SEÇÃO V - GÊNESE, MORFOLOGIA E CLASSIFICAÇÃO DO SOLO

GENESIS AND CLASSIFICATION OF OXISOLS IN A HIGHLAND TOPOSEQUENCE OF THE UPPER JEQUITUINHONHA VALLEY (MG)(1)

Celmo Aparecido Ferreira(2), Alexandre Christófaro Silva(3), Pablo Vidal Torrado(4) & Welington Willian Rocha(5)

SUMMARY

The Brazilian System of Soil Classification (SiBCS) is a taxonomic system, open and in permanent construction, as new knowledge on Brazilian soils is obtained. The objective of this study was to characterize the chemical, physical, morphological, micro-morphological and mineralogical properties of four pedons of Oxisols in a highland toposequence in the upper Jequitinhonha Valley, emphasizing aspects of their genesis, classification and landscape development. The pedons occupy the following slope positions: summit - Red Oxisol (LV), mid slope (upper third) – Yellow-Red Oxisol (LVA), lower slope (middle third)– Yellow Oxisol (LA) and bottom of the valley (lowest third) - "Gray Oxisol" ("LAC"). These pedons were described and sampled for characterization in chemical and physical routine analyses. The total Fe, Al and Mn contents were determined by sulfuric attack and the Fe, Al and Mn oxides in dithionite-citrate-bicarbonate and oxalate extraction. The mineralogy of silicate clays was identified by X ray diffraction and the Fe oxides were detected by differential X ray diffraction. Total Ti, Ga and Zr contents were determined by X ray fluorescence spectrometry. The "LAC" is gray-colored and contains significant fragments of structure units in the form of a dense paste, characteristic of a gleysoil, in the horizons A and BA. All pedons are very clayey, dystrophic and have low contents of available P and a pH of around 5. The soil color was related to the Fe oxide content, which decreased along the slope. The decrease of crystalline and low- crystalline Fe along the slope confirmed the

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(2) Mestre em Produção Vegetal pela Universidade Federal dos Vales do Jequitinhonha e Mucuri – UFVJM. Rua Jacutinga 783, Padre Eustáquio, CEP 30730-430 Belo Horizonte (MG). E-mail: agrocel_1@yahoo.com.br

(3) Professor do Departamento de Engenharia Florestal, UFVJM. Caixa Postal 38, CEP 39100-000 Diamantina (MG). E-mail: alexandre.christo@ufvjm.edu.br

(4) Professor do Departamento de Solos e Nutrição de Plantas, Escola Superior de Agricultura "Luiz de Queiroz" – ESALQ/USP. Caixa Postal 9, Av. Pádua Dias 11, CEP 13418-900 Piracicaba (SP). E-mail: pablo@carpa.ciagri.usp.br

(5) Professor do Departamento de Agronomia, UFVJM. E-mail: ww.willianr@yahoo.com.br

loss of Fe from the "LAC". Total Si increased along the slope and total Al remained constant. The clay fraction in all pedons was dominated by kaolinite and gibbsite. Hematite and goethite were identified in LV, low-intensity hematite and goethite in LVA, goethite in LA. In the "LAC", no hematite peaks and goethite were detected by differential X ray diffraction. The micro-morphology indicated prevalence of granular microstructure and porosity with complex stacking patterns.. The soil properties in the toposequence converged to a single soil class, the Oxisols, derived from the same source material. The landscape evolution and genesis of Oxisols of the highlands in the upper Jequitinhonha Valley are related to the evolution of the drainage system and the activity of excavating fauna.

Index terms: soil color, iron oxides, soil classification, Pale Oxisol.

RESUMO: *GÊNESE E CLASSIFICAÇÃO DE LATOSSOLOS EM TOPOSSEQUÊNCIA DAS CHAPADAS DO ALTO VALE DO JEQUITINHONHA (MG)*

O Sistema Brasileiro de Classificação de Solos (SiBCS) é um sistema taxonômico, aberto e que se encontra em construção permanente, conforme são obtidos novos conhecimentos sobre solos brasileiros. O objetivo deste trabalho foi efetuar as caracterizações química, física, morfológica, micromorfológica e mineralógica de quatro pedons de Latossolos em topossequência de uma chapada do Alto Vale do Jequitinhonha, enfatizando aspectos de sua gênese, classificação e da evolução da paisagem. Tais pedons ocupam as seguintes posições da vertente: topo – Latossolo Vermelho (LV), terço médio – Latossolo Vermelho-Amarelo (LVA), terço inferior – Latossolo Amarelo (LA) e sopé – Latossolo Amarelo, de cor cinzenta, aqui denominado "Latossolo Acinzentado" ("LAC"). Esses pedons foram descritos e amostrados para caracterização com análises químicas e físicas de rotina. Os teores totais de Fe, Ti, Al, Mn e Si foram determinados pelo método do ataque sulfúrico, e os óxidos de Fe, Al e Mn foram avaliados nos extratos de ditionito-citrato-bicarbonato e oxalato. A mineralogia das argilas silicatadas foi identificada pela difratometria de raios X, e a dos óxidos de Fe, pela difratometria diferencial de raios X. Por espectrometria de fluorescência de raios X, foram determinados os teores totais de Ti, Ga e Zr. O "LAC" apresentou cores acinzentadas e significativos fragmentos de unidades estruturais na forma de uma massa adensada, característica de Gleissolos, nos horizontes A e BA. Todos os pedons são muito argilosos, distróficos, com baixos teores de P disponível e pH em torno de 5. Os óxidos de Fe refletiram a cor dos solos e diminuíram ao longo da vertente. A diminuição dos teores de Fe cristalino e de baixa cristalinidade ao longo da vertente confirmou a perda de Fe do "LAC". O Si total aumentou ao longo da vertente e o Al total permaneceu constante. A fração argila, em todos os pedons, é dominada por caulinita e gibbsita. No LV, foram identificados hematita e goethita; no LVA, hematita com baixa intensidade e goethita; no LA, goethita; e no "LAC" não foram identificados picos de hematita e de goethita no difratograma diferencial de raios X. A micromorfologia mostrou a predominância da microestrutura granular e porosidade do tipo empilhamento complexo. Os atributos dos solos da topossequência convergem para uma única classe de solo, a dos Latossolos, que são provenientes do mesmo material de origem. A evolução da paisagem e a gênese dos Latossolos das chapadas do Alto Vale do Jequitinhonha estão relacionadas com a evolução da rede de drenagem e com a ação da fauna escavadora.

Termos de indexação: cor do solo, óxidos de ferro, classificação de solos, Latossolo Pálido.

INTRODUCTION

The Brazilian System of Soil Classification – SiBCS (Embrapa, 2006) comprises 13 soil orders, one of which are the Oxisols. In Brazil, such soils cover a total surface of about 331,637,200 ha, corresponding to approximately 39 % of the Brazilian territory (Espig et al., 2005). These soils are the most weathered of the Earth surface, and are found predominantly on the summit of plateaus and on slopes, in the region of the Cerrado (savanna-like vegetation in Brazil). They have been described as deep, nutrient-poor, practically without primary minerals (Gomes et al., 2004).

The Oxisols sustain a large fraction of the agricultural, livestock and forestry production in Brazil, since their physical properties are highly suitable for mechanization and large-scale production.

The Oxisols, according to the SiBCS (Embrapa, 2006), are divided in the suborders: Brown Oxisol, Yellow Oxisol, Yellow-Red Oxisol, and Red Oxisol. The criterion used in the differentiation of suborders is the color of the oxic B horizons (Bw) of these soils. The SiBCS is a taxonomic system, open and in permanent construction, as new knowledge on Brazilian soils is obtained.

In some pedological studies the presence of a gray Oxisol was noticed, which was called "Pale Oxisol" (Ker, 1998). In the upper Jequitinhonha valley-MG, Resende et al. (1980) identified extensive areas with Gray Oxisols. Silva et al. (2007) mapped 65,000 ha of land, of which 3,500 ha correspond to a map unit where the "Gray Oxisol – "LAC"" is associated with Yellow Oxisol. In Ceará, Teófilo & Frota (1982) report the occurrence of "Gray Oxisol"; 11,750 ha with this soil were mapped in the state (IPIECE, 2004).

At the Reunião Nacional de Correlação de Solos (RCC, 2005), two pedons were presented (PROFILE VII RCC – 5 MG and PROFILE VII RCC – 12 MG), preliminarily classified as "Pale Oxisol". Since this is not an official terminology of the SiBCS (Embrapa, 2006) and this Oxisol type requires further research, it was suggested, after extensive debate, that Profile VII RCC – 5 MG should be included in the suborder Yellow Oxisol. For Profile VII RCC – 12 MG, the temporary classification "Gray Oxisol" was proposed, as a suggestion of a new suborder in the SiBCS.

Figueiredo et al. (2006) proposed a combined study of the physical, mineralogical, and chemical properties, essential to support interpretations of existing relations between the pedoenvironment and the evolutional process of the soils. In this sense, Almeida et al. (2003) justified the research that contributed to the discussion about the introduction of a new suborder of Brazilian Oxisols, besides establishing a clearer definition of their color ranges.

The objective of this study was to characterize the chemical, physical, morphological, micromorphological, and mineralogical characteristics of the Oxisols in a toposequence of the tablelands soils that occupy most of the agricultural lands in the upper Jequitinhonha Valley-MG, emphasizing aspects of soil genesis, classification and landscape evolution.

MATERIAL AND METHODS

Characterization of the study area

The study area is located in southeastern Brazil, northeastern Minas Gerais State, in Itamarandiba, in the region of the upper Jequitinhonha Valley (between 17 ° 42 ' and 17 ° 43 ' S and 42 ° 47 ' and 42 ° 49 ' W) (Figure 1).

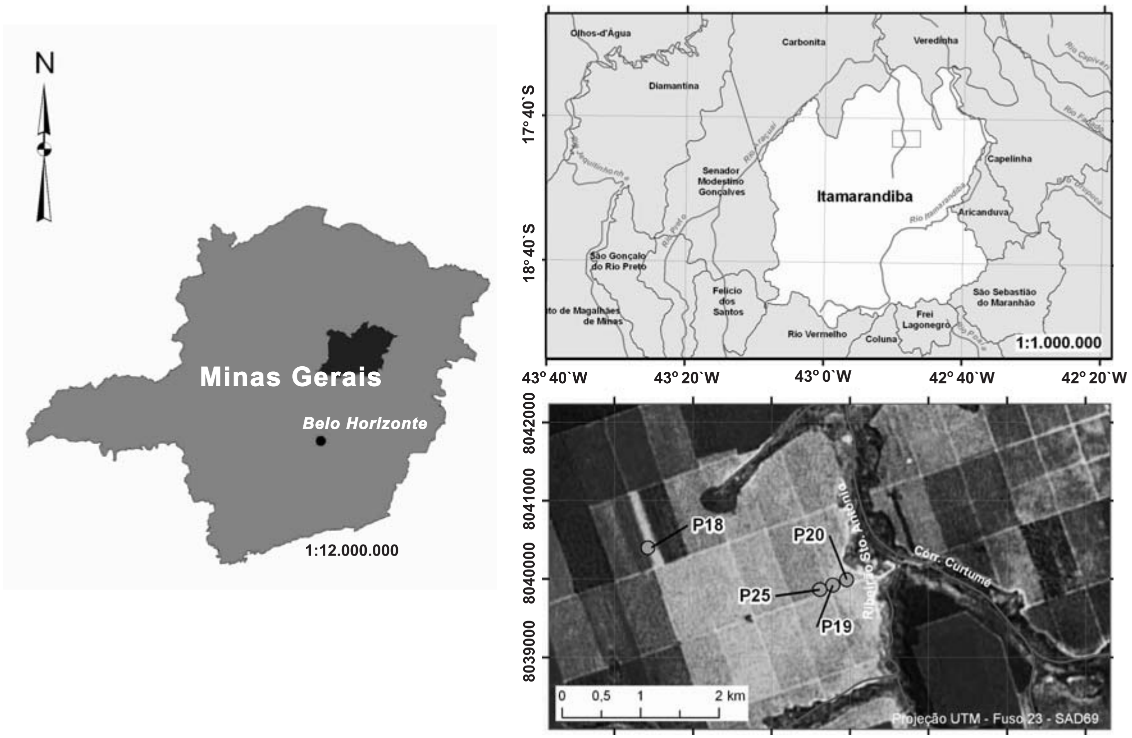


Figure 1. Location of the toposequence, LV (P18), LVA (P25), LA (P19) and "LAC" (P20).

The toposequence under study is part of the geomorphologic unit of the Jequitinhonha Plateau, where plain areas and highlands (average altitude of about 900 m) alternate with dissected areas (Minas Gerais, 1983). The widespread lateritic cover of these highlands makes the exposure of schists of the Macaúbas Group in the study area difficult (Baars et al., 1997).

The regional climate is tropical with a dry winter season, Aw according to Köppen´s climate classification (Baars et al., 1997). The annual average rainfall is 1,170 mm and annual average temperature approximately 21.5 °C, with 24–26 °C in the hottest month (January) and 18–22 in the coldest (July) (Baars et al., 1997). The vegetation consists of savanna formations, with a predominance of Cerrado *Stricto sensu* vegetation (Ribeiro & Walter, 1998). However, extensive reforestation with *Eucalyptus* spp. has replaced large parts of the original Cerrado vegetation on the flattened highland surfaces.

Fieldwork

Four trenches were opened in the toposequence, for a morphologic description of the soils (Santos et al., 2005) and collection of deformed and undisturbed samples in the following slope positions: summit Red Oxisol (LV), mid-slope – Yellow-Red Oxisol (LVA), lower slope – Yellow Oxisol (LA) and bottom of the valley “Gray Oxisol” ("LAC"), with the respective altitudes (970, 915, 900, and 830 asl) and distances to the river (1,175, 895, 700, and 0 m) (Figure 1).

In the described pedons, soil penetration resistance (PR) was determined in the layers 0–10, 10–20 and 20–40 cm, using a portable spring penetrometer. Soil samples with preserved structures were collected, using an Uhland sampler with two rings (height 2 cm, diameter 6 cm). Five rings were collected per pedon and layer.

The basic infiltration rate (BIR) was determined in all pedons, in the layers 0–20 and 20–40 cm, using two infiltrometer rings (Mantovani et al., 2006).

Laboratory work

Chemical analyses

In all horizons and subhorizons of the pedons the pH in water and in KCl, available P, organic matter (M.O.), K^+, Ca^{2+}, Mg^{2+}, Al^{3+} and H + Al were evaluated, according to Embrapa (1997). From the results, the sum of bases (SB), CEC at a pH of 7.0 – (T), effective CEC (t), Al saturation (m), base saturation (V) and delta pH (ΔpH) were calculated.

The contents of Fe_2O_3, Al_2O_3, TiO_2 and MnO were determined after treating the air-dried fine earth (ADFE) with H_2SO_4 1:1 (volume – sulfuric attack). The SiO_2 was extracted from the residue with NaOH, following the method recommended by Embrapa (1997). The poorly crystalline Fe, Al and Mn oxides and hydroxides were extracted by ammonium oxalate at a pH of 3.0 (Camargo et al., 1996). The highly crystalline oxides, hydroxides and oxyhydroxides were extracted by the dithionite-citrate-bicarbonate method (DCB) (Embrapa, 1997). Iron, Al, and Mn in the extracts were determined by atomic absorption spectrometry. By X ray fluorescence spectrometry, using EMMA (Energy Dispersive Miniprobe Multielement Analyzer) the contents of titanium (Ti), gallium (Ga), zirconium (Zr) were determined according to Cheburkin & Shotyc (1996), to verify the similarity of source materials within and among the pedon horizons.

Physical analyses

The granulometry was analyzed using ADFE; the sand fraction by sieving; clay and silt by the pipette method; soil density (Sd) by the volumetric ring method; particle density (Pd) by a pycnometer; and the total pore volume (TPV) was calculated from the relation TPV = (1 – Sd/Pd) x 100 (Embrapa, 1997).

To quantify the granular aggregates and those with structural units in the form of dense mass in the "LAC", 1 kg of soil from each horizon and sub horizon was sampled and the aggregates with structural units in the form of dense mass separated with tweezers. The mass of the separated parts was determined and related to the total mass.

To determine penetration resistance (PR), soil samples with preserved structures were saturated with distilled water for 48 h. The PR tests began after sample saturation and consisted in measuring soil resistance within the ring by the penetrometer and weighing the samples immediately after. This procedure was repeated until the moisture level of the soil sample within the ring did not allow any further PR measurements. The sample was then oven-dried at 105 °C for 24 h. Using the values of the wet and dry soil masses, soil moisture was calculated from the PR values. Based on the data of PR versus moisture, exponential mathematical models were obtained (Nunes et al., 2007).

Mineralogical analysis

The mineralogical composition of the total sand was determined in the Bw horizon of each pedon by counting the grains under a binocular magnifying glass, and permanent slides were prepared in Canada Balsam, analyzed under a petrographic microscope, according to the method proposed by Winchell & Winchell (1959) and utilized for the SiBCS (Embrapa, 2006).

The mineralogical composition of the clay fraction was determined qualitatively by X ray diffraction technique, prepared and treated according to Jackson (1969). The mineralogy of the Fe oxides was evaluated by differential X ray diffraction (DXRD) (Schulze, 1981). The pasty samples were analyzed in an X ray diffractometer with Cu anode (Cu $\kappa\alpha$ 1.54 å) and Ni filter, at a scan rate of 1.2° 2θ min^{-1}, scan range of 3° to 90° 2θ, and acceleration tension and current of 40 kv/ 40 ma.

Micro-morphological analyses

The samples with preserved structure were collected in cardboard boxes and impregnated with crystal resin 1.0#11 R + styrene monomer + dye and catalyst, to obtain thin sections, as described by Castro (1985). These were analyzed under a petrographic microscope, according to instructions of Bullock et al. (1985).

RESULTS AND DISCUSSION

Morphology of Oxisols

According to the current SiBCS (Embrapa, 2006), the pedons were classified along the slope as Red Oxisol (LV) – A prominent, very clayey texture. As Yellow-Red Oxisol (LVA) – A prominent, very clayey texture. As Yellow Oxisol (LA) – A moderate, very clayey texture and as Yellow Oxisol, A moderate, very clayey texture, denominated in this study as “Gray Oxisol” ("LAC").

The wet color (Munsell) of the Bw horizon represents one of the main morphologic properties (Table 1) for the differentiation of the suborders according to the SiBCS (Embrapa, 2006), ranging from 2.5YR 3/4 (dark-reddish-brown) in the LV to 5YR 4/4 (reddish-brown) in LVA, to 7.5YR 5/8 (strong brown) in LA and to 10YR 6/2 (light-gray-brown) in "LAC". The color changes with the slope position, shifting from red (2.5YR) to yellow-red (5YR) on the mid-slope, to Yellow (7.5YR) on the lower slope and to Gray (10YR) at the bottom of the valley. The textures of all pedons are very clayey. The structure of the Bw horizons is predominantly granular. However, in the field, fragments of structural units in the form of a dense mass were verified in "LAC", especially in the A and BA horizons. The consistency is slightly hard to friable and plastic and sticky in all pedons, with the exception of the A and BA horizons of "LAC", which are hard and firm. Porosity is high in all pedons and the transition between the horizons is plain and gradual or diffused, except for "LAC", where the transition is undulated and light or undulated and diffused (Table 1).

The morphology of the "LAC" differed from the others, especially with regard to color, structure, consistency, and transition between the horizons (Table 1). Table 2 shows an estimate of the structure type of "LAC". The surface horizons contains numerous fragments of structural units in the form of a dense mass, while in the Bw horizons the occurrence of such fragments is less common.

The gray color of the "LAC" and the current good drainage allow the inference that the soil had developed under reducing conditions in the past (Resende et al., 2002). The granular structure in the horizons AB, B_{w1} and Bw2 (Table 1) strengthens the hypothesis that as drainage improved, the excavating fauna (especially ants and termites) intensified their activity in this profile, especially in the surface layers, converting the dense forms of structural units into granular aggregates (Schafer, 2001). On the surface layers the action of the soil fauna was less intense, possibly due to lower moisture over the course of the year. The drier the massive structural units, the harder they become (Campos et al., 2003), which hampers the fauna activity. The formation of organic mineral complexes on the surface may also have stabilized the fragments of structural units to form a dense mass (Breemen & Buurman, 2002; Inda Junior et al., 2007).

Physical characterization

The only horizons with Sd > 1 g cm^{-3} were A and BA of "LAC" (Table 3), which can be related to the structure, because they were the only horizon with hematite and goethite in the clay fraction (Figure 3) and presented fragments of structural units in the form of a dense mass of more than 350 g for each 1 kg of soil (Table 2) In a toposequence of Oxisols, Ghidin et al. (2006) observed the formation of a subangular block structure in the lower parts. The Sd values found by these authors confirmed the above results.

The Pd of the toposequence soils ranged from 2.44–2.53 g cm^{-3}, with a mean of 2.47 g cm^{-3}, and was higher in LV and lower in LA and "LAC" (Table 3). The Pd of the Bw horizon of the studied Oxisols correlated linearly and positively (r = 0.93) with the total Fe content obtained by sulfuric attack. These values were consistent with those found in the lithosequence studied by Cunha et al. (2005), where the average Pd value in Oxisols originating from an acid rock was 2.45 and 2.82 g cm^{-3} in the Oxisols derived from basic rock. This difference was attributed to lower quartz and higher Fe compound contents in the soils developed from basic rock.

The TPV of the studied soils was above 60 % in all horizons, with the exception of the A horizon of "LAC" (52 %), due to its greater Sd (Table 3), associated with structural units in the form of a dense mass (Table 2). The average TPV was 64 % (Table 3). This value is representative of a great part of the Oxisols (Marques, 2000) and shows the good drainage conditions of these soils.

The granulometric analysis of the soils showed predominance of the clay fraction (Table 3), resulting in the categorization of all pedons in the very clayey textural class.

The low values of the silt fraction and the silt/clay ratio (Table 3) in all horizons of all pedons of the slope indicated an advanced soil weathering degree, essential for the classification of all pedons as Oxisols (Embrapa, 2006).

The PR of these soils was evaluated by Nunes et al. (2007) in the layers 0–10, 10–20 and 20–40 cm, who observed PR of < 2 MPa in all soils, except in

Table 1. Morphological properties of Oxisols in the toposequence

Pedon	Hz.	Depth(1)	Color(2) Münsel	Tex(3)	Structure(4)	Consistence(5)			Por(6)	Trans(7)	
						D	Hu	W		Top	Sha
		cm									
LV	A	0–28	2.5YR 3/3	VC	0 and Wk, Mo, Li, Me, SB that apart in 0	SH	Fr	P, P	1	Pl	G
	AB	28–41	2.5YR 3/4	VC	0 and a little of Wk and Mo, Li and Me, SB that apart in 0	SH	Fr	P, P	1	Pl	D
	Bw1	41–97	2.5YR 3/4	VC	0	-	VFr	P, P	1	Pl	D
	Bw2	97–150+	2.5YR 3/6	VC	0	-	VFr	P, P	1		
LVA	A	0–31	5YR 3/3	VC	Wk, Li and Me, SB that apart in 0	-	F	P, P	1	Pl	G
	BA	31–49	5YR 4/4	VC	Wk, Li and Me, SB that apart in 0	-	F	VP, P	1	Pl	D
	Bw1	49–115	5YR 4/4	VC	Wk, Li and Me, SB that apart in 0	-	F	VP, P	1	Pl	D
	Bw2	115–150+	5YR 4/4	VC	Wk, Lo and Me, SB that apart in 0	-	F	VP, P	1		
LA	A	0–25	7.5YR 4/4	VC	0 and Wk to Mo, Li and Me, SB that apart in 0	SH	Fr	VP, P	1	Pl	G
	AB	25–39	7.5YR 4/6	VC	0 and Wk to Mo, Li and Me, SB that apart in 0	SH	Fr	VP, P	1	Pl	D
	BA	39–90	7.5YR 5/6	VC	0	-	Fr	VP, P	1	Pl	D
	Bw	90–150+	7.5YR 5/8	VC	0	-	MFr	VP, P	1		
“LAC”	A	0–18	10YR 6/1	VC	Mixed, with Ma and Wk to Mo, Li and Me, AB and SB that apart in 0	H	F	VP, P	1	Un	C
	BA	18–52	10YR 6/2	VC	Mixed, with Ma and 0 and Wk, Li and Me, SB that apart in 0	H	F	VP, P	1	Un	D
	Bw1	52–119	10YR 6/2	VC	0 and Wk, Li and Me, SB that apart in 0	-	Fr	VP, P	1	Un	D
	Bw2	119–150+	10YR 6/2	VC	0 and Wk, Li and Me, SB that apart in 0	-	Fr	VP, P	1		

(1) Depth: horizon depth. (2) Wet color: 2.5YR 3/3, 2.5YR 3/4: Dark-Reddish Brown 2.5YR 3/6: Dark-Red, 5YR 3/3: Brown-Dark-Reddish, 5YR 4/4: Brown-Reddish, 7.5YR 4/4: Brown, 7.5YR 4/6, 7.5YR 5/8: Strong Brown, 10YR 6/1: Gray and 6/2 Brown-Light-Gray. (3) Tex: Texture: Very Clayey. (4) Structure: 0: Strong, Very small and Granular; Degree: Weak (Wk), Moderate (Mo), Class: Small (Sm) and medium (Me); Type: Angular Blocks (AB), Sub-angular Blocks (SB) and Massive (Ma). (5) Consistency: Dry (D): Slightly hard (SH); Moist (Moi): Very Friable (VFr), Friable (Fr), Firm (F); Wet (W): Very plastic (VP), Plastic (P) and Sticky (S). (6) Por: porosity: 1 Many, Small, Medium and Large. (7) Trans: transition between horizons: Topography (Top): Plane (Pl), Undulated (Un) and Sharpness; Clear (Cle): Gradual (G), Diffuse (D) and Light (Li).

Table 2. Characterization of "LAC" profile structure

Pedon	Hz	Depth	Granular structure	Structural units in the form of a dense mass
		cm	g kg^{-1}	
“LAC”	A	0– 18	640	360
	BA	18– 52	580	420
	Bw1	52–119	860	140
	Bw2	119–150+	880	120

"LAC", where values reached 2.55 MPa. This was possibly associated with fragments of structural units in the form of a dense mass in the A and BA horizons of the "LAC" (Table 2), similar to the differences regarding BIR (Table 3).

Chemical characterization

In general, the organic matter content in the pedons was low and decreased with depth and certainly influenced the SB, t, T and Al^{3+} (Table 4). All horizons were classified as dystrophic (Embrapa, 2006).

The Al^{3+} and H contents decreased with depth, parallel to organic matter contents. The formation of an organometallic complex with Al increased the resistance of organic matter decomposition and minimized Al losses (Inda Junior et al., 2007). Similarly, Al saturation (m) was > 46 % in the surface horizons and < 43 % in the sub surface horizons (Table 4). These results agree with data of horizons in a soil sequence reported by Rodrigues & Klamt (1978).

The pH of the soils is acidic, with negative ΔpH in all samples, indicating a net negative charge and the kaolinitic nature (Figure 2) of these pedons (Pötter & Kämpf, 1981; Andrade et al., 1997). The high acidity, low SB and high availability of exchangeable Al are the results of intensive soil leaching (Pötter & Kämpf, 1981).

Table 3. Soil physical properties of the toposequence

Pedon	Hz	Depth(1)	Sd(2)	Pd(3)	TPV(4)	Sand			Silt	Clay	Relation	BIR(5)
						Thick	Thin	Total			Silt/Clay	
		cm	g cm^{-3}		%	g kg^{-1}						mm h^{-1}
LV	A	0–28	0.88	2.44	64	138	50	188	88	725	0.12	192
	AB	28–41	0.89			82	24	106	129	765	0.17	180
	Bw1	41–97	0.84	2.53	67	43	43	86	138	777	0.18	
	Bw2	97–150+	0.86			38	51	89	128	783	0.16	
LVA	A	0–31	0.94	2.44	61	118	29	147	44	809	0.05	188
	BA	31–49	0.93			54	54	108	27	865	0.03	120
	Bw1	49–115	0.95	2.47	62	71	24	95	24	882	0.03	
	Bw2	115–150+	0.78			37	49	86	37	877	0.04	
LA	A	0–25	0.94	2.50	62	149	23	172	23	805	0.03	200
	AB	25–39	0.92			96	21	117	43	840	0.05	150
	BA	39–90	0.85			74	43	117	43	840	0.05	
	Bw	90–150+	0.84	2.44	66	67	48	115	58	827	0.07	
"LAC"	A	0–18	1.21	2.50	52	214	14	228	86	686	0.13	60
	BA	18–52	1.02			102	57	159	46	795	0.06	20
	Bw1	52–119	0.82	2.44	66	95	68	163	95	743	0.13	
	Bw2	119–150+	0.85			95	63	158	42	800	0.05	

(1) Depth.: Horizon depth. (2) Sd: soil density. (3) Pd: Particle density. (4) TPV: Total pore volume. (5) BIR: Basic infiltration rate.

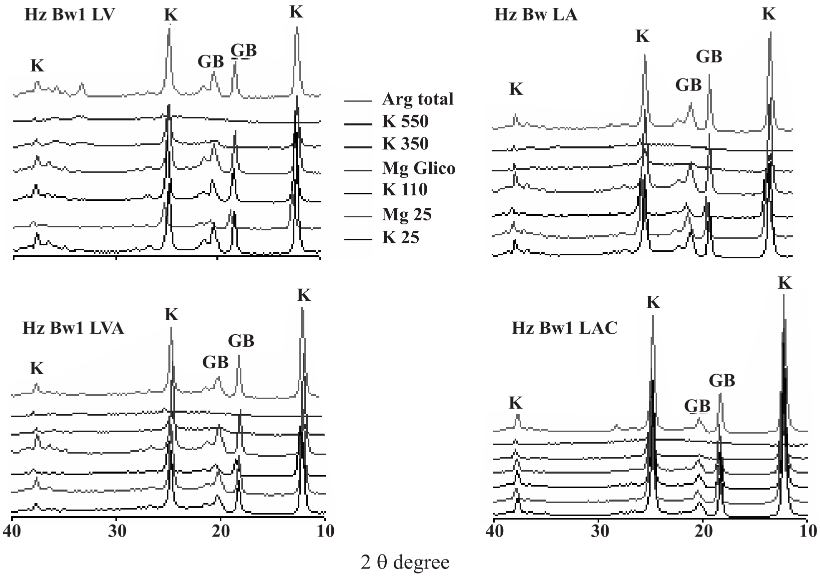


Figure 2. Mineralogy of clay iron-free fraction of the Bw horizons of pedons of the toposequence, where K: kaolinite and GB; gibbsite.

The contents of available P were very low in all soils, which is very common in Oxisols . These low P contents are linked to the low V %, which, aside from representing a characteristics of these soil classes, indicate high weathering and leaching degrees (Curi & Franzmeier, 1984).

The Ki indices of the B horizon of the studied pedons were relatively low (Table 5), ranging from 0.74 to 1.12, making the classification of B horizon as oxic B horizon possible (Ki < 2.2). According to the criteria suggested by SiBCS (Embrapa, 2006), which relate the Ki and Kr indices to the clay mineralogical fraction,

Table 4. Soil chemical properties in the toposequence

Pedon	Hz	OM [(1)]	pH		ΔpH [(2)]	P [(3)]	K	Ca^{2+}	Mg^{2+}	Al^{3+}	H	SB [(3)]	T [(4)]	T [(5)]	M [(6)]	V [(7)]
			H_2O	KCl												
		dag kg^{-1}				— g kg^{-1} —		cmol$_c$ dm^{-3}							%	
LV	A	1.9	4.7	4.0	-0.7	0.7	24.0	0.3	0.2	0.8	5.7	0.6	1.36	7.1	59	8
	AB	1.7	5.3	4.2	-1.1	0.4	15.0	0.3	0.2	0.5	4.2	0.5	1.04	5.2	48	10
	Bw1	0.8	5.5	4.3	-1.2	0.3	9.0	0.4	0.2	0.3	3.4	0.6	0.92	4.3	33	14
	Bw2	0.3	5.4	4.8	-0.6	0.2	11.0	0.2	0.2	0.3	2.4	0.4	0.73	3.1	41	14
LVA	A	2.1	4.2	4.0	-0.2	1.0	7.0	0.3	0.2	1.0	8.1	0.5	1.52	9.6	66	5
	BA	0.4	4.5	4.1	-0.4	0.4	5.0	0.2	0.2	0.4	4.3	0.4	0.81	5.1	49	8
	Bw1	1.0	4.7	4.2	-0.5	0.1	8.0	0.4	0.2	0.4	4.3	0.6	1.02	5.3	39	12
	Bw2	0.1	4.7	4.4	-0.3	0.1	5.0	0.3	0.2	0.2	4.0	0.5	0.71	4.7	28	11
LA	A	0.8	4.8	4.0	-0.8	1.0	6.6	0.5	0.2	0.6	8.4	0.7	1.31	9.7	47	7
	AB	0.9	5.1	4.2	-0.9	0.5	5.0	0.2	0.1	0.5	3.7	0.3	0.81	4.5	62	7
	BA	0.5	5.1	4.2	-0.9	0.3	5.0	0.3	0.1	0.3	3.0	0.4	0.71	3.7	42	11
	Bw	0.1	5.3	4.5	-0.8	0.2	5.0	0.4	0.2	0.2	2.8	0.6	0.81	3.6	25	17
"LAC"	A	0.9	4.7	3.8	-0.9	0.7	32.0	0.5	0.2	1.2	3.5	0.8	1.98	5.5	61	14
	BA	0.3	4.8	4.0	-0.8	0.3	9.0	0.2	0.1	0.7	2.3	0.3	1.02	3.3	68	10
	Bw1	0.1	4.8	4.1	-0.7	0.2	6.0	0.3	0.2	0.3	2.1	0.5	0.82	2.9	37	18
	Bw2	0.1	4.8	4.4	-0.4	0.3	6.0	0.4	0.2	0.3	1.6	0.6	0.92	2.5	33	24

(1) OM: Organic Matter. (2) Δ pH: pH KCl – pH H_2O. (3) SB: Sum of bases. (4) t: Effective CEC. (5) T: CEC at pH 7. (6) m: Al saturation. (7) V: Base saturation.

Table 5. Total oxide contents determined by sulfuric attack, Ki and Kr indices and Fe_2O_3/TiO_2 ratio of the toposequence soils

Pedon	Hz	SiO_2	Al_2O_3	Fe_2O_3	MnO	TiO_2	Ki[(1)]	Kr[(2)]	Fe_2O_3/TiO_2
		g kg^{-1}							
LV	A	172.0	357.8	116.7	≤ 0.1	8.20	0.82	0.67	14.23
	AB	176.0	358.9	118.8	≤ 0.1	8.10	0.83	0.69	14.67
	Bw1	158.0	364.2	119.6	≤ 0.1	8.20	0.74	0.61	14.59
	Bw2	173.0	376.0	120.1	≤ 0.1	8.70	0.78	0.65	13.80
LVA	A	198.0	357.3	56.8	≤ 0.1	7.20	0.94	0.85	7.89
	BA	197.0	363.7	56.7	≤ 0.1	6.80	0.92	0.84	8.34
	Bw1	227.0	373.9	57.0	≤ 0.1	6.90	1.03	0.94	8.26
	Bw2	211.0	371.7	57.6	≤ 0.1	7.00	0.96	0.88	8.23
LA	A	174.0	356.0	49.9	≤ 0.1	8.60	0.83	0.76	5.80
	AB	177.0	365.0	50.2	≤ 0.1	8.20	0.82	0.76	6.12
	BA	191.0	365.3	52.2	≤ 0.1	8.70	0.89	0.81	6.00
	Bw	211.0	373.3	50.9	≤ 0.1	8.50	0.96	0.88	5.99
"LAC"	A	228.0	332.0	13.2	≤ 0.1	7.70	1.17	1.14	1.71
	BA	210.8	349.1	12.5	≤ 0.1	8.20	1.02	1.00	1.52
	Bw1	235.0	356.5	12.3	≤ 0.1	8.30	1.12	1.09	1.48
	Bw2	228.5	361.8	12.7	≤ 0.1	8.50	1.07	1.05	1.49

(1) Ki = [(% SiO_2 x 1.697)/ % Al_2O_3]. (2) Kr = (% SiO_2 x 1.697)/[% Al_2O_3) + (% Fe_2O_3 x 0.64)].

the Bw_1 horizon of the LV on the top was gibbsitic/oxidic, while the other horizons (A, AB and Bw_2) were kaolinitic-oxidic. All horizons of the other pedons were kaolinitic.

Hsu (1989) found that gibbsite formation was favored by Si removal from the higher parts of the landscape, and kaolinite formation in turn forwarded by a higher Si concentration in the lower parts, which would recombine with Al. This finding was confirmed in the toposequence studied. The Al_2O_3 contents varied slightly along the slope and within the studied pedons, but the SiO_2 content tended to increase with depth within all pedons and downhill (Table 5). The recombination of Si compounds with Al compounds favored the neogenesis of kaolinite (Möller & Klamt, 1983). The decrease of Si content from the summit to the lower part of the Oxisol toposequence was verified by Curi &Franzmeier (1984). All pedons underwent strong silica losses, as is typical of ferralitic weathering (Rodrigues & Klamt, 1978; Breemen & Buurman, 2002), but the SiO_2 values were highest in the "LAC", indicating that this profile was in a zone of solute accumulation.

Another hypothesis for the higher SiO_2 contents in "LAC" would be a relative enrichment (Michelon et al., 2004), since Fe loss could have favored a residual concentration of other elements. However, this relative increase was only verified for SiO_2; Al_2O_3, MnO, and TiO_2 which remained approximately constant within and among the pedons. According to Valadares & Camargo (1983), the correlation between Mn and Fe of sulfuric attack is positive, which is not confirmed in this study, since the Mn contents were lower in all pedon, and decreased along the toposequence (Table 5). The differences in soil colors are reflected by Fe_2O_3 contents (Marques et al., 2004). Since the contents of TiO_2 did practically not vary among the pedons, the Fe_2O_3/TiO_2 ratio followed the decrease in Fe oxide levels from the highest to the lowest slope positions. The ratio of Fe_2O_3/TiO_2 has been used to evidence the drainage effects on the coloration of Oxisols, where lower values represent conditions of poor drainage (Oliveira et al., 1991; Alleoni & Camargo, 1994). It is therefore presumed that at some moment in the soil evolution, the drainage would have gradually slowed down from the summit to the foot.

The Mn oxides determined by oxalate and DCB extraction were very low all along the toposequence (Table 6).

The low crystalline and crystalline Fe oxides showed similar trends in the evaluation based on oxalate and DCB extraction, respectively (Table 6). There was evidence of Fe loss by leaching, since the contents of Fe oxides (Table 6) also followed this trend (Gualberto et al., 1987). The degree of Fe oxide crystallinity increased with soil depth and decreased along the toposequence (Table 6), as observed by Demattê et al. (1994) and Andrade et al. (1997). The pedons of LV, LVA and LA were marked by the predominance of crystalline forms, identified by the Fe_o/Fe_d ratio of < 0.07 (Torrent et al., 1980; Gualberto et al., 1987; Melo et al., 2001). In the "LAC", the Fe_o/Fe_d ratio was 0.71 - 0.48, which may be related to the presence of components of low Fe crystallinity (Andrade et al., 1997; Corrêa et al., 2003). In environments under reducing conditions the crystalline Fe oxides in less stable precipitates are dissoluted, as indicated by the Fe_o/Fe_d ratio of 0.5–1 (Schwertmann & Kämpf, 1983). Thus, these oxides become less crystalline and are removed from the soil in the lower toposequence, where conditions are strongly favorable for hydromorphism and the oxide removal.

In this sense, "LAC" would have been affected by more severe hydromorphical conditions that resulted in the removal of Fe oxides, since the transformation of Fe^{3+} to Fe^{2+} and vice versa in this environment

Table 6. Oxide contents based on oxalate and dionite-citrate-bicarbonate (DBC) extraction and their relation to the toposequence soils

Pedon	Hz	Oxalate			DCB			Fe_o/Fe_d [1]	Al_o/Al_d [2]
		MnO	Fe_2O_3	Al_2O_3	MnO	Fe_2O_3	Al_2O_3		
		g kg^{-1}							
	Bw1	0.04	0.33	1.89	0.04	0.70	2.50	0.48	0.75
LV	A	0.06	3.56	5.28	0.14	95.79	21.21	0.04	0.25
	Bw1	0.06	2.38	4.36	0.16	113.26	21.47	0.02	0.20
LVA	A	0.03	2.48	4.02	0.09	35.88	12.42	0.07	0.32
	Bw1	0.06	1.43	4.50	0.09	36.45	14.74	0.04	0.31
LA	A	0.14	1.88	4.76	0.08	33.90	15.00	0.06	0.32
	Bw	0.04	0.88	3.60	0.07	31.23	14.13	0.03	0.25
“LAC”	A	0.05	0.43	2.78	0.07	0.61	3.72	0.71	0.75

(1) Fe_2O_3 determined by oxalate/Fe_2O_3 by DCB. (2) Al_2O_3 determined by oxalate/Al_2O_3 by DCB.

explain this aspect, in terms of Fe. The colors, the presence of fragments from structural units in the form of a dense mass (Table 3), the lower porosity and BIR (Table 4) also evidence that "LAC" was predominantly under reducing conditions.

The behavior of the Al oxides was also similar to the Fe oxides. The Al oxide contents in the two extracts decreased in depth and from the summit to the foot of the slope in the toposequence, while the Al_o/Al_d ratio decreased with depth in the pedons and increased from the highest to the lowest position of the toposequence (Table 6). The highest values of the oxalate/DCB ratio, of Fe as well as Al on the surface, indicate more crystalline forms in the sub-surface layer, which can be related to organic complexes acting on the surface as inhibitor of oxide crystallization (Andrade et al., 1997).

The values of the Al_o/Al_d ratio in the pedons of LV, LVA and LA were consistent with the value of about 0.3 for Oxisols found by Alleoni & Camargo (1994), indicating crystalline Al forms. The higher value of the ratio in "LAC" (0.75) however indicates poorly crystalline forms (Andrade et al., 1997).

The Zr/Ti ratio was used as an indicator of discontinuities due to the rather inert character of Zr and Ti in the weathering process (Cruz, 2006). This relation remains constant in the Oxisol toposequence, in the vertical as well as in the lateral soil development (Table 7).

The similarity of the source material was confirmed by the Ga/Zr ratio, which is regular within and among the pedons (Table 7). Ga and Zr accumulate residually in soils and the Ga/Zr ratio therefore remains constant during the development of soils from materials of similar origin (Marques, 2000).

Mineralogical characterization

In the B horizon of all studied pedons, a strong predominance of quartz was verified in the sand fraction. Tourmaline and staurolite were found in the B horizon of all pedons and Zr was found in all but the B horizon of the "LAC" (Table 8).

Table 7. Trends and ratios of Ti, Ga and Zr in toposequence soils

Pedon	Hz	Ti	Ga	Zr	Zr/Ti	Ga/Zr
		%	— mg kg^{-1} —			
LV	A	2.4	59	465	0.02	0.13
	Bw1	2.8	66	546	0.02	0.12
LVA	A	2.2	66	558	0.03	0.12
	Bw1	2.5	74	620	0.02	0.12
LA	A	2.4	69	631	0.03	0.11
	Bw	2.5	65	614	0.02	0.11
“LAC”	A	2.3	85	763	0.03	0.11
	Bw1	2.0	81	709	0.03	0.11

The quartz content and sand fraction of the B horizon of the studied pedons ranged, respectively, between 96 % ("LAC") and 92 % (LV) of the sand fraction (Table 8) and between 8.6 % (LV) and 16.3 % ("LAC") of the fine earth fraction (Table 3). It can be concluded that all horizons contained less than 4 % of primary changeable minerals and their diagnostic sub-surface horizons can therefore be classified as Bw (Embrapa, 2006).

The phyllosilicate and gibbsite mineralogy of all specimens was similar (Figure 2).

The mineralogy of the Oxisols studied agrees with descriptions of various authors (Resende et al., 1980; Fontes et al., 2001; Kämpf & Curi, 2003; Weber et al., 2005).

Kaolinite is the only phyllosilicate found in quantities that exceed the X ray detection limit, which is approximately 5 %, according to Moore & Reynolds (1997). Kaolinite as well as gibbsite dominate the mineralogy of the studied soils and are highly crystalline.

Fe oxides were identified by DXRD (Schulze, 1981). Thus, based on the diffraction (Figure 3) it can be said that the mineralogy of the Fe oxides along the slope agrees with the pedon color (Table 1), with the

Table 8. Mineralogy of the sand fraction of the Bw horizons of pedons of the toposequence

Pedon	Horizon	Quartz	Opaque minerals nonmagnetic	Other minerals	Other minerals
		g kg^{-1}			
LV	Bw2	920	40	40	Turmaline, zircon, rutile and staurolite.
LVA	Bw2	940	30	30	Turmaline, zircon, epidote, staurolite, anatase and biotite.
LA	Bw	940	30	30	Staurolite, tourmaline, epidote, rutile and zircon.
“LAC”	Bw2	960	10	30	Staurolite, tourmaline and epidote

Fe_2O_3 levels determined by sulfuric attack (Table 5) and with the Fe_2O_3 levels determined by oxalate and DCB extraction (Table 6)

The reflections of the diffractogram of LV indicated hematite (0.252 nm) and goethite (0.245 nm). The red coloration of this soil confirmed the presence of hematite (Torrent et al., 1980; Kämpf & Schwertmann, 1983) and according to Resende (1976) cited in Resende et al. (2002), about 1 % of hematite in the soil can stain soils red. The LVA diffractions indicated a low-intensity peak of hematite in Bw_1 and goethite in the other horizons. In LA, the reflection indicating goethite (0.418 nm) was prevailing and pyrolusite suspected. In "LAC", no Fe oxides were identified, if present at all, while in the B horizons one of the reflections indicating the presence of pyrolusite (0.317 nm) was observed more clearly.

Micromorphological characterization

Numerous Oxisols have a granular structure or microstructure. The micro-morphological details are shown (Figure 4) to emphasize this aspect.

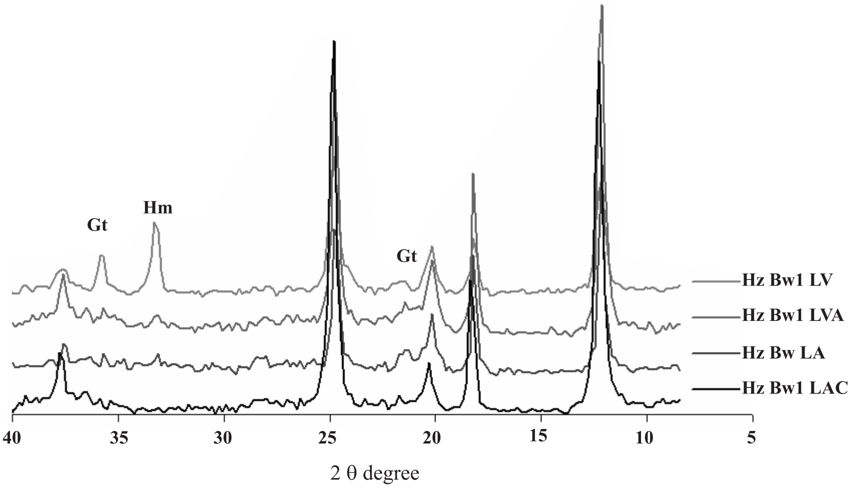
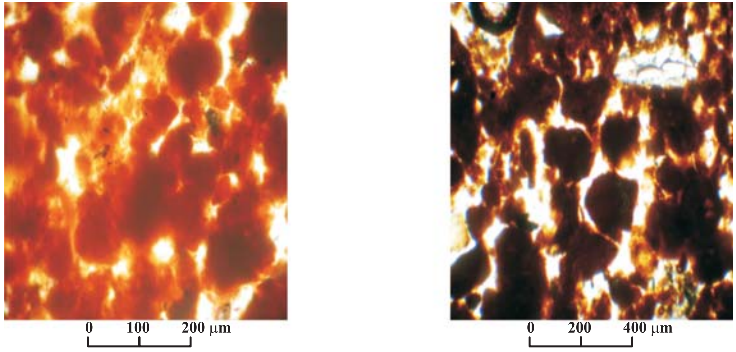


Figure 3. Diffraction obtained by DXRD (total Clay – K25) of the horizon Bw of pedons of the toposequence, where Hm: hematite and Gt: goethite.



(a) LV- Bw2 horizon

(b) LVA - A horizon

(c) LA - A/BA horizon

(d) "LAC" – Bw1 horizon

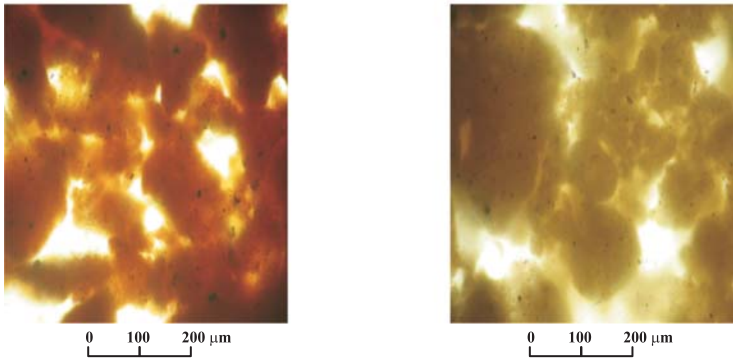


Figure 4. Photomicrographs of the pedons of the toposequence.

In the very clayey Oxisols of the toposequence, granular microstructures (discrete microaggregates) and dense granules (coalesced microaggregates) were predominant (Figure 4), with similar sizes within and among the pedons (0.02–0.7 mm), with a mode of approximately 0.17 mm. The degree varied from moderately to strongly developed, corresponding to an enaulic distribution pattern. The porosity of these soils is dominated by the complex stacking pattern, which was found in this soil class with the presence of channels and sometimes cavities, most likely of biological origin, confirming the intense material movement caused by the fauna of these soils. Similar descriptions of Oxisols were presented elsewhere (Andrade et al., 1997; Gomes et al., 2004).

Relief evolution and genesis of Oxisols

The highlands of the upper Jequitinhonha Valley are separated by dissected areas, formed by ravine slopes. The predominant relief class is slightly undulated and gradually changes to undulated towards the slopes, where a relief rupture clearly defines the area caved by the actual drainage network. Near the watercourses in this area, Plintosols transitioning to Gleysols are found (Ferreira, 2008).

Oxisols occur in highlands, where Red Oxisols predominate in the highest ranges. As the altitude decreases, the Yellow-Red Oxisols come to predominate, close up to the border slopes, where a narrow strip of Yellow Oxisols precedes the band of "Gray Oxisols"; both are found all along the highland border slope. Similar landscapes have been described by Motta et al. (2002). These authors have listed locations of occurrence of various Oxisols with the characteristic environment of Fe-oxide formation (Schwertmann & Taylor, 1989; Kämpf & Curi, 2000) and the varying colors of these soils.

A landscape evolution model of the studied soils was proposed (Figure 5). Underlying the model, knowledge of the area together with geomorphological studies (King, 1953; Saadi, 1995; Motta et al., 2002) played an important role in the elaboration of the model and understanding of the current landscape.

The regional relief would have been carved over a long period in the Low Tertiary on a a largely uniform plain surface (Figure 5a), corresponding to the peneplain resulting from the South American erosion cycle, which in turn is considered the primordial element of the Brazilian landscape. The highlands at an altitude of 800–1,000 m are representative of the relief of the South American Surface (Saadi, 1995). According to the author, these tablelands are covered by a colluvial–alluvial sheet, developed consecutively to the dissection of the tertiary surface. This sheet is probably the source material of the Oxisols of the tablelands.

In the Tertiary, the tableland would have been separated by a drainage network with a low degree of dissection (Figure 5b), with rounded headwater basins, comparable to the current seasonal lakes on the tableland near Minas Novas, in the region of the Upper Jequitinhonha Valley. The Oxisols (Figure 5c) were also found on surface I described by Motta et al. (2002) for soils of the Central Plateau of Brazil, which in turn is related to the South American Surface described by King (1956).

The distribution of different-colored Oxisols appears to reflect significant variations in the groundwater as a result of the installation of the actual drainage system. In the Pleistocene glacial periods, the sea level had oscillated more than 100 m (Leinz & Amaral, 1974). In the colder periods, the level dropped considerably, resulting in a deep incision of the drainage network (Figure 5d) of the Jequitinhonha river, at the regional base level.

The drainage of the soils that occupied the lower and poorly drained areas of the landscape during the Pleistocene improved gradually. However, the gray colors stayed, since practically all Fe^{3+} had been removed during the long period in which reducing conditions had predominated (Schwertmann & Taylor, 1989; Peterschmitt et al., 1996; Kämpf & Curi, 2000).

As drainage improved, the activity of the excavating soil fauna (ants, termites and annelids) was intensified, converting the structural soil units in the form of a dense mass, inherited from ancient depleted soils, into granular aggregates (Table 2, Figure 4). The absence of hematite and goethite in this soil can be evidence that the origin and maintenance of its

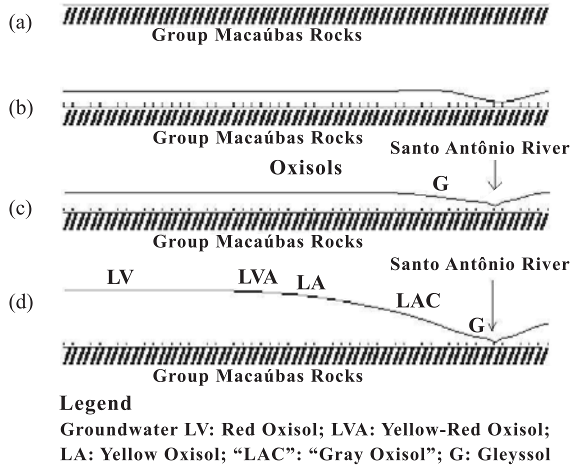


Figure 5. Landscape evolution model of the upper Jequitinhonha valley. (a) Schists of the Macaúbas Group exposed on an erosion surface; (b) Regolith formation and the beginning of the drainage network; (c) Oxisols formation from regolith exposed to the process of soil formation, especially oxide removal and transformation; (d) Deep incision of the drainage network, thickening of regolith and differentiation of Oxisols.

granular structure was the consequence of fauna activity.

Gradually, by biological processes such as the action of fauna and chemical oxidation due to the improvement of the drainage conditions, these Gleysols were transformed into Oxisols. Thus, due to the very clayey texture, friable consistency, high porosity, diffuse transition between horizons, low density, high acidity, dystrophic and kaolinitic character in the B horizon, the "LAC" can be classified as Oxisol.

The granular structure (Table 1) and granular microaggregates with relative enaulic distribution (Figure 4) are evidence of the activity of excavating fauna in "LAC".

The lower Fe_2O_3 contents in these pedons (Tables 5 and 6) and the scarcity of hematite and goethite (Figure 3), expressed by the gray color, showed that this soil had undergone a long period of reducing conditions; these colors persisted, even under the oxidizing conditions found in "LAC" nowadays.

Summing up, the gray colors persisted and the biological and chemical processes gave rise to the “Gray Oxisol”, classified as Yellow Oxisol – LA in the SiBCS (Embrapa, 2006), despite the morphological differences to LA.

CONCLUSIONS

1. The soil properties of the toposequence converged to a single soil class, the Oxisols, which originated from materials of similar origin.

2. The evolution of the landscape and genesis of the Oxisols of the tablelands in the upper Jequitinhonha valley are related to the evolution of the drainage network and the activity of excavating fauna.

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