0.0	1.2	0.09	0.07	1.4	10.1	40.5	52.0	3	88	3	124.4	8.1
	O3	5.1	4.3	0.9	0.0	0.04	0.04	1.0	5.2	29.6	35.8	3	84	3	103.3	8.0
	O/Cr	5.2	4.5	0.8	0.0	0.02	0.01	0.8	1.7	11.6	14.1	6	68	4	34.7	1.5
	Cr	5.1	4.7	0.8	0.0	0.02	0.01	0.8	0.6	7.5	8.9	9	43	19	12.4	2.5
P12	O1	4.8	4.0	0.4	1.9	0.30	0.20	2.8	9.3	24.8	36.9	8	77	7	98.5	6.0
	O2	4.8	3.9	0.0	1.2	0.11	0.08	1.4	12.0	39.0	52.4	3	90	3	96.1	5.4
	A	4.8	4.1	0.8	0.0	0.03	0.03	0.9	7.7	20.6	29.2	3	90	1	51.2	2.6
	Cr/R	4.9	4.2	0.7	0.0	0.03	0.02	0.7	5.2	5.8	11.7	6	88	1	13.5	1.5
P13	O1	5.0	4.1	0.5	1.7	0.54	0.12	2.9	5.6	24.1	32.6	9	66	6	278.7	18.2
	O2	4.6	4.1	0.3	1.7	0.73	0.13	2.9	4.0	63.5	70.4	4	58	6	272.2	21.9
P14	H1	4.4	3.9	0.3	0.5	0.08	0.10	1.0	2.3	25.3	28.6	4	70	3	96.1	6.5
	H2	4.4	3.8	0.2	0.5	0.07	0.10	0.9	2.4	29.1	32.4	3	73	2	89.5	5.8

[1] According to the *Manual de Descrição e coleta de solo no campo* (Santos et al., 2013); [2] P assimilable; pH(H_2O): pH in water-saturated soil paste (1:2.5); K^+ (Mehlich-1); Ca^{2+}, Mg^{2+}, and Al^{3+} (KCl 1 mol L^{-1}); H+Al (Calcium acetate 0.5 mol L^{-1} at pH 7.0); EB: exchangeable bases sum; T: potential cation exchange capacity (at pH 7.0); V: bases saturation; m: aluminum saturation; C_{org}: organic carbon (Teixeira, 2017).

The *pedons* located closer to the edge of the escarpment in greater slopes are the ones that presented the highest C_{org} values, superficial diagnostic horizon O histic, and in these, there is the presence of the andic properties (Table 4). The data presented in table 1 suggested that the occurrence of the andic properties is somehow more related to the distance from the edge of the escarpment and the slope of the terrain than in relation to the altitude and hillside position. *Pedons* with andic properties are in slopes greater than 10 % at variable altitudes and hillside position; however, they are closest to the Serra Geral Formation’s escarpment edge.

According to the criteria of IUSS Working Group WRB (2015) and Santos et al. (2018), the horizons O histic of the soils these study have andic properties. The occurrence of andic properties are associated with the highland environment with high humidity and low temperatures, favored by a relatively fast weathering, in an acid environment, rich in organic material, associated with the formation of organometallic complexes, with a predominance of Al in these forms (as suggested by the low Si_o values and the high Al_p / Al_o ratio in table 4), therefore, these are non-allophanic andic soils with organometallic

Table 4. Andic properties of soils in the highlands in southern Brazil

Pedon	Horizon[(1)]	Bulk Density	P retention	Al_o	Fe_o	Si_o	Al_p	Al_o + 0.5 Fe_o	Al_p/Al_o	Melanic Index	Andic Properties[(2)]
		Mg m^{-3}	——	——	——	%	——	——			
P1	A1	0.75	48.5	0.46	0.40	0.08	0.63	0.67	1.36	2.3	non-andic
	A2	0.83	54.0	0.50	0.51	0.07	0.90	0.76	1.80	2.6	non-andic
P2	O	0.49	93.0	1.29	1.44	0.06	4.85	2.01	3.77	2.1	aluandic
	A	0.75	92.7	1.28	1.47	0.09	2.18	2.01	1.71	1.6	aluandic
P3	O	0.52	93.4	1.32	2.60	0.07	2.31	2.62	1.75	1.7	aluandic
	AO	0.61	95.5	1.50	2.11	0.03	2.30	2.56	1.53	1.9	aluandic
	2A	0.80	89.5	1.26	1.54	0.06	1.86	2.03	1.48	2.2	aluandic
P4	O1	0.44	95.4	1.65	1.44	-	1.60	2.38	0.97	2.1	aluandic
	O2	0.54	93.9	1.65	1.39	0.02	1.72	2.34	1.04	2.2	aluandic
P5	A1	0.77	78.6	1.00	0.88	0.14	1.58	1.46	1.56	2.4	protoandic
	A2	0.79	86.7	1.00	1.02	0.09	1.92	1.53	1.87	2.3	protoandic
P6	O1	0.49	95.5	1.43	2.13	0.12	2.05	2.50	1.43	1.7	aluandic
	O2	0.60	98.5	1.83	2.87	0.06	1.64	3.27	0.90	1.5	aluandic
	OA	0.72	97.7	2.00	2.40	0.01	2.58	3.20	1.29	1.6	aluandic
	A	0.80	98.3	1.73	2.15	0.05	2.89	2.80	1.67	2.2	aluandic
P7	O	0.52	81.4	0.84	1.00	0.05	1.23	1.34	1.48	2.9	non-andic
	A	0.66	79.9	0.74	0.66	0.04	0.85	1.07	1.14	3.3	non-andic
P8	O1	0.63	91.6	1.50	1.97	0.12	1.61	2.45	1.10	1.7	aluandic
	O2	0.69	97.3	1.80	1.91	0.08	2.19	2.80	1.19	2.0	aluandic
	A	0.78	91.3	1.40	1.21	0.06	1.94	2.03	1.36	1.8	aluandic
P9	O1	0.63	96.0	1.97	1.35	-	3.02	2.64	1.54	1.6	aluandic
	O2	0.69	98.9	2.72	2.09	0.03	2.20	3.76	0.81	2.4	aluandic
	A	0.80	98.5	2.23	1.46	0.04	2.30	2.96	1.03	2.4	aluandic
P10	O1	0.55	94.7	1.93	0.77	0.00	1.34	2.31	0.70	2.2	aluandic
	O2	0.62	94.4	1.46	1.79	0.01	2.30	2.35	1.57	1.5	aluandic
P11	O1	0.51	90.0	1.33	1.42	0.01	2.36	2.04	1.77	2.4	aluandic
	O2	0.55	98.9	2.48	3.39	0.02	3.28	4.17	1.32	2.0	aluandic
	O3	0.59	99.1	3.91	2.97	0.56	7.15	5.39	1.83	1.5	aluandic
P12	O1	0.50	96.6	1.83	1.60	0.27	2.59	2.63	1.41	2.0	aluandic
	O2	0.53	97.5	1.92	2.75	0.04	3.38	3.29	1.76	2.2	aluandic
	A	0.78	98.3	1.93	2.70	0.03	4.24	3.28	2.20	2.4	aluandic
P13	O1	0.50	98.0	2.14	0.90	-	3.22	2.59	1.50	1.9	aluandic
	O2	0.52	98.6	2.70	1.11	-	2.57	3.25	0.95	2.2	aluandic
P14	H1	0.72	78.0	0.73	0.61	0.01	0.83	1.04	1.14	1.6	non-andic
	H2	0.75	75.0	0.69	0.58	0.01	0.77	0.98	1.12	2.1	non-andic

[(1)] According to the *Manual de descrição e coleta de solo no campo* (Santos et al., 2013). [(2)] IUSS Working Group WRB (2015). Al, Fe, and Si extracted by ammonium acid oxalate solution (Alo, Feo, and Sio), according to McKeague and Day (1966), and sodium pyrophosphate (Alp), according to Bascomb (1968), using an optical emission spectrometer with ICP-OES plasma.

complexes or aluandic soils. Soils with andic properties of the aluandic type are generally dark, rich in organic matter in surface (topsoil), present varied morphology according to McDaniel et al. (2012), and generally have pH(H_2O) <4.5, according to IUSS Working Group WRB (2015).

Table 5. Soil classification in the highlands in southern Brazil

Pedon	SiBCS[1] / WRB[2]
P1	*Cambissolo Húmico Alumínico típico* Cambic Umbrisol (Clayic, Colluvic, Hyperdystric)
P2	*Cambissolo Hístico Alumínico típico, aluândico* Hyperdystric Umbric Aluandic Andosol (Clayic)
P3	*Cambissolo Hístico Alumínico típico, aluândico* Hyperdystric Umbric Aluandic Andosol (Clayic, Colluvic, Fulvic)
P4	*Organossolo Fólico Sáprico típico, aluândico* Umbric Leptic Aluandic Andosol (Hyperdystric, Siltic, Fulvic)
P5	*Cambissolo Húmico Alumínico típico* Cambic Umbrisol (Protoandic, Clayic, Colluvic, Hyperdystric, Profundihumic)
P6	*Cambissolo Hístico Alumínico típico, aluândico* Hyperdystric Umbric Aluandic Andosol (Clayic, Melanic)
P7	*Cambissolo Húmico Distroférrico típico* Cambic Umbrisol (Clayic, Colluvic, Hyperdystric)
P8	*Cambissolo Hístico Distrófico típico, aluândico* Hyperdystric Umbric Aluandic Andosol (Loamic, Colluvic, Fulvic)
P9	*Organossolo Fólico Sáprico cambissólico, aluândico* Ombric Sapric Folic Histosol (Andic, Hyperdystric)
P10	*Cambissolo Hístico Alumínico léptico, aluândico* Umbric Folic Aluandic Andosol (Hyperdystric, Clayic, Colluvic)
P11	*Organossolo Fólico Sáprico típico, aluândico* Umbric Folic Aluandic Andosol (Siltic, Fulvic, Melanic)
P12	*Organossolo Fólico Sáprico típico, aluândico* Umbric Leptic Aluandic Andosol (Hyperdystric, Siltic, Fulvic)
P13	*Organossolo Fólico Sáprico lítico, aluândico* Leptic Sapric Folic Histosol (Ombric, Andic, Hyperdristric)
P14	*Organossolo Háplico Sáprico típico* Leptic Umbrisol (Clayic, Hyperdystric, Hyperhumic)

[1] Brazilian Soil Classification System (Santos et al. 2018). [2] World Reference Base for Soil Resources (IUSS Working Group WRB, 2015).

The pH($H_2$0) of the horizons with andic properties of the surveyed soils ranged from 4.3 to 5.2, with most samples with values ≤5.0. Considering that the formation and maintenance of allophanes occurs at pH($H_2$0) >4.9 (Shoji and Fujiwara, 1984), the environment of this study does not favor the occurrence of these minerals, but the formation of organometallic complexes with a predominance of Al complexed by organic acids, such as was evidenced by the high Al_p / Al_o ratio.

In non-allophanic andic soils, a large part of Al complexed with humus can be preferentially dissolved by sodium pyrophosphate; therefore, the Al_p / Al_o ratio is often used to identify these soils (Dümig et al., 2008). According to the criteria of Nanzyo et al. (1993), this ratio should be between 0.1-0.4 for allophanics and between 0.8-1.0 for non-allophanics. Aran et al. (2001) found non-allophanic andic soils in northeastern France, on ancient volcanic rocks, with a large accumulation of organic matter and low pH, and considered the Al_p / Al_o ratios >0.8 relatively high, also suggesting that Al was complexed mainly with organic compounds.

In soils with andic properties, aluminum protects the organic part of Al-humus complexes against biodegradation. These complexes have limited mobility and moderate solubility;

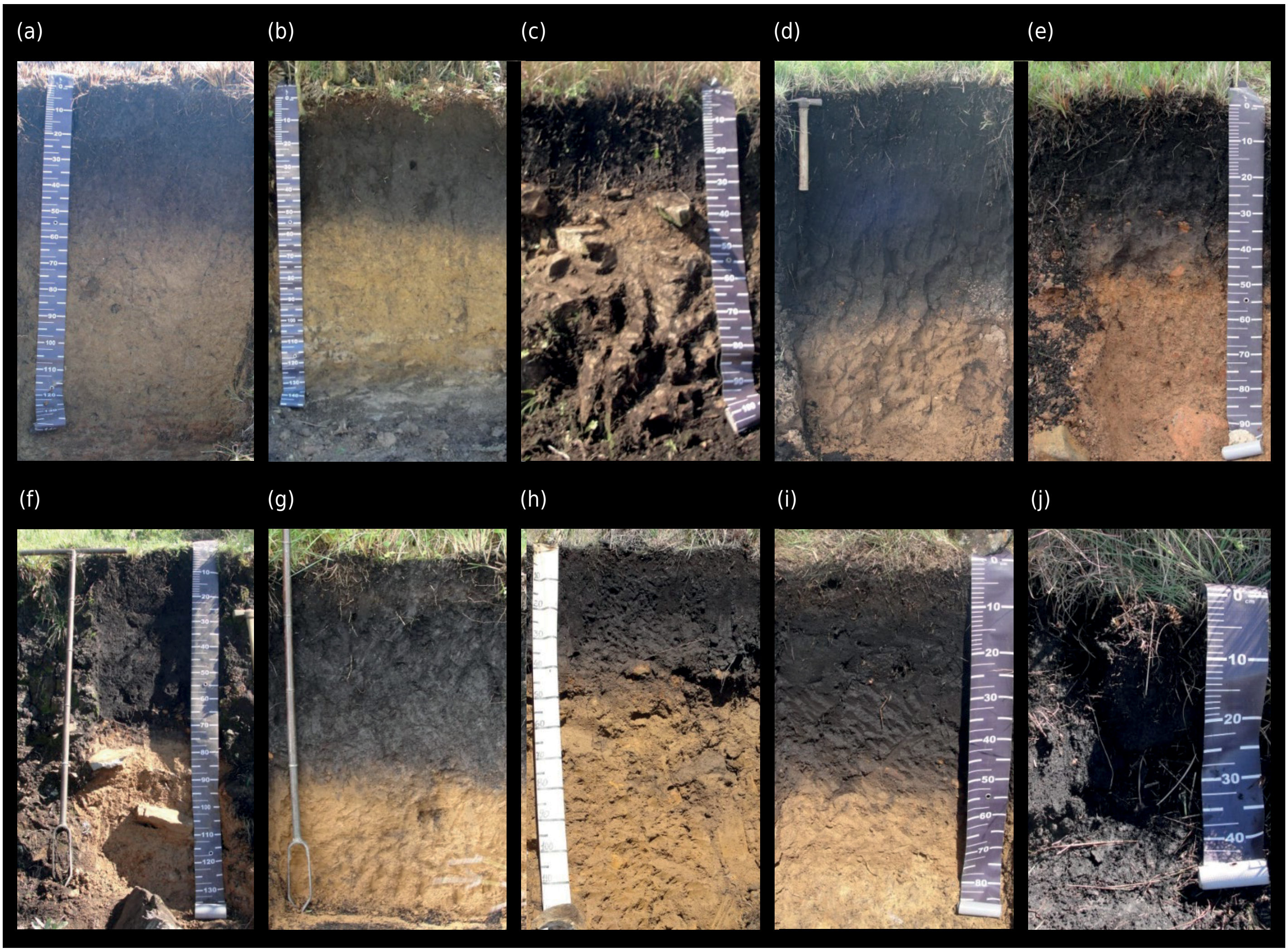

Figure 2. Soil profiles with andic properties in southern Brazil. (a) P2 - *Cambissolo Hístico Alumínico típico, aluândico* / Hyperdystric Umbric Aluandic Andosol (Clayic); (b) P3 - *Cambissolo Hístico Alumínico típico, aluândico* / Hyperdystric Umbric Aluandic Andosol (Clayic, Colluvic, Fulvic); (c) P4 - *Organossolo Fólico Sáprico típico, aluândico* / Umbric Leptic Aluandic Andosol (Hyperdystric, Siltic, Fulvic); (d) P6 - *Cambissolo Hístico Alumínico típico, aluândico* / Hyperdystric Umbric Aluandic Andosol (Clayic, Melanic); (e) P8 - *Cambissolo Hístico Distrófico típico, aluândico* / Hyperdystric Umbric Aluandic Andosol (Loamic, Colluvic, Fulvic); (f) P9 - *Organossolo Fólico Sáprico cambissólico, aluândico* / Ombric Sapric Folic Histosol (Andic, Hyperdystric); (g) P10 - *Cambissolo Hístico Alumínico léptico, aluândico* / Umbric Folic Aluandic Andosol (Hyperdystric, Clayic, Colluvic); (h) P11 - *Organossolo Fólico Sáprico típico, aluândico* / Umbric Folic Aluandic Andosol (Siltic, Fulvic, Melanic); (i) P12 - *Organossolo Fólico Sáprico típico, aluândico* / Umbric Leptic Aluandic Andosol (Hyperdystric, Siltic, Fulvic); (j) P13 - *Organossolo Fólico Sáprico lítico, aluândico* / Leptic Sapric Folic Histosol (Ombric, Andic, Hyperdristric).

and this combination promotes the accumulation of organic matter in the topsoil, culminating in the formation of a surface horizon with intense dark color and high content of organic matter (Driessen et al., 2001), giving to these soils high porosity of strongly developed aggregate structures, which is mainly responsible for the low BD of non-allophanic andic soils, and a high water retention capacity (Nanzyo, 2002; McDaniel et al., 2012).

The high phosphate retention in soils with andic properties occurs due to the large specific surface area and strong affinity of allophanes, imogolite, ferrihydrite and/or organometallic complexes with phosphorus (Parfitt, 1990; Nanzyo, 2002). Phosporous retention occurs through the formation of internal sphere complexes at sites of high and low affinity and precipitation of Al-phosphate minerals (McDaniel et al., 2012).

In summary, according to the criteria recently adopted in SiBCS (Santos et al., 2018), as suggested by Santos Junior (2017) based on IUSS Working Group WRB (2015), there are *Cambissolos Hístico* (P2, P3, P6, P8, and P10) and *Organossolo Fólico* (P4, P9, P11, P12, and P13), all with a superficial diagnostic horizon O hystic, with andic properties, aluandic, while *Cambissolos Húmicos* (P1, P5, and P7) and *Organossolo Háplicos* (P14) did not meet one or more of the required criteria.

CONCLUSIONS

The *Cambissolos Hísticos* and *Organossolos Fólicos* that occur in a narrow band on the escarpment edges of the Serra Geral Formation in the southern Santa Catarina plateau and northeastern plateau of the state of Rio Grande do Sul, above 900 m altitude, have andic properties.

The cold climate and high cloudiness of these high-altitude areas favor the formation of a constantly humid environment and the acid weathering of the source material, accumulation of organic matter in the soil, and its stabilization by the formation of organo-metallic complexes, especially Al-humus. The combination of these factors gives the diagnostic histic horizons low density, high phosphate retention, and $Al_o + ½Fe_o \geq 2$ % values, meeting the criteria required for andic properties.

ACKNOWLEDGMENTS

Our thanks to CAPES/FAPESC for granting the scholarship to the first author and to Embrapa Solo, for the financial contribution and for carrying out the soil characterization analyses of this study, through the SiBCS Project (PA 02.14.01.008.00.03).

AUTHOR CONTRIBUTIONS

Conceptualization: Jaime Barros dos Santos Junior (equal) and Jaime Antonio de Almeida (equal).

Methodology: Jaime Barros dos Santos Junior (equal) and Jaime Antonio de Almeida (equal).

Software: Jaime Barros dos Santos Junior (lead) and Jaime Antonio de Almeida (supporting).

Validation: Jaime Barros dos Santos Junior (lead) and Jaime Antonio de Almeida (supporting).

Formal analysis: Jaime Barros dos Santos Junior (lead) and Jaime Antonio de Almeida (supporting).

Investigation: Jaime Barros dos Santos Junior (equal) and Jaime Antonio de Almeida (equal).

Resources: Jaime Barros dos Santos Junior (equal) and Jaime Antonio de Almeida (equal).

Data curation: Jaime Barros dos Santos Junior (equal) and Jaime Antonio de Almeida (equal).

Writing – original draft: Jaime Barros dos Santos Junior (lead) and Jaime Antonio de Almeida (supporting).

Writing – review and editing: Jaime Barros dos Santos Junior (equal) and Jaime Antonio de Almeida (equal).

Visualization: Jaime Barros dos Santos Junior (equal) and Jaime Antonio de Almeida (equal).

Supervision: Jaime Antonio de Almeida (lead) and Jaime Barros dos Santos Junior (supporting).

Project administration: Jaime Antonio de Almeida (lead) and Jaime Barros dos Santos Junior (supporting).

Funding acquisition: Jaime Antonio de Almeida (lead) and Jaime Barros dos Santos Junior (supporting).

REFERENCES

Acevedo-Sandoval O, Prieto-Garcia F, Gordillo-Martínez A. Identificar las fracciones de aluminio en un Andosol del estado de Hidalgo, México. Rev Soc Geol Esp. 2008;21:125-32.

Aran D, Gury M, Jeanroy E. Organo-metallic complexes in an Andosol: a comparative study with a Cambisol and Podzol. Geoderma. 2001;99:65-79. https://doi.org/10.1016/S0016-7061(00)00064-1

Armas-Espinel S, Hernandez-Moreno JM, Muñoz-Carpena R, Regalado CM. Physical properties of "sorriba" – cultivated volcanic soils from Tenerife in relation to andic diagnostic parameters. Geoderma. 2003;117:297-311. https://doi.org/10.1016/S0016-7061(03)00130-7

Arnalds O, Hallmark CT, Wilding LP. Andisols from different regions of Iceland. Soil Sci Soc Am J. 1995;59:161-9. https://doi.org/10.2136/sssaj1995.03615995005900010025x

Auxtero E, Madeira M. Phosphorus desorbability in soils with andic properties from the Azores, Portugal. Rev Cienc Agrar. 2009;31:423-33. https://doi.org/10.19084/rca.15716

Bascomb CL. Distribution of pyrophosphate - extractable iron and organic carbon in soils of various groups. Eur J Soil Sci. 1968;19:251-68. https://doi.org/10.1111/j.1365-2389.1968.tb01538.x

Bäumler R, Caspari T, Totsche KU, Dorji T, Norbu C, Baillie IC. Andic properties in soil developd from nonvolcanic materials in Central Bhutan. J Plant Nutr and Soil Sci. 2005;168:703-13. https://doi.org/10.1002/jpln.200521793

Bäumler R, Zech W. Characterization of Andisols developed from nonvolcanic material in Eastern Nepal. Soil Sci. 1994;158:211-7. https://doi.org/10.1097/00010694-199409000-00007

Bech-Borras J, Fedoroff N, Sole A. Etude des andosols d'Olot (Gerona, Espagne) - 3e partie: Micromorphologie. Cah ORSTOM. 1977;XV:381-90.

Bellieni G, Comin-Chiaramonti P, Marques LS, Melfi AJ, Nardy AJR, Papatrechas C, Piccirillo EM, Roisemberg A, Stolfa D. Petrogenetic aspects of acid and basaltic lavas from the Paraná plateau (Brazil): Geological, mineralogical and petrochemical relationships. J Petrol. 1986;27:915-44. https://doi.org/10.1093/petrology/27.4.915

Bennema J, Camargo MN. Segundo esboço parcial de classificação de solos brasileiros: subsídios a IV Reunião Técnica de Classificação de Solos. Rio de Janeiro: Ministério de Agricultura. Divisão de Pedologia e Fertilidade do Solo; 1964.

Besser ML, Vasconcellos EMG, Nardy AJR. Platô de São Joaquim, Província Magmática do Paraná: feições de campo e questões genéticas. Bol Paran Geocien. 2015;72:13-28. https://doi.org/10.5380/geo.v72i0.35875

Blakemore LC, Searle PL, Daly BK. Methods for chemical analysis of soils. Wellington: New Zealand Soil Bureau; 1987. (Scientific Reports, 80).

Buytaert W, Deckers J, Wyseure G. Description and classification of nonallophanic Andosols in south Ecuadorian alpine grasslands (páramo). Geomorphology. 2006;73:207-21. https://doi.org/10.1016/j.geomorph.2005.06.012

Caner L, Bourgeon G, Toutain F, Herbillon AJ. Characteristic of non-allophanic andisol derived from low-activity regoliths in Nilgiri Hills (Southern India). Eur J Soil Sci. 2000;51:553-63. https://doi.org/10.1111/j.1365-2389.2000.00344.x

Clemente EP. Ambientes terrestres da Ilha da Trindade, Atlântico Sul: caracterização do solo e do meio físico como subsídio para a criação e uma unidade de conservação [tese]. Viçosa, MG: Universidade Federal de Viçosa; 2006.

Clemente EP, Schaefer CEGR, Oliveira FS, Albuquerque Filho MR, Alves RV, Sá MMF, Melo VF, Corrêa GR. Topossequência de solos na Ilha da Trindade, Atlântico Sul. Rev Bras Cienc Solo. 2009;33:1357-71. https://doi.org/10.1590/S0100-06832009000500028

Dahlgren RA, Shoji S, Nanzyo M. Mineralogical characteristics of volcanic ash soils. In: Shoji S, Nanzyo M, Dahlgren RA, editors. Volcanic ash soils: genesis, properties and utilization. Amsterdam: Elsevier; 1993. p. 101-43.

Delvaux B, Strebl F, Maes E, Herbillon AJ, Brahy V, Gerzabek M. An Andosol–Cambisol toposequence on granite in the Austrian Bohemian Massif. Catena. 2004;56:31-43. https://doi.org/10.1016/j.catena.2003.10.003

Driessen P, Deckers J, Spaargaren O, Nachtergaele F. Lecture notes on major soils of the world. Rome: Food and Agriculture Organization of the United Nations; 2001. (World Soil Resources Reports, n. 94).

Dümig A, Schad P, Kohok M, Beyerlein P, Schwimmer W, Kögel-Knabner I. A mosaic of nonallophanic Andosols, Umbrisols and Cambisols on rhyodacite in the southern Brazilian highlands. Geoderma. 2008;145:158-73. https://doi.org/10.1016/j.geoderma.2008.01.013

Falkenberg DB. Matinhas nebulares e vegetação rupícola dos Aparados da Serra Geral (SC/RS), sul do Brasil [tese]. Campinas: Universidade Estadual de Campinas; 2003.

Fasolo PJ, Potter RO, Hochmuller DP, Cardoso A, Jacomine PKT, Larach JOI, Camargo MN, Carvalho AP. Estudo expedito de solos do Estado de Santa Catarina, para fins de classificação, correlação e legenda preliminar. Rio de Janeiro: Embrapa Solos; 1980. (Boletim Técnico, 65).

Garcia-Rodeja E, Silva BM, Macias F. Andosols developed from non-volcanic materials in Galicia, NW Spain. J Soil Sci. 1987;38:573-91. https://doi.org/10.1111/j.1365-2389.1987.tb02156.x

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

Jakab S, Fazakas C, Füleky G. Andosols of the East Carpathian volcanic range. Acta Univ Sapientiae Agric Environ. 2011;3:110-21.

Jiomeneck PST, Tematio P, Wilson MA, Yemefack M. Andolization of soils on a Strombolian Cone at Mount Bambouto, Cameroon. Open J Soil Sci. 2011;1:97-105. https://doi.org/10.4236/ojss.2011.13013

Johnson-Maynard JL, McDaniel PA, Falen AL, Ferguson DE. Chemical and mineralogical conversion of Andisols following invasion by bracken fern. Soil Sci Soc Am J. 1997;61:549-55. https://doi.org/10.2136/sssaj1997.03615995006100020025x

Ker JC. Caracterização química, física, mineralógica e micromorfológica de solos Brunos subtropicais [dissertação]. Viçosa, MG: Universidade Federal de Viçosa; 1988.

Ker JC, Resende M. Caracterização química e mineralógica de solos Brunos subtropicais do Brasil. Rev Bras Cienc Solo. 1990;14:215-25.

Kubotera H, Kusaba T, Shima T, Shishibe I, Kagei M. Properties of nonallophanic Andosols surface horizons around Kuju Plateau to the northern area of Aso Somma. J Soil Sci Plant Nutr. 2015;86:17-23. https://doi.org/10.20710/dojo.86.1_17

Kubotera H, Kusaba T, Shishibe I. Distribution and horizons sequence of non-allophanic Kuroboku soils in Kuju Plateau, Kyushu, Japan. Pedologist. 2013;57:72-80. https://doi.org/10.18920/pedologist.57.2_72

Kuinchtner A, Buriol GA. Clima do estado do Rio Grande do Sul segundo a classificação climática de Köppen e Thornthwaite. Discip Sci Ser Cienc Exatas. 2001;2:171-82. https://doi.org/10.37779/nt.v2i1.1136

Lowe DJ, Palmer DJ. Andisols of New Zealand and Australia. JIFS. 2005;2:39-65.

Machado MR. Endemismo pedológico e os solos da Ilha da Trindade – Atlântico Sul, Brasil. Rev Depart Geog. 2017;11:238-48. https://doi.org/10.11606/rdg.v0ispe.132762

Machado MR. O papel da avifauna na transformação geoquímica de substratos na Ilha da Trindade, Atlântico Sul [dissertação]. Belo Horizonte: Universidade Federal de Minas Gerais; 2016.

Mateus ACC, Varajão AFDC, Oliveira FS, Petit S, Schaefer CEGR. Non-allophanic Andosols of Trindade Island, south Atlantic: a new soil order in Brazil. Rev Bras Cienc Solo. 2020;44:e0200007. https://doi.org/10.36783/18069657rbcs20200007

McDaniel PA, Lowe DJ, Arnalds O, Ping CL. Andisols. In: Huang PM, Sumner ME, editors. Handbook of soil science. 2nd ed. Boca Raton: CRC Press (Taylor & Francis); 2012. p. 33.29-33.48.

McKeague JA, Day JH. Dithionite and oxalate extractable Fe and Al as aids in differentiating various classes of soils. Can J Soil Sci. 1966;46:13-22. https://doi.org/10.4141/cjss66-003

Milani EJ, Faccini UF, Scherer CMS, Araújo LM, Cupertino JA. Sequences and stratigraphic hierarchy of the Paraná Basin (Ordovician to Cretaceous), Southern Brazil. Bol IG USP. 1998;29:125-73. https://doi.org/10.11606/issn.2316-8986.v29i0p125-173

Mota FS. Estudos do clima do estado do Rio Grande do Sul segundo o sistema de W. Koeppen. Rev Bras Geogr. 1951;13:275-84.

Msanya BM, Otsuka H, Araki S, Fujitake N. Characterization of volcanic ash soils in southwestern Tanzania: Morphology, physicochemical properties, and classification. Afr Stud Monogr. 2007;34:39-55. https://doi.org/10.14989/68484

Nanzyo M. Unique properties of volcanic ash soils. Glob Environ Res. 2002;6:99-112.

Nanzyo M, Shoji S, Dahlgren R A. Physical characteristics of volcanic ash soils. In: Shoji S, Nanzyo M, Dahlgren R A, editors. Volcanic ash soils: genesis, properties and utilization. Amsterdam: Elsevier; 1993. p. 189-201.

Nardy AJR, Oliveira MAF, Betancourt RHS, Verdugo DRH, Machado FB. Geologia e estratigrafia da Formação Serra Geral. Geociências. 2002;21:15-32.

Ndayiragije S, Delvaux B. Selective sorption of potassium in a weathering sequence of volcanic ash soils from Guadeloupe, French West Indies. Catena. 2004;56:185-98. https://doi.org/10.1016/j.catena.2003.10.010

Ndayiragije S, Delvaux B. Coexistence of allophane, gibbsite, kaolinite and hydroxyl-Al-interlayered 2:1 clay minerals in a perudic Andosol. Geoderma. 2003;117:203-14. https://doi.org/10.1016/S0016-7061(03)00123-X

Novák P, Khel T, Vopravil J, Lagová J. Do Andosols occur in the Czech Republic? Soil Water Res. 2010;5:161-71. https://doi.org/10.17221/24/2010-SWR

Orlandi Filho V, Krebs ASJ, Giffoni LE. Coluna White, Serra do Rio do Rastro, SC: Seção geológica clássica do continente Gonduana no Brasil (Sítio 024). In: Winge M, Schobbenhaus C, Souza CRG, Fernandes ACS, Berbert-Born M, Queiroz ET, Campos DA, editores. Sítios geológicos e paleontológicos do Brasil. 2 ed. Brasília, DF: CPRM; 2009. v. 2. p. 71-86.

Parfitt RL. Allophane in New Zealand - a review. Aust J Soil Res. 1990;28:343-60. https://doi.org/10.1071/SR9900343

Peate DW. The Paraná-Etendeka Province. In: Mahoney JJ, Coffin M, editors. Large igneous provinces: Continental, oceanic and planetary flood volcanism. Washington: American Geophysical Union; 1997. p. 217-45.

Pigna M, Violante A. Adsorption of sulfate and phosphate on Andisols. Commun Soil Sci Plant Anal. 2003;34:2099-113. https://doi.org/10.1081/CSS-120024051

Pinheiro J, Tejedor-Salguero M, Rodriguez A. Genesis of placic horizons in Andisols from Terceira Island Azores, Portugal. Catena. 2004;56:85-94. https://doi.org/10.1016/j.catena.2003.10.005

Potter RO, Carvalho AP, Flores CA, Bognolo I. Solos do Estado de Santa Catarina. Rio de Janeiro: Embrapa Solos; 2004. (Boletim de Pesquisa e Desenvolvimento n. 46).

Poulenard J, Herbillon AJ. Sur l’existence de trois categories d’horizons de réference dans les Andosols. C R Acad Sci. 2000;331:651-7. https://doi.org/10.1016/S1251-8050(00)01467-1

Quantin P, Dabin B, Bouleau A, Lulli L, Bidini D. Characteristics and genesis of two Andosols in Central Italy. In: Fernandes-Caldas E, Yaalon DH, editors. Catena Supplement. 1985;7:107-17.

Roisenberg A, Viero AP. O vulcanismo mesozóico da Bacia do Paraná no Rio Grande do Sul. In: Holz M, Ros LF, editors. Geologia do Rio Grande do Sul. Porto Alegre: CIGO/ UFRGS; 2000. p. 335-54.

Sá MMF. Caracterização ambiental, classificação e mapeamento dos solos da Ilha da Trindade, Atlântico Sul [dissertação]. Viçosa, MG: Universidade Federal de Viçosa; 2010.

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

Santos Junior JB. Solos com propriedades ândicas derivados de litologias da Formação Serra Geral em ambientes altomontanos do sul do Brasil [tese]. Lages: Universidade do Estado de Santa Catarina; 2017.

Santos RD, Lemos RC, Santos HG, Ker JC, Anjos LHC, Shimizu SH. Manual de descrição e coleta de solo no campo. 6. ed. rev. e ampl. Viçosa, MG: Sociedade Brasileira de Ciência do Solo; 2013.

Shoji S, Dahlgren RA, Nanzyo M. Genesis of volcanic ash soils. In: Shoji S, Nanzyo M, Dahlgren RA, editors. Volcanic ash soils: genesis, properties and utilization. Amsterdam: Elsevier; 1993. p. 37-72.

Shoji S, Fujiwara T. Active aluminum and iron in the humus horizons of Andosols from northeastern Japan: Their forms, properties, and significance in clay weathering. Soil Sci. 1984;137:216-26. https://doi.org/10.1097/00010694-198404000-00002

Shoji S, Saigusa M. Amorphous clay materials of Towada ando soils. Soil Sci Plant Nutr. 1977;23:437-55. https://doi.org/10.1080/00380768.1977.10433063

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

Stewart K, Turner S, Kelley S, Hawkesworth C, Kirstein L, Mantovani M. 3-D, 40 Ar-39 Ar geochronology in the Paraná continental flood basalt province. Earth Planet Sci Lett. 1996;143:95-109. https://doi.org/10.1016/0012-821X(96)00132-X

Takahashi T, Shoji S. Distribution and classification of volcanic ash soils. Glob Environ Res. 2002;6:83-97.

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

Van Reeuwijk LP. Procedures for soil analysis, 6th. ed. Wageningen: International Soil Reference and Information Center; 2002.

Volkoff B, Cerri CC, Melfi JA. Húmus e mineralogia dos horizontes superficiais de três solos de campo de altitude dos estados de Minas Gerais, Paraná e Santa Catarina. Rev Bras Cienc Solo. 1984;8:277-83.

Wada K. The distinctive properties of Andosols. In: Stewart BA, editor. Advances in soil science. New York: Springer-Velag; 1985:173-29. https://doi.org/10.1007/978-1-4612-5088-3_4.