SEÇÃO V - GÊNESE, MORFOLOGIA E CLASSIFICAÇÃO DO SOLO

GENESIS OF THE SOMBRIC HORIZON IN ULTISOLS (RED ARGISOLS) IN SOUTHERN SANTA CATARINA, BRAZIL[1]

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SUMMARY

Dark subsurface horizons, with properties similar to the sombric horizon characterized by the USA Soil Taxonomy, are frequent in Southern Brazil. The genesis of this horizon is controversial and poorly understood. This study aimed to describe the occurrence of sombric-like horizons in Ultisols in the South of Santa Catarina State, at low altitudes, and suggest possible processes of humus transference, accumulation and persistence in these horizons. Physical, chemical and mineralogical properties of four Ultisols were evaluated; three were sampled in a toposequence, and another representative one in an isolated profile (RSP). The dark subsurface horizons coincide with the AB and BA transitional genetic horizons; they are acid, low in base saturation, and have a similar clay mineralogy in all horizons. Very high amounts of Fe and Al extracted by ammonium oxalate and sodium pyrophosphate solution as well as maximum Al extracted by $CuCl_2$ solution were observed in these dark subsurface horizons, indicating a possible migration of these elements in the form of organometallic complexes. The contents of Al plus ½ Fe extracted from the RSP soil horizons with ammonium oxalate indicated spodic materials in the sombric-like horizon, although the soil morphology was not compatible with Spodosols. Maximum contents of fine clay were also found in the sombric-like horizon, suggesting Fe and Al migration as clay-humic substances. However, the hypothesis that sombric-like horizons in these soils are a relict feature of a grass paleovegetation, different from the current dense seasonal forest, should not be discarded but investigated in further studies.

Index terms: dark subsurface horizon, podzolization, buried A horizon, clay-humic substances, climatic changes.

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RESUMO: *GÊNESE DO HORIZONTE SÔMBRICO EM ARGISSOLOS VERMELHOS DO SUL DE SANTA CATARINA*

Horizontes subsuperficiais escuros, similares ao sômbrico da Soil Taxonomy (EUA), são frequentes em solos do Sul do Brasil. A gênese desse horizonte, entretanto, é controvertida, havendo poucos estudos sobre o tema. O presente trabalho objetivou descrever a ocorrência de horizontes com morfologia similar à do sômbrico em Argissolos do extremo sul de Santa Catarina, em condições de baixa altitude, bem como sugerir possíveis mecanismos responsáveis pela transferência, acumulação e permanência do húmus nesses horizontes. Foram descritos e amostrados três perfis de Argissolos Vermelhos numa topossequência e num perfil isolado, representativo dessa classe de solo, os quais foram avaliados quanto a vários atributos físicos, químicos e mineralógicos. Os horizontes subsuperficiais escuros coincidem com horizontes genéticos AB e, ou, BA, são ácidos e pobres em bases e têm mineralogia da fração argila similar à dos horizontes sub e sobrejacentes. Os valores máximos de Fe e Al extraídos com oxalato de amônio e com pirofostato de sódio ocorreram nesses horizontes transicionais escuros, assim como o teor de Al extraído com solução de $CuCl_2$, indicando possível migração destes elementos na forma de compostos organometálicos. Os teores de Al + ½ Fe extraídos com oxalato de amônio nos horizontes sômbricos são compatíveis com os teores da definição de material espódico, embora o solo não apresente morfologia compatível com a dos solos da classe Espodossolo. Máximos valores de argila fina também foram constatados no horizonte sômbrico, sugerindo que o Fe e o Al possam ter migrado na forma de compostos argilo-húmicos. Entretanto, não pode ser desconsiderada a hipótese (que necessita de maiores investigações para sua comprovação) de que estes horizontes sômbricos sejam uma feição relíquia de uma paleovegetação graminosa diferente da atual floresta estacional densa.

Termos de indexação: horizonte subsuperficial escuro, podzolização, horizonte A enterrado, compostos argilo-húmicos, mudanças climáticas.

INTRODUCTION

In the South of Santa Catarina State, in the surroundings of the cities of Criciúma and Içara, there is a large area of Ultisols with a peculiar feature; dark subsurface horizons are interlayered between lighter A and red B horizons. The position of these horizons is coincident with that of transitional AB and, or BA horizons.

The hypothesis that this morphology indicates sombric horizons, as defined by the Soil Taxonomy (USDA, 1975), was first proposed by Klamt[5] during a soil exploratory trip to that region, together with Dr. R.B. Daniels, in the mid 80's. On this occasion, the hypothesis that these horizons could be buried A horizons was discarded, because the dark subsurface horizons were observed in all soils in several adjacent segments of the landscape.

Sombric horizons were first identified by Belgian pedologists who worked in the Congo, nowadays Zaire, where they were found a number of soil types such as Ultisols, Alfisols, Inceptisols and Oxisols. Their occurrence seems to be restricted to cold and mountainous intertropical regions, at altitudes between 1.500 and 2.000 m asl (Eswaran & Tavernier, 1980; Frankart, 1983; Smith, 1986). Sys et al. (1961) defined it as a horizon originated by illuvial accumulation of organic matter, of black, dark gray or dark grayish brown color, located under a B2 horizon in kaolinitic soils at high altitudes.

By the Soil Taxonomy (Survey Staff, 1999, 2003) sombric horizons are defined as subsurface horizons with free drainage, containing illuvial humus not associated with Al, as in the spodic horizon, nor dispersed by sodium as in the natric horizon. It has a lower value and/or chroma than the overlying horizon, and commonly but not necessarily, a higher organic matter content as well. It is formed on an argilic, kandic, cambic or even oxic horizon, and can easily be confused with a buried A horizon; it can be distinguished in the field by monitoring lateral variations or by analyses of thin sections (USDA, 1975; Soil Survey Staff, 1999).

Although the presence of sombric horizons is a diagnostic characteristic for soil classification by the Soil Taxonomy (USDA, 1975) at the large group level, their genesis has been little studied. Most authors agree on an illuvial origin of sombric horizons, however, all unanimously confirm that the genesis mechanisms are practically unknown (Frankart, 1983; Smith, 1986).

According to Sys et al. (1961), the formation of sombric horizons would have occurred by the illuviation of organic compounds, which is a

[5] KLAMT, E. Relatório de viagem de reconhecimento de solos do Sul do Brasil, 1988 (not paginated).

prerequisite in the definition of sombric horizons of the Soil Taxonomy (USDA, 1975). The requisite of Al absence associated with humus in the sombric horizon, as defined by the Soil Survey Staff (1999; 2003) seems to be much more a tentative of a proposal to differentiate it from the spodic horizon than a solidly based scientific criterion, particularly because of the small number of studies on the genesis of these horizons. Therefore, the possibility that humus can be accumulated by a mechanism similar to podzolization, that is, in the form of organometallic compounds, needs to be considered since the differences between spodic and sombric horizons are not yet completely understood.

An alternative mechanism proposed by Faivre (1990) attributed the origin of sombric horizons in soils of the Colombian Andes to the migration and precipitation of clay-humic complexes. Micromorphological analyses of these soils showed that the dark film stated on the aggregates of the sombric horizon consisted of organo-ferri-argillans compounds, indicating that the humus may have migrated in association with clay minerals, as plasmic material, rather than with soluble organ metallic compounds as is the case during podzolization (DeConninck, 1980).

In a recent study, Caner et al (2003) proposed a more detailed understanding of the genesis of sombric horizons in soils of Southern India, attributing their occurrence to climatic changes in the past. According to the authors, the sombric horizons studied could be considered relicts of a thick layer of organic matter deposited in the surface soil layers during a dryer period, where C4 plants (grasses) predominated that were later substituted by C3 plants (forests) in a wetter time, which resulted in a reduction of the dark humus color of the surface-near horizons.

This study had the objective of describing the occurrence of sombric-like horizons at low altitudes in Ultisols in Southern Santa Catarina, Brazil, based on analyses of the physical, chemical and mineralogical properties, as well as of proposing possible mechanisms of humus transfer and accumulation in these horizons.

MATERIAL AND METHODS

Soil and environment general characterization

Soil profiles with a morphology similar to sombric horizons are relatively common in the South of Santa Catarina State, Brazil, notably in the counties of Orleans, Urussanga, Cocal, Criciúma, Içara and Morro da Fumaça. These horizons occasionally indicate characteristics of buried A horizons; in this case their occurrence is determined by local and specific factors. In other situations, the darkening is restricted to the top of the B horizon, similar to the morphology of soils of the class previously defined as Gray Brown Podzolic (Oliveira et al., 1982), but also observed in Ultisols of pediments developed from granite or sedimentary rocks.

In Criciúma and Içara, though, more pronounced dark subsurface horizons are observed in Dystrophic Red Argisols (Ultisols) of medium A and clay B horizon texture that occupy a relatively homogeneous area of more than 700 km². These soils generally have dark subsurface horizons that are coincident with the AB and/or BA transitional horizons with lower color values than the overlying and underlying horizons (Figure 1). The darkening of these horizons is normally uniform in the entire soil matrix indicating a strong interaction between organic compounds and the mineral fraction. From the BA horizon, the

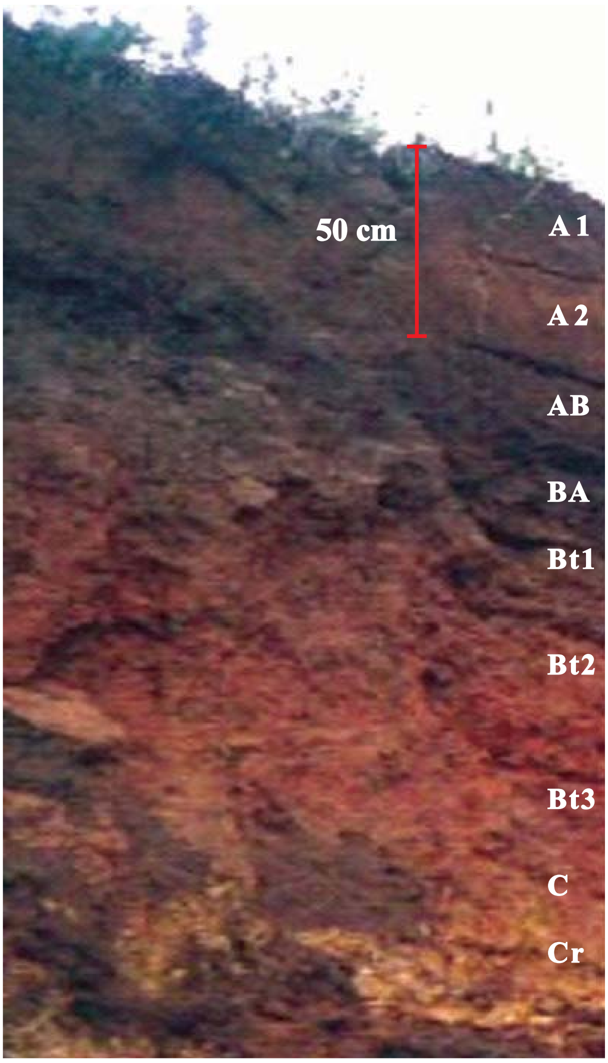

Figure 1. General view of the representative profile of the Red Argisols with a sombric horizon (corresponding to AB and BA genetic horizons). Location: county of Içara, Santa Catarina State, Brazil.

darkening degree decreased gradually, and an pronounced deposition of dark colored cutans (organs) that stand out clearly from the red matrix of the Bt horizon can be observed. These features seem to indicate a contemporaneous process of organic compound migration from the top horizons.

These soils occur in areas with a predominantly slightly hilly relief with hilly parts, developed from Permian sedimentary rocks of the Rio Bonito formation, Guatá Group, consisting mainly of siltites, with arenite intercalated (DNPM, 1986). At some rare sites, this geological formation also produced diabase outcrops that stand out at a higher position in the landscape. The sandier texture of the surface horizons of most soils seems to indicate a possible contribution of allochthonous material. The original vegetation of the region was a Dense Ombrophile Forest, completely destroyed by intense anthropic activities (Santa Catarina, 1986). Nowadays such soils have turned into highly urbanized areas, although the diversified agricultural activities of micro and small farmers still prevail. The regional climate is Cfa (Köeppen) with mean annual temperatures between 16 and 18 °C and rainfall of around 1.400 mm.

One of the peculiarities of these soils is their location at low altitudes, between 50 and 100 m asl, where the presence of sombric horizons is uncommon (Frankart, 1983; Smith, 1986).

Figure 2. Map of Santa Catarina state (at the top) with Criciúma, and the extended map of the region of Criciúma (at the bottom) indicating the sampling sites of Red Argisols from the toposequence (P1, P2 and P3) and the representative profile (RP).

Soil profile selection, description and sampling

Three Ultisol profiles were described and sampled in a transect of a toposequence with a hilly relief, near a diabase dike. The profiles were located on distinct slopes nearly 1.500 m away from each other, at the top or interfluve position (P3), slope (P2) and footslope (P1). They were selected with the intention of confirming the presence of dark subsurface horizons in different slope segments, to test the hypothesis of being buried A horizons.

At another site, near the city of Içara, in an area with a moderately hilly relief, a representative profile (RP) of an Ultisol was described, sampled and used for most of the physical, chemical and mineralogical analyses. This soil profile was selected because the textural gradient is higher and expresses the sombric horizon more clearly, besides, the characteristic feature of darkened aggregate surface is also observed in the Bt1 and Bt2 horizons. All soil profiles were described according to the Manual de Descrição e Coleta do Solo à Campo (Lemos & Santos, 1996), and samples were collected from each horizon and/or morphologic feature (Figure 2).

Physical, chemical and mineralogical analyses

Sand fraction was determined by sieving, total clay by the Boyoucos method and silt by the difference, all according to Embrapa (1979). In the RP, the total sand fraction of each horizon was separated into five subfractions, according to the USDA classification (1975): very fine (VFS), fine (FS), medium (MS), coarse (CS) and very coarse sand (VCS), to detect differences between the horizons that could indicate any lithological discontinuity. In this profile, the total clay of each horizon was also fractionated into fine clay (diameter < 0.2 µm) and coarse clay (2–0.2 µm) by centrifugation procedures proposed by Jackson (1965).

The chemical analyses for an analytic characterization of the profiles consisted of: exchangeable Ca^{2+}, Mg^{2+}, K^+, Na^+ and Al^{3+}, titratable H + Al, pH in water and in KCl 1 mol L^{-1}, and organic C, as proposed by Tedesco et al. (1985). Based on these properties, the CEC at pH 7.0, sum of bases (S) and base saturation (V) were also calculated, according to Embrapa (1979).

In RP, Fe and Al were extracted from the fine earth with ammonium oxalate solutions (Fe_o and Al_o) at pH 3.0 in the dark (Schwertmann, 1964), dithionite-citrate-bicarbonate (Fe_d and Al_d), according to Mehra & Jackson (1960), and 0.1 mol L^{-1} sodium pyrophosphate (Fe_p and Al_p) at pH 10 according to USDA (1996). Al was extracted with $CuCl_2$ solution (Al_{Cu}), according to Juo & Kamprath (1979), and all were quantified by inductively coupled plasma spectrophotometry (ICP).

The clay fraction of the selected horizons was separated from silt by dispersion and flocculation, based on Stokes' law. Part of these samples were saturated with K and heated to 25, 110 and 330 °C, and another part was saturated with Mg and treated with glycerol. These samples were analyzed by X ray diffractometry (RXD) using oriented clay mounts with an equipment containing a vertical goniometer, Fe tube and angular speed of 1 ° 2θ/min. The criteria for mineral identification were obtained from Brown & Brindley (1980) and Whithig and Allardice (1986).

RESULTS AND DISCUSSION

General profile characteristics

In the three soil profiles of the toposequence, the dark subsurface horizons corresponded to AB or BA transitional horizons as suggested by their lower value and chroma in relation to the overlying horizons (Table 1). In P1, the organic matter content of AB is higher than of A2 but slightly lower than A1; in the other profiles, despite the darker color, the organic matter contents in the dark subsurface horizons AB and/or BA were not higher than in the overlying horizons (Table 1). In the three profiles a pronounced clay increment was observed in the deeper layers, with maximum values in the horizons Bt1 (P1) and Bt2 (P2 and P3); however, the texture gradient in these soils is much lower than in the RP (Table 2) and the clay contents higher than in the surface horizons. This latter characteristic can be associated to the contribution of more clayey allochtonous material in the surface from soils developed from diabase dikes near the toposequence, a condition not verified in the RP. The three profiles show a strong acid reaction, low base saturation and high exchangeable Al levels,

Table 1. Morphological, granulometric and chemical properties of three Red Argisols with dark subsurface horizons profiles on a toposequence in the region of Içara-Criciúma, Santa Catarina State, Brazil

Profile	Hor.	Depth	Color	Structure [1]	Granulometry			pH	OM	$Ca^{2+} + Mg^{2+}$	K^+	Na^+	Al^{3+}	H + Al	S	CEC	V
					Sand	Silt	Clay	KCl								pH 7	
		cm			dg kg^{-1}				%	mmol$_c$ kg^{-1}							%
P1	A1	0-25	7.5YR 3/3,u 10YR 5.5/4,s	weak.med/coar subang blocky	12	52	36	3.7	2.86	33.5	2.3	0.7	8.3	33.0	36.5	69.5	52
	A2	25-37	7.5YR 3/4,u 10YR 5/4,s	weak med/fine subang blocky	11	46	43	3.6	1.86	30.5	2.3	1.0	13.1	45.3	33.8	79.1	43
	AB	37-67	5YR 3/2,u 7.5YR 3.5/3,s	mod fine/med subang blocky	6	35	59	3.6	2.75	19.5	2.7	0.9	27.6	68.5	23.1	91.6	25
	Bt1	67-120	2.5YR 3.5/6,u	mod. coar/med subang blocky	4	31	65	3.5	1.59	16.5	1.8	0.7	36.3	70.4	19.0	89.4	21
P2	A	0-34	7.5YR 4/5,u 9YR 5/4,s	mod fine/med subang blocky	14	49	37	3.7	2.34	14.0	0.9	0.6	21.1	41.4	15.5	56.9	27
	BA	34-77	7.5YR 3/4,u 7.5YR 3.5/4,s	mod fine/med subang blocky	8	32	60	3.7	1.92	39.5	0.8	0.5	17.5	48.3	40.8	89.1	46
	Bt1	77-94	5YR 3/4,u	mod fine/med subang blocky	6	29	65	3.5	1.31	17.0	0.7	0.4	34.5	48.8	18.1	66.,9	27
	Bt2	94-150	2.5YR 4/6,u	mod med/fine subang blocky	7	26	67	3.4	1.13	10.0	0.7	0.5	39.2	49.3	11.2	60.5	18
	Bt3	150-197	2.5YR 3/6,u	mod med/fine subang blocky	7	30	63	3.5	0.69	4.5	0.6	0.5	36.7	44.3	5.6	49.9	11
	Bt4	197-220	2.5YR 3/5,u	mod med/fine subang blocky	6	33	61	3.5	0.52	6.0	0.7	1.1	41.2	44.3	7.8	52.1	15
P3	A	0-40	7.5YR 4/6,u 9YR 5/4,s	mod med/fine subang blocky	17	46	37	3.5	2.70	10.5	1.6	0.6	29.9	52.0	12.7	64.7	20
	AB	40-70	7.5YR3/2.5,u	mod med/fine subang blocky	12	35	53	3.5	2.22	13.0	1.7	0.7	37.1	66.5	15.4	81.9	19
	BA	70-84	7.5YR 3/4,u	mod med/fine subang blocky	12	34	54	3.5	1.0	12.5	1.2	0.7	33.3	53.7	14.4	68.1	21
	Bt1	84-98	5YR 3/4,u	mod med/fine subang blocky	10	33	57	3.5	1.27	13.0	1.2	0.6	38.0	52.2	14.	67.0	22
	Bt2	98-135	5YR 4/6,u	mod med/ coar subang blocky	10	33	57	3.5	0.98	8.0	1.4	0.5	41.2	48.8	9.9	58.7	16
	Bt3	135-158	2.5YR3.5/6,u	mod med/ coar subang blocky	10	38	52	3.4	0.48	7.0	1.5	0.7	43.9	44.1	9.2	53.3	17

[1] d: dry, m: moist; mod: moderate, med: medium, coar: coarse, subang: subangular; OM: organic matter.

especially in the subsurface horizons. The CEC at pH 7.0 was always higher in the dark horizons AB or BA than in the under and overlying horizons (Table 1) probably due to the influence of humified organic compounds. Combined with the relatively high B/A texture gradient, the clay films found in the B horizons from these soils were described as moderate to strong degree and of normal to abundant quantity which, together with the other soil properties, classifies them as dystrophic Red Argisols (Embrapa, 1999; 2006) and Sombriudults (Soil Survey Staff, 2003).

In the RP, where the surface horizons are sandier, the darker horizons correspond to transitional AB and BA and their values are lower than the over and underlying horizons (Table 2). There seems to be a strong interaction between the organic and mineral compounds from the matrix of these horizons, which causes a regular darkening both on the inside and surface of the aggregates. In the BA, though, the presence of organic and mineral cutans (argillans and organans) can be easily observed in the macromorphologic analysis, without lens. In field tests with hydrogen peroxide carried out in these horizons no boiling was observed, which excluded the possibility that the dark depositions could be Mn compounds. In the Bt1 and Bt2 horizons, the presence of cutans was marked, concentrated as dark spots disseminated in the cracks between aggregate and on their surface, with a red matrix. In these depositions, carefully sampled by scraping with a scalpel, the C contents are higher than of the horizon matrix (Table 2, Bt2 horizon). Clay skins were described as moderate and common in Bt1, strong and abundant in Bt2, and strong and common in Bt3, indicating argilluviation processes. This feature, associated with the high texture gradient, indicates the presence of a B textural horizon, according to Embrapa (2006) and a kandic horizon, according to the Soil Survey Staff (2003). These characteristics classify the RP, respectively, in both systems, as (sombric) Red Argisols and Sombriudult.

Similarly to the toposequence profiles, the RP shows a highly acid reaction, is poor in bases and has high exchangeable Al contents in the B horizon. The organic matter contents are slightly higher in AB and BA compared to A2. Besides, in these horizons, the CEC at pH 7 is higher than in the others.

The A1 horizon of the RP has much higher organic matter contents than AB and BA, while the color is lighter. This characteristic is probably related to the lower participation of humified organic compounds in this horizon and to the presence of more stable organic compounds in AB and BA. This also explains the higher CEC in the AB and BA horizons, since stable humus results in high negative charges in the soil. Caner et al. (2003) attributed the darker color of subsurface horizons in soils from an Indian plateau to chromatic and chemical differences of the organic material. Highly aromatic humic acids, type A (Kumada, 1987) were found in dark horizons but were absent in the surface horizons.

Sand and clay fractionation

The percentage of many sand subfractions from A1 to Bt1 in the RP is fairly similar. From there on, there is a pronounced increase in the medium sand (MS) proportion with a concomitant reduction in the fine sand (FS) and very fine sand (VFS) fractions (Figure 3). Breaks in the uniformity of the sand

Table 2. Morphological, granulometric and chemical properties of a representative profile of Red Argisols in Içara, Santa Catarina State, Brazil

Profile	Hor.	Depth	Color moist	Structure (1)	Granulometry			pH		OM	$Ca^{2+} + Mg^{2+}$	K^+	Na^+	Al^{3+}	H + Al	S	CEC pH 7	V
					Sand	Silt	Clay	H_2O	KCl									
		cm			dg kg^{-1}					%	mmol$_c$ kg^{-1}							%
RP	A1	0-20	10YR 3.5/4	weak med/coar gran/single grains	73	8	19	4.7	3.7	2.51	14.0	2.2	0.2	9.1	25.9	16.4	42.3	39
	A2	20-50	10YR 3/4	weak coar/very coar gram/sing grain	71	9	20	4.9	3.9	1.26	11.0	1.4	0.1	7.7	23.7	12.5	36.2	35
	AB	50-73	9.0YR2.5/2	weak med/coar gran/single grain	63	9	28	4.6	3.7	1.78	18.0	0.9	0.2	18.1	47.3	19.1	66.4	29
	BA	73-90	8.5YR2.5/2	mod med/coar subang blocky	54	9	37	4.6	3.6	1.83	11.5	1.2	0.1	24.3	50.2	12.8	63.0	20
	Bt1	90-113	7.5YR 3/4	mod med/fine subang blocky	45	9	46	4.7	3.6	1.37	10.5	1.3	0.1	24.2	36.5	11.9	48.4	25
	Bt2	113-150	2.5YR 4/6	mod med/fine subang blocky	44	7	49	4.6	3.6	0.62	10.5	0.8	0.1	18.9	30.0	11.4	41.4	28
	Bt2									0,92	(Cutans in agregate surfaces)							
	Bt3	150-172	2.5YR3.5/6	mod med/fine subang blocky	50	8	42	4,5	3.6	0.36	11.0	0.6	0.1	16.6	23.6	11.7	35.3	33
	C	172-195	-	-	37	10	53	4,7	3.5	0.26	12.5	0.7	0.2	26.6	30.5	13.4	43.9	30
	CR	195-210	-	-	11	20	69	4.7	3.4	0.30	48.5	1.5	0.3	69.0	60.6	50.3	110.6	45

(1) mod: moderate; med: medium; coar: coarse; gran: granular; sing: single; subang: subangular; OM: organic matter.

subfractions between horizons of a same profile have been used frequently as supporting criteria of identification of lithological discontinuities (Brinckman, 1979; Almeida et al., 1997). This uniformity break indicates a possible contribution of allochtonous material in the surface-nearer soil layers (Brinckman, 1979; Cabrera-Martinez et al., 1988), probably by wind action, whose influence could have been extended up to horizon Bt1. Wind action generally causes particle segregation intensifying the transport and deposition of finer particles, which may have contributed to the formation of these differences. It is therefore suggested that past depositional events contributed to the development of these soils, probably from parent material similar to that from the underlying lithology, but with a finer granulometry. Since the uniformity break occurs in the profile zone under the dark horizons, this feature can however not be used as an evidence that they had been buried, suggesting, on the contrary, that the formation of sombric horizons had occurred by pedogenetic processes subsequent to depositional events.

This interpretation is reinforced when the fine clay increase in depth is analyzed based on the fine clay/ coarse clay ratio (Figure 4). Clearly, the ratio increases up to the BA horizon and decreases from there on. The maximum fine clay accumulation does therefore not coincide with the illuvial horizon with maximum total clay accumulation that occurs in Bt2, which suggests probable polygenetic events in this soil formation. Consequently, the sombric horizons seems to have been formed in a time after the textural B horizon formation, indicating that humus could have migrated in association with the fine clay, in a process similar to that proposed by Faivre (1990).

Clay fraction mineralogy

Based on the relative intensities of the diffractogram peaks of the RP clay fraction, the following minerals were identified, in decreasing order: kaolinite > 2:1 clay minerals > quartz ≥ gibbsite, evidencing a very similar mineralogy of the clay fraction in the A1, BA and Bt2 horizons, with an increase of 2:1 clay minerals from the base to the soil surface (Table 3). In the C and CR horizons the kaolinite peaks were larger, with a band formation in C between 10 and 14 Å and in CR a large peak of approximately 10 Å, indicating the possible presence of interstratified mica/ vermiculite (Cradwick & Wilson, 1972, Sawhney, 1989). Second order peaks of these clay minerals can be responsible for the enlargement of the kaolinite-indicating peaks (Aparicio & Galán, 1999). There was a partial collapse only of the 2:1 clay mineral interlayers in the K saturated samples heated to 100 and 300 °C. This behavior, associated to the unaltered peaks in the region 14 Å in the diffractograms of the Mg and glycerol-saturated samples indicates that the 2:1 clay minerals are vermiculites with interlayered hydroxy-Al polymers (Barnhisel & Bertch, 1989).

In the P3 of the toposequence, the minerals found were the same as in the RP, whereas the 2:1 clay mineral proportion was significantly higher (Table 3). As in the RP, no mineralogical differences that could indicate any lithological discontinuities between the dark subsurface horizons and the others were found.

The mineralogical evaluation together with the results of clay and sand fractions indicate that the genesis of dark horizons was more influenced by the action of intern pedogenetic than by extern depositional processes, so the possibility that the dark subsurface horizons are buried A horizons is rather unlikely. The high textural contrast, especially of the RP, along with the strong presence of clay skins in the structural

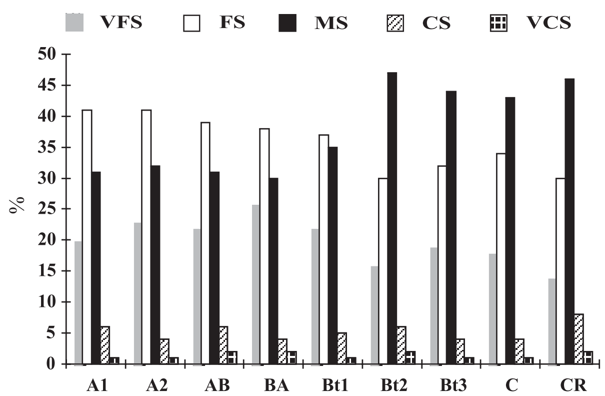

Figure 3. Total sand fractionation from the representative profile of Red Argisols from Içara, Santa Catarina (VFS: very fine sand, FS: fine sand, MS: medium sand, CS: coarse sand, VCS: very coarse sand).

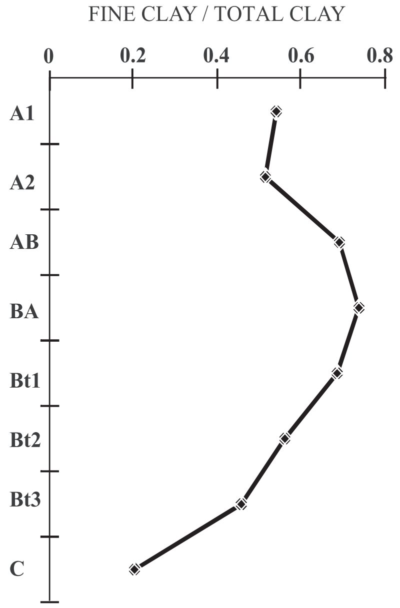

Figure 4. Fine clay/total clay ratio of the horizons of a representative profile of Sombric Red Argisol from Içara, Santa Catarina State, Brazil.

aggregates of the B horizon in all profiles, as well as the increase in the ratio fine clay/total clay with depth, are complementary evidences that reinforce this interpretation.

Iron and aluminum analysis

The Fe_d contents (Table 4) that indicate mainly crystalline forms of Fe oxides/oxydroxides (goethite and hematite, in this case) gradually increase from the A1 to Bt2 horizon, decreasing from there (Figure 5b). This behavior was expected since the Fe_d curve followed the increase of the clay contents in depth. The same trend was found for Al_d (Figure 6b), but not for Fe_o and Al_o; these values increase up to a maximum in the BA horizon and decrease substantially from there (Figures 5a and 6a). The ammonium oxalate solution extracts mainly Fe and Al from low crystallinity forms of Fe and Al compounds (Schwertmann, 1964) also including those linked to organic compounds. The same curve inflexion is observed for Fe_p and Al_p (Figure 7), where the maximum values coincide with the dark subsurface horizons AB and BA. The sodium pyrophosphate solution extracts above all Fe and Al forms strongly complexed with organic matter (USDA, 1996). Therefore, the fact that the Fe_p and Al_p contents are substantially higher than Fe_o and Al_o (Table 4) indicates that the non crystalline Fe and Al forms are mainly associated to organic compounds, opposite to what the Fe_o/Fe_d ratio seems to indicate (Table 4).

The same form of the Al_p and Al_o curve is observed in the solution of $CuCl_2$ (Figure 8) where the maximum Al values also coincide with the dark subsurface horizons. This solution, because of the low pH it causes during extraction and the high complexing power of the Cu ion, extracts mainly non-reactive Al linked to organic matter (Juo & Kamprath, 1979).

The shape of the curves of Al_p, Al_o, Al_{Cu}, Fe_p, and Fe_o indicates an accumulation of these elements in the dark subsurface horizons, although it can not be definitely stated that they were originated from sandier surface horizons, because there is no typical eluvial horizon between the A subhorizons and the dark horizons.

Table 3. Relative areas of peaks from 1:1 and 2:1 clay minerals, gibbsite and quartz obtained from diffractograms of the clay fraction of some horizons from the representative profile (RP) and in the profile P3 of dystrophic Red Argisols from Içara, Santa Catarina State, Brazil

Profile	Horizon	Kaolinite	Vermiculite Interlayered with Hydroxy-Al	Mica (Illite)	Gibbsite	Quartz
RP	A1	79	13	-	3	5
	BA	79	13	2	3	3
	Bt2	83	9	3	2	3
	Cr	85	9	3	2	1
P3	A1	58	33	2	5	2
	AB	60	30	2	5	2
	BA	60	30	2	5	2
	Bt2	70	25	1	3	1

Table 4. Iron and aluminum analysis in soil horizons of the representative profile (RP) determined with dithionite-citrate-bicarbonate (d), ammonium oxalate (o), sodium pyrophosphate (p) and copper chloride ($CuCl_2$)

Profile	Horizon	Fe			Fe_o/Fe_d	Al				(Al + ½ Fe)$_o$
		d	o	p		d	o	p	$CuCl_2$	
		mg kg^{-1}				mg kg^{-1}				%
RP	A1	14100	1119	2034	0.079	2835	1023	1515	323	0.16
	A2	15278	1470	---	0.096	3525	1462	---	390	0.22
	AB	25405	2318	6356	0.091	6757	2806	5102	723	0.40
	BA	32472	3294	8801	0.101	8699	4336	6917	823	0.60
	Bt1	414 94	1981	---	0.048	9878	3310	---	672	0.43
	Bt2	51971	805	2446	0.016	9334	1910	1340	444	0.23
	Bt3	43008	649	---	0.015	6281	1382	---	368	0.17
	C	41363	530	---	0.013	6237	1496	---	--	0.18
	CR	40603	488	---	0.012	7059	2111	---	--	0.24

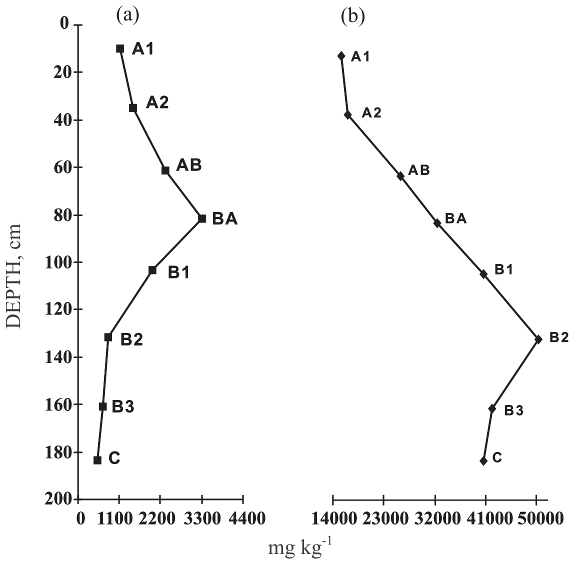

Figure 5. Iron contents extracted with ammonium oxalate (a) and dithionite-citrate-bicarbonate (b) from the representative profile of Red Argisols from Içara, Santa Catarina State, Brazil.

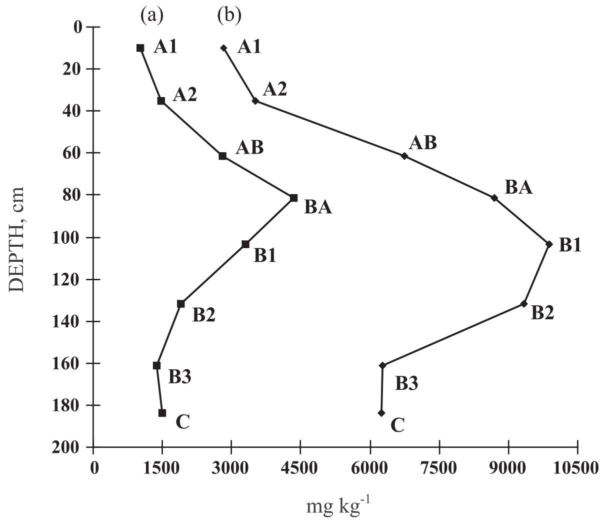

Figure 6. Al extracted with amonium oxalate (a) and with dithionite-citrate-bicarbonate (b) from the representative profile of Red Argisols from Içara, SC.

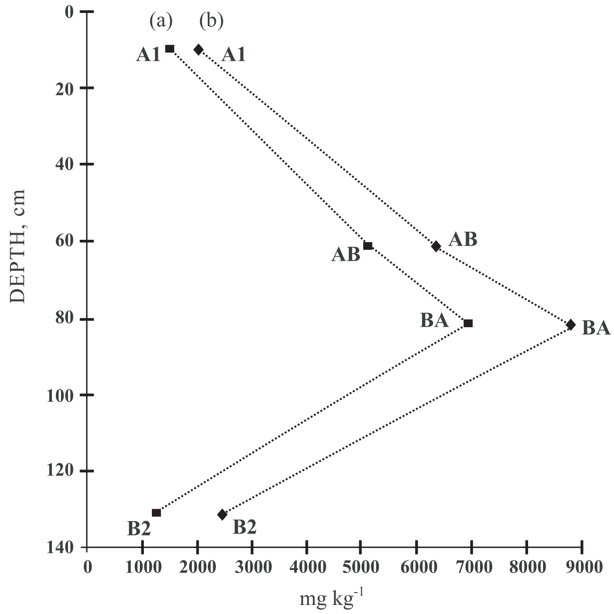

Figure 7. Al (a) and Fe (b) extracted with sodium pyrophosphate from the representative profile of Red Argisols from Içara, SC.

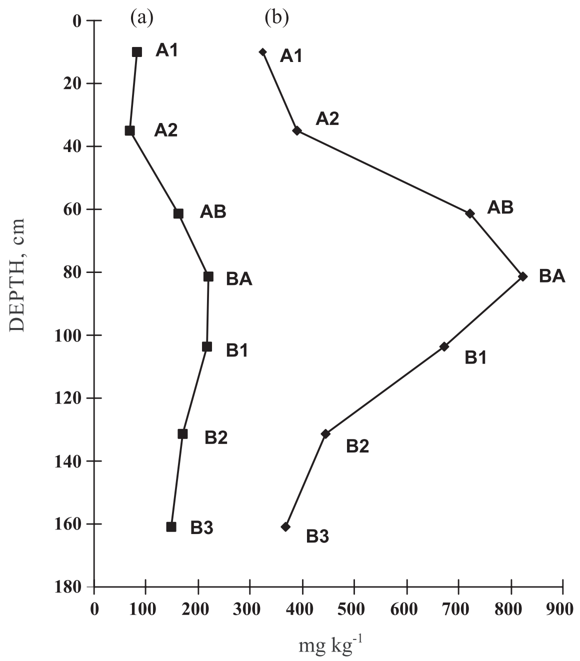

Figure 8. Al extracted with KCl (a) and $CuCl_2$ solutions (b) from the representative profile of Red Argisols from Içara, SC.

One hypothesis is that these elements have migrated in the form of organometallic compounds associated to clay minerals, as indicated by the coincidence of maximum values of these properties with those of the ratio fine clay/total clay in the sombric horizon. Their immobilization in the AB or BA horizons, though, can be caused by gradual saturation of the organic compounds with Fe and Al that favor their stabilization (DeConinck, 1980), and/or due to fine clay flocculation in the transitional horizons.

In this way, the migration mechanisms of organic compounds containing Fe and Al are to some extent similar to podzolization, as suggested by DeConinck (1980) and Lundström et at. (2000), but differ from it especially by the interaction of these compounds with fine clay. These mechanisms seem to be similar to those described by Faivre (1990), for soils in the Andes, which suggest the formation of sombric horizons by migration of clay-humic complexes.

Characteristics that indicate podzolization processes are also given by the increase in depth of Al + ½ Fe percentage extracted with ammonium oxalate. These values increased from 0.16 in the A1 horizon to 0.22 in the A2 and 0.40 in AB and reached a maximum of 0.60 in the BA and gradually decreased to values of about 0.17 in the C horizon (Table 4). Values higher than 0.5 indicate spodic material, according to criteria recently adopted by the Soil Taxonomy (Soil Survey Staff, 2003) and the Brazilian Soil System Classification (Embrapa, 2006).

However, the hypothesis that the dark subsurface horizons constitute a relict feature of a thick surface horizon formed under a grassland vegetation in dryer (and cold) past conditions, according to a hypothesis formulated by Caner et al. (2003) for soils in India, cannot be discarded. The original vegetation (current) of the studied area is a Dense Ombrophile Forest, under which the soil humus generally has a lighter color and the surface horizons are less thick than under grass vegetation. In this way, the current climate could have contributed to the loss of darkening in the surface-near horizons, whereas it was preserved it in the subsurface layers. This hypothesis also requires further studies. In recent studies on the Campos Gerais Plateau in the States of Santa Catarina and Rio Grande do Sul (Behling, 1995; Behling et al., 2004) the existence of a relatively dry period after the Last Glacial Maximum (12 and 20,000 years BP) was inferred which seems to have lasted until 4,000–1,500 years ago, from when on the climate began to become wetter, favoring the forests on the grassland of the Plateau region.

Dark subsurface horizons with sombric- like morphology (Soil Survey Staff, 1999, 2003) are frequent in soils from Southern Brazil. They were observed in soils of the extinct classes of Gray Brown Podzolic (Oliveira et al., 1992; Oenning, 2001), Red Podzolic (Cararo & Almeida, 1996) and, to a lesser extent, in Latosols and Cambisols. So, considering the changes that are being introduced in the Brazilian Soil System Classification (Embrapa, 1999, 2006), the inclusion of the definition of a sombric horizon or character as diagnostic attribute seems to be pertinent in the subdivision of the above classes, at the lower categorical levels of the system. In view, however, of the lack of studies on the mechanisms and processes leading to the sombric horizon formation and the incomplete definition of this horizon by the Soil Taxonomy (Soil Survey Staff, 2003), the proposal of the creation of a "sombric character" seems to be more adequate.

It is therefore tentatively suggested that the sombric character be defined as "horizon or subhorizon coincident with the inferior part of an A horizon, or from any part of a B horizon, where all the following characteristics are found: (a) Absence of a set of characteristics and properties that define a spodic or placic *or* planic diagnostic horizon; (b) Absence of typical features of a buried A horizon, confirmed by the identification of dark subsurface horizon in distinct slope segments, evaluated by lateral tracing; (c) In the dried sample, the colors are darker than of the overlying horizons with values and chroma that are at least one unit lower, while the organic C contents can be higher or not; (d) Absence of a preceding genetic E horizon and; and (e) Minimum thickness of 2.5 cm".

To the authors´ current knowledge, dark subsurface horizons have only been found in Southern Brazil in the orders Argisols, Latosols and Cambisols of the Soil Brazilian System Classification - SiBCS (mainly Ultisols, Oxisols and Inceptisols, in the Soil Taxonomy, respectively), although their occurrence in other orders such as Luvisols is not unlikely. It is therefore suggested that the presence of the sombric character be adopted as a diagnostic attribute in the classification of these soils from the fourth categorical level onwards of the SiBCS. Based thereon, the classification proposed for the studied soils up to the fourth level would be: sombric dystrophic Red Argisols (Argissolos Vermelhos distróficos sômbricos).

FINAL CONSIDERATIONS

1. The hypothesis that the dark subsurface horizons could be buried A horizons was discarded, because these horizons occur in different slope segments, the soil mineralogy in the clay fraction was very similar in the different soil profiles and because the percentages of the sand subfractions up to the horizons below the dark ones were regular.

2. The confirmation of the presence of spodic material, according to criteria of the Soil Taxonomy (Soil Survey Staff, 2003) together with the maximum Al and Fe values extracted with ammonium oxalate, sodium pyrophosphate and copper chloride from the dark subsurface horizons AB and BA indicate that these metals may have been accumulated in the cited horizons by illuviation from the surface-nearer horizons in the form of organometallic compounds, in a processes similar to podzolization. However, the absence of an overlying eluvial E horizon contrasts with this interpretation.

3. The fact that the maximum fine clay accumulation coincided with the dark subsurface horizons AB and BA, and not with the horizons of highest clay accumulation in the representative profile suggests that the organic compounds associated with Al and Fe could have migrated and accumulated in these horizons as clay-humic complexes during events after the textural B horizon development.

4. The morphology and position of the dark subsurface horizons in the studied soils is similar to that of sombric horizons found in other regions of the world. Nevertheless, the results on their genesis were

not conclusive; apart from podzolization and migration/ accumulation of clay-humic complexes, other mechanisms/ processes may be involved in the cited horizon formation.

5. Given the significant occurrence of soils with sombric-like morphology in Southern Brazil, but the lack of reliable criteria that permit a precise definition and differentiation in relation to the spodic horizons, the definition of a "sombric character" in the Brazilian System of Soil Classification (SiBCS) is proposed. We suggest that the studied soils are tentatively classified as Argissolos Vermelhos distróficos sômbricos (sombric dystrophic Red Argisols) by this system, equivalent to the great group Sombriudult in the Soil Taxonomy system.

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