Ciência e Agrotecnologia 40(4):443-453, Jul/Aug. 2016
http://dx.doi.org/10.1590/1413-70542016404019916

Xanthic- and Rhodic-Acrudoxes under cerrado vegetation: differential internal drainage and covarying micromorphological properties

Latossolos Amarelos e Vermelhos sob vegetação de cerrado: drenagem interna diferencial e atributos micromorfológicos covariantes

Alba Lucia Araujo Skorupa[1], Diego Tassinari[1], Sérgio Henrique Godinho Silva[2],
Giovana Clarice Poggere[1], Yuri Lopes Zinn[1], Nilton Curi[1]*

[1]Universidade Federal de Lavras/UFLA, Departamento de Ciência do Solo/DCS, Lavras, MG, Brasil
[2]Universidade Federal dos Vales do Jequitinhonha e Mucuri/UFVJM, ICA, Campus Unaí, Unaí, MG, Brasil
*Corresponding author: niltcuri@dcs.ufla.br
Received in May 12, 2016 and approved in June 11, 2016

ABSTRACT

Soil internal drainage plays a major role in soil genesis, and it is mostly dependent on topography. However, the existence of sedimentary and meta-sedimentary rock strata with variable dip angle allows for strong differences in internal drainage for identical topographies, which result in a marked differentiation in the properties of overlain soils. This work aimed to investigate the micromorphology of soils formed from different dip angles of rock strata and their relationships to internal drainage, in Minas Gerais, Brazil. Over horizontal strata, a Xanthic Acrudox lacking hematite and with blocky structure has developed. Over strata with 45° dip angle, strong drainage has resulted in intense desilication, forming a Rhodic Acrudox having hematite and with strong fine granular structure. Micromorphological analyses showed that both soils contain relict nodules which are probably being dissolved in the current environment, whereas only the Xanthic Acrudox has nodules in current processes of formation due to slower drainage. The Cr horizon of both soils, but mainly the Xanthic Acrudox, presented a much slower saturated hydraulic conductivity than the respective overlying horizons, which was associated with a pattern of poorly connected fissural pores as seen in thin sections. The Cr horizon of the Rhodic Acrudox showed a matrix impregnated by Mn and Fe oxides in an unusual pattern of microlamination and hypocoatings that appear to be unstable, dissolving in the current, strongly drained environment. The soil color is a reliable indicator of such differential pedogenesis in these conditions.

Index terms: Soil genesis; xanthization; rubefication; plinthite; saprolith.

RESUMO

A drenagem interna desempenha um importante papel na gênese de solos e é principalmente dependente da topografia. Contudo, a existência de estratos de rochas sedimentares e meta-sedimentares com ângulo de inclinação variável permite forte diferença na drenagem interna em locais de topografia semelhante, o que resulta em marcante diferenciação de propriedades dos solos acima. Este trabalho teve como objetivo investigar a micromorfologia do solo com estratos de rochas com diferentes ângulos de inclinação e suas relações com a drenagem interna dos solos, em Minas Gerais, Brasil. Sobre estratos horizontalizados, formou-se um Latossolo Amarelo ácrico típico sem hematita e de fraca estrutura média em blocos subangulares. Sobre estratos com ângulo de inclinação de 45°, a drenagem forte resultou em intensa dessilicatização, formando um Latossolo Vermelho ácrico contendo hematita e de estrutura forte muito pequena granular. As análises micromorfológicas mostraram que ambos os solos contêm nódulos reliquiais que estão provavelmente sendo dissolvidos no ambiente atual, enquanto somente o Latossolo Amarelo possui nódulos em processo de formação, devido à drenagem mais lenta. Os horizontes Cr de ambos os solos, mas principalmente do Latossolo Amarelo, apresentaram condutividade hidráulica saturada muito menor do que os horizontes sobrejacentes, em associação ao padrão de poros fissurais pouco conectados. O horizonte Cr do Latossolo Vermelho apresentou uma matriz impregnada por óxidos de Mn e Fe em padrão microlaminado incomum e hipocoberturas, aparentemente instáveis, dissolvendo-se no ambiente atual excessivamente drenado. A cor do solo é um indicador confiável destes diferentes sistemas pedológicos.

Termos para indexação: Gênese de solos; xantização; rubeificação; plintita; saprolito.

INTRODUCTION

Soils are the result of the interaction of climate, time and organisms on parent materials on a specific topography (Jenny, 1941). In the humid tropics, weathering-leaching processes are generally intense, and thus most soils are deep and composed of resistant minerals, such as quartz, kaolinite and oxides. Although useful, this generalization often fails to explain differences in the proportion between those minerals even in these very old soils (Resende et al., 2011). In this sense, for more detailed studies, micromorphological analyses may contribute to a better understanding of soil genesis and its properties. Gomes et al. (2004)

used soil micromorphology and X-ray diffraction analyses to study the genesis of different Oxisols and Quartzpsamments in the Cerrado biome, in Brazil, located at varying geomorphic surfaces. Lima Neto et al. (2010) evaluated the mechanisms involved in the formation of cohesive horizons of Oxisols and Ultisols in Brazilian Coastal Plains, in the State of Alagoas, applying micromorphological analyses. Ferreira, Fernandes and Curi (1999) studied the formation of structure of Oxisols of the southestern Brazil and, with the support of micromorphology, developed and proposed models to explain the occurrence of blocky and granular structures in Oxisols.

However, there can be specific conditions in which soil genesis and properties can vary despite the same combination of the five classic soil forming factors. The depth of the water table has a strong effect on many soil properties and it can be relatively superficial even in higher parts of the landscape, depending on factors such as impervious layers or slow internal drainage (Jenny, 1941). For instance, in the Campos da Mantiqueira region in southern Minas Gerais, Brazil, Oxisols commonly develop from mica-schists, where topography is flat or gently undulated. However, the morphology and properties of these Oxisols may vary considerably according to the dip angle of the subjacent rock strata or schistose planes, which can vary widely (Ogunsanwo, 1986) and control soil internal drainage (Chagas et al., 1997). When the dip angle is zero, i.e. the strata are horizontal, soils are moderately drained, which favors the formation and stability of goethite, absence of hematite and, thus, a yellower hue. In addition, silica removal is also slower. In contrast, when the dip angle of the strata is pronounced, internal drainage is faster, and, thus, hematite formation and desilication are favored, resulting in redder Oxisols.

In the concept of Simonson (1959), horizon differentiation is determined by the intensity of silica removal and the transformation (hydration) of iron oxides. The above-mentioned conditioned is clearly a case where soil internal drainage, as controlled by strata dip angle, acts as a dependent factor of soil formation. Similar trends for yellow and red soils were compiled for the US southeastern Piedmont (Richardson; Daniels, 1993) and in Northern Minas Gerais (Ferreira et al., 2010), but in both cases soil internal drainage is independent on topography. However, in some cases, different soils with varying internal drainage may be formed under the same topography. Chagas et al. (1997) studied two contrasting Oxisols in Minas Gerais, Brazil, and reported that the orientation of their parent material layers had great influence on genesis and properties of those soils. However, these same authors stated that more detailed studies should be carried in the same region in order to elucidate the genesis of those contrasting Oxisols.

In this sense, this work aimed to investigate how soil micromorphology varies with differential internal drainage of Oxisols under Cerrado vegetation in southern Minas Gerais, Brazil. The tested hypothesis is that internal drainage, not associated with relief, influences properties which are reflected on micromorphological analysis.

MATERIAL AND METHODS

Study region description and sampling

The study area is located in the Campos da Mantiqueira region, in the southern part of the State of Minas Gerais, Brazil (Figure 1a). The area comprises dissected plateaus along the northwestern rims of the Mantiqueira Range. The climate is tropical humid, with mean annual temperature and precipitation of 19.2 °C and 1,435 mm, respectively (Chagas et al., 1997). The native vegetation is typically Cerrado on Oxisols. The rainy season is from November to April, making up about 80% of mean annual precipitation. Potential annual evapotranspiration is 888 mm, with an annual water deficit of 53 mm. The dominant soils are Oxisols on flatlands and gentle slopes, developed from mica-schists of the Andrelândia Group, aged 540-1,000 Myrs (Ribeiro et al., 2003). The dip angle of strata of these rocks varies randomly in the region, alternating between horizontal and inclined orientation.

A series of field trips were conducted in order to assess the combinations of rock strata dip angle and soil color in the landscape, finally selecting one pair of Oxisols of contrasting red and yellow colors. These Oxisols occur associated in upslope, midslope and footslope positions in the landscape (Giarola et al., 1997), being distinguished only in detailed soil maps. The studied soils were classified according to Soil Taxonomy (Soil Survey Staff, 2010) and Brazilian System of Soil Classification (Embrapa, 2013) as Xanthic Acrudox (typic acric Yellow Latosol, in the Brazilian classification), moderately drained, over horizontal strata (zero dip angle), clayey texture, and Munsell color 7.5YR, and Rhodic Acrudox (typic acric Red Latosol), strongly drained, over rock strata with dip angle of approximately 45˚, clayey texture, and Munsell color 2.5YR (Figure 1b and 1c). Both soils were situated at the same midslope position in the landscape, at altitude of 1,000 m. For each soil, a pit was excavated and samples were collected in triplicate from A, B and Cr horizons for saturated hydraulic conductivity and micromorphological analyses. The preservation of the original fabric of rock strata and dip angle in the Cr horizons warrants their classification as saproliths (Wald; Graham; Schoeneberger, 2013).

Analytical Methods

Saturated hydraulic conductivity and particle size distribution analyses

Undisturbed soil samples were collected in triplicate for saturated hydraulic conductivity (Ksat) determination with 8.0 cm height vs. 7.0 cm diameter metal cores vertically inserted in the center of each horizon of both soils (Figure 1c). For the Cr horizon of the Rhodic Acrudox, samples were also collected in triplicate parallel

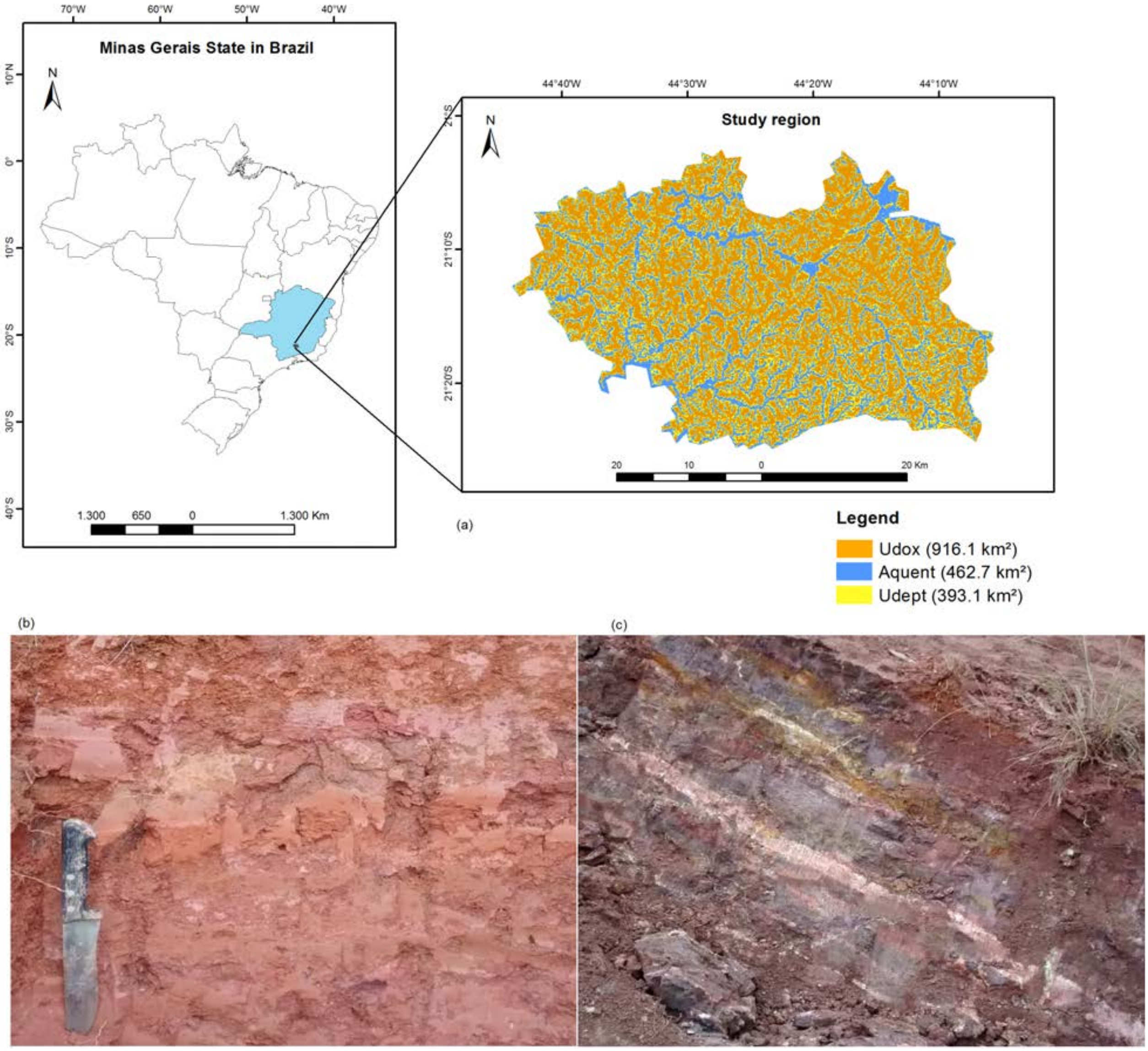

Figure 1: Location (a) and view of Cr horizons of the Xanthic- (b) and Rhodic- (c) Acrudoxes in Minas Gerais, Brazil.

to the orientation of the parent material layers. The constant head permeameter method was used for saturated hydraulic conductivity (Klute; Dirksen, 1986; Lima et al., 1990). Particle size distribution was determined by the pipette method (Gee; Or, 2002) after dispersion with 1.0 mol L^{-1} NaOH and slow shaking.

Micromorphological analyses

Undisturbed samples for soil micromorphology studies were collected from the A, B and Cr horizons with Kubiena boxes and covered with a PVC film. These samples were air-dried for several days and subsequently oven-dried at 40 °C for seven days, 60 ºC for three days and 100 ºC for 24 hours, aiming to reduce cracking due to rapid drying. Afterwards, the samples were impregnated with epoxy resin, and de-aerated under vacuum to prevent air bubbles and to allow full resin penetration for three days. Then, samples were heated at 100 ºC during 4 hours for hardening and subsequently at 140 ºC during 4 hours for curing. The hardened resin blocks were cut vertically in regard to the soil surface, polished and glued onto glass slides (2.7 x 4.6 cm) with de-aerated Hillquist® epoxy resin 7A/3B, and heated for 1 min. at 105 ºC. The mounted slides were cut and polished to a thickness of 30 µm for micromorphological analyses. The thin sections were analyzed under a petrographic microscope equipped with polarized light and described according to Stoops (2003). The presence of Mn oxides was tested by effervescence with H_2O_2 10%, and other opaque materials were examined with reflected light.

Statistical analyses

Statistical analyses for evaluating differences for Ksat among soil horizons of the same soil and between the two soil classes were performed applying the Scott-Knott test, at 5% probability, with the software SISVAR.

RESULTS AND DISCUSSION

Internal drainage of soils

Results for each sampled horizon is presented in Table 1. Interestingly, the Xanthic Acrudox presented a saturated hydraulic conductivity 60-times less in the B horizon (Table 1) than in the A horizon, which in turn had the greatest value among the horizons of this soil. The Cr horizon presented the least value, but without statistical differences from the B horizon, according to Scott-Knott test, at 5% probability. In the Rhodic Acrudox, the B horizon presented the greatest saturated hydraulic conductivity among the soil horizons. Furthermore, comparing this soil property in the same horizon between the two soils, Ksat was significantly greater in the Rhodic Acrudox. This is explained by the small, well-developed granular structure in this soil horizon, favored by higher contents of oxidic clay (Chagas et al., 1997; Ferreira; Fernandes; Curi, 1999). This granular structure results in a large macroporosity of the packing void type (Stoops, 2003), which, by definition, is highly connected and thus favors internal drainage.

Table 1: Saturated hydraulic conductivity of the sampled horizons.

Soil	Horizon	Ksat (mm/h)
Xanthic Acrudox	A	155.8aA
	B	2.6bB
	Cr	0.9bB
Rhodic Acrudox	A	123.0bA
	B	369.9aA
	Cr	2.4cB
	Cr*	7.0cA

*Sampled parallel to the dip angle of this horizon. Lowercase letters compare the horizons of the same soil, whereas uppercase letters compare the same horizon between both soils. The same letters do not differ statistically according to Scott-Knott test, at 5% probability.

The Ksat of samples parallel to dip angle in the Cr horizon of the Rhodic Acrudox was significantly different from both vertical samples of this Cr horizon and to the Cr horizon of the Xanthic Acrudox. It confirms that water is more easily drained in this soil as compared to the Xanthic Acrudox.

Micromorphology of soils

Table 2 summarizes thin section description for the studied soils, whereas Figure 2 shows low magnification (40X) images of the most representative parts of the thin sections. Microstructure in the Xanthic Acrudox varied from granular in the A horizon to subangular blocky in the B horizon, whereas in the Rhodic Acrudox the opposite trend was described. These data agree with saturated hydraulic conductivity values in both soils.

Table 2: Micromorphological description of Xanthic- and Rhodic-Acrudoxes sampled horizons.

Horizon	Xanthic Acrudox	Rhodic Acrudox
A	Well-developed granular microstructure, peds (12.5 to 50 mm dia.); compound packing voids; porosity: 30-40%; random distribution pattern; c/f$_{24\mu m}$ pattern; c/f related distribution: single spaced equal enaulic. Coarse Material: angular and subangular quartz, dominant; mica (25-86 µm, ± 5% of the coarse fraction), opaque grains. Organic material: live, decayed and charred roots (0.92 mm, ±1% of total area). Micromass: yellowish brown, crystallitic micaceous b-fabrics. Pedofeatures: centimetricorthic Fe nodules, highly porous, translucent in XPL.	Weakly separated, well-developed subangular blocky to granular microstructure, accommodating peds (1-2 mm), planar voids, channels and packing voids; porosity: 30-40%; random distribution pattern; c/f: 24 µm pattern; c/f related distribution: open porphyric. Coarse Material: angular and subangular quartz, dominant; rare mica (<20µm, <1% of the coarse fraction). Opaque grains. Organic material: live roots. Red micromass, undifferentiated to crystallitic micaceous b-fabrics. Pedofeatures: few anorthic Fe nodules (170 µm), translucent in XPL.
B	Weakly separated, well-developed subangular blocky microstructure, accommodating peds (50 µm), planar voids, channels and vughs; porosity: 10-20%; random distribution pattern; c/f: 24 µm pattern; c/f related distribution: close porphyric. Coarse Material: angular and subangular quartz, dominant; mica (120 µm, ± 10% of the coarse fraction). Organic material: not observed. Micromass: yellowish brown (goethite), crystallitic micaceous b-fabrics. Pedofeatures: milimetric anorthic Fe nodules, including mica, porous, translucent in XPL.	Well-developed granular microstructure, peds (max. 0.6 mm dia.); compound packing voids; porosity: 30-40%; random distribution pattern; c/f$_{24\mu m}$ pattern; c/f related distribution: open porphyric. Coarse Material: angular and subangular quartz, dominant; rare mica (<1% of the coarse fraction), opaque grains (130 µm, <1%). Organic material: not observed. Red (hematite) micromass, undifferentiated b-fabric. Pedofeatures: milimetric anorthic Fe nodules, of two types: opaque highly porous, and non-porous translucent in XPL, both with weathering rinds.
Cr	Apedal, planar voids highly accommodated suggesting artifact of oven-drying, vughs; porosity: <5%; random distribution pattern; c/f$_{24\mu m}$ pattern; c/f related distribution: close to single spaced porphyric. Coarse Material: subangular quartz, dominant; mica (25-86 µm, ± 5% of the coarse fraction), opaque grains. Organic material: not observed. Micromass: yellowish brown, crystallitic micaceous b-fabrics. Pedofeatures: centimetricorthic Fe nodules, not porous, translucent in XPL.	Apedal, unaccommodated planar voids vughs; porosity: 10-20%; banded distribution pattern; c/f$_{24\mu m}$ pattern; c/f related distribution: close to single spaced porphyric. Coarse Material: angular and subangular quartz, dominant; and mica (100µm). Organic material: not observed. Micromass: yellow and red crystallitic micaceous b-fabrics. Pedofeatures: Possible Mn oxides deposit, Fe oxide hypocoatings in dissolution process.

Coarse material in both soils is chiefly comprised by angular to subangular quartz of similar sizes (Figure 2). The fine material or micromass is yellowish brown in the Xanthic Acrudox, reflecting the absence of clay-sized hematite, which causes the red color of micromass in the A and B horizons of the Rhodic Acrudox. In both soils, the micromass is not striated, except for elongated domains of micas or their alteromorphs (crystallitic micaceous b-fabrics), especially in the Xanthic Acrudox. In the Rhodic Acrudox, the micromass is often undifferentiated, suggesting optical isotropy caused by higher contents of fine-grained gibbsite than laminar kaolinite (Chagas et al., 1997; Stoops, 2003). In both cases, the non-striated micromass suggests that wet-dry cycles have limited or no effects on expansion/contraction of clay domains, which is typical of low-activity clayey soils (Buol et al., 2011).

In the Cr horizon, microstructure in both soils is apedal or massive, although planar voids are present, but probably with limited connectivity. In the Rhodic Acrudox, identification of the micromass is difficult due to its irregular distribution within the silty matrix (Table 1), following a pattern that, to the best of our knowledge, has not yet been described in the literature (Figures 2 and 3). It is also possible that this sparse Fe oxide distribution into a quartz silt matrix is the cause for the contrast between the red color seen by the naked eye (Table 1) and the indistinct colors predominant in the thin section of the Rhodic Acrudox Cr horizon (Figures 2 and 3).

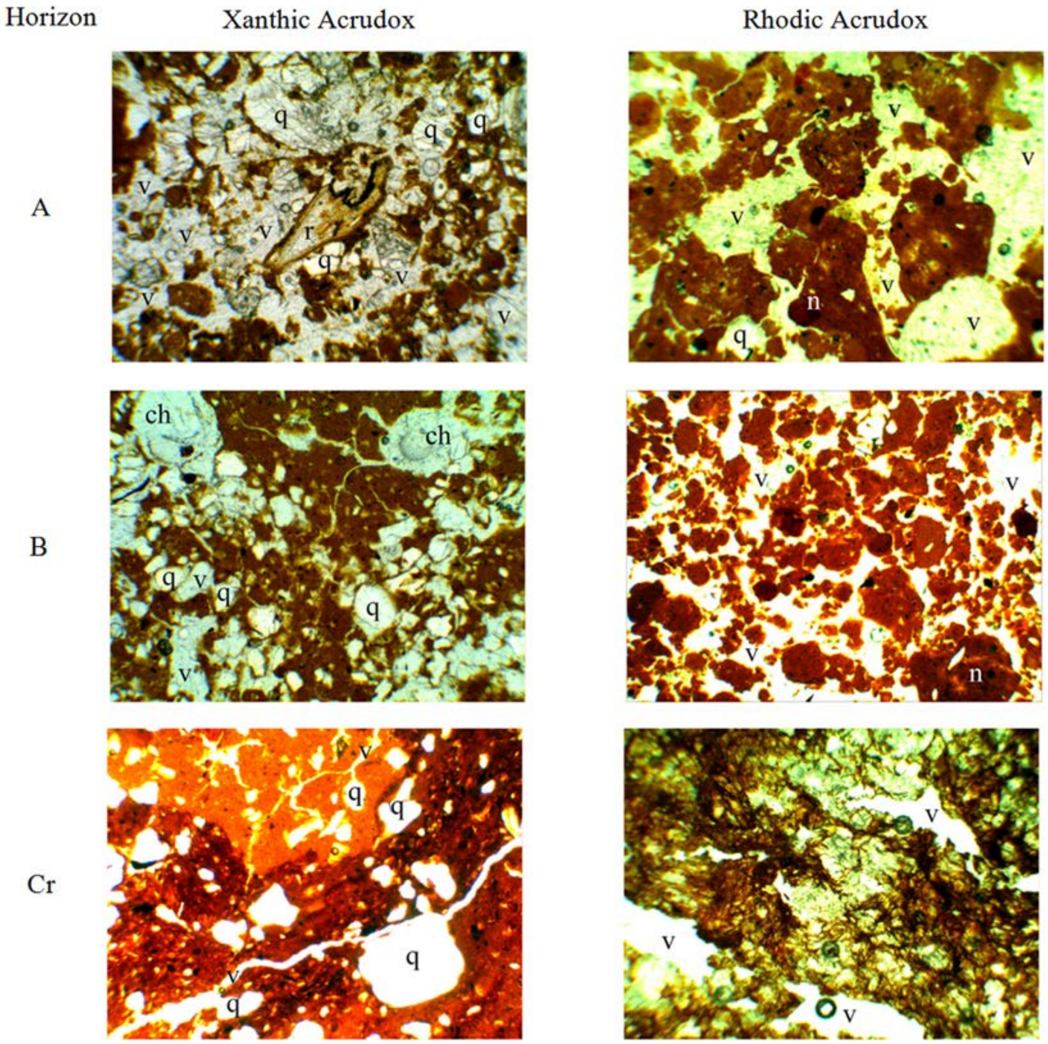

Figure 2: Thin sections of A, B and Cr horizons of the studied Oxisols. Note the massive microstructure of the Cr horizon, contrasting with the granular or blocky pattern of the B horizon. Note also the different b-fabric of the mottle zones in the Cr horizon of the Xanthic Acrudox. Images are 2-3 mm wide. q: quartz; r: root; ch: channel void; v: void; n: nodule.

Both soils presented nodules of Fe oxides as pedological features in the A and B horizons, but with contrasting nature. In the Xanthic Acrudox, nodules are typically larger and, in many cases, including the A horizon, are orthic, i.e. resulting from the current impregnation of the soil matrix by Fe oxides. When nodules in this soil show an internal fabric different from that of the surrounding soil (i.e. anorthic), they contain coarse mica (Figures 4a and 4b). The Rhodic Acrudox presented two types of anorthic nodules, one opaque (Figure 4c) and another of an anisotropic, lightly-colored fabric when in crossed polarizers (Figure 4d), probably due to a siliceous microcrystalline matrix impregnated with crystalline iron oxides (Zinn; Carducci; Araujo, 2015). In the Cr horizon, nodules were not observed in the Rhodic Acrudox (Table 2), whereas in the Xanthic Acrudox nodules are probably plinthite, which was identified during field morphology description (Chagas et al., 1997; Giarola et al., 1997). Plinthite often forms due to iron oxide precipitation under alternating reducing and oxidant conditions originated from the oscillation of a perched water table (Kämpf; Curi, 2000).

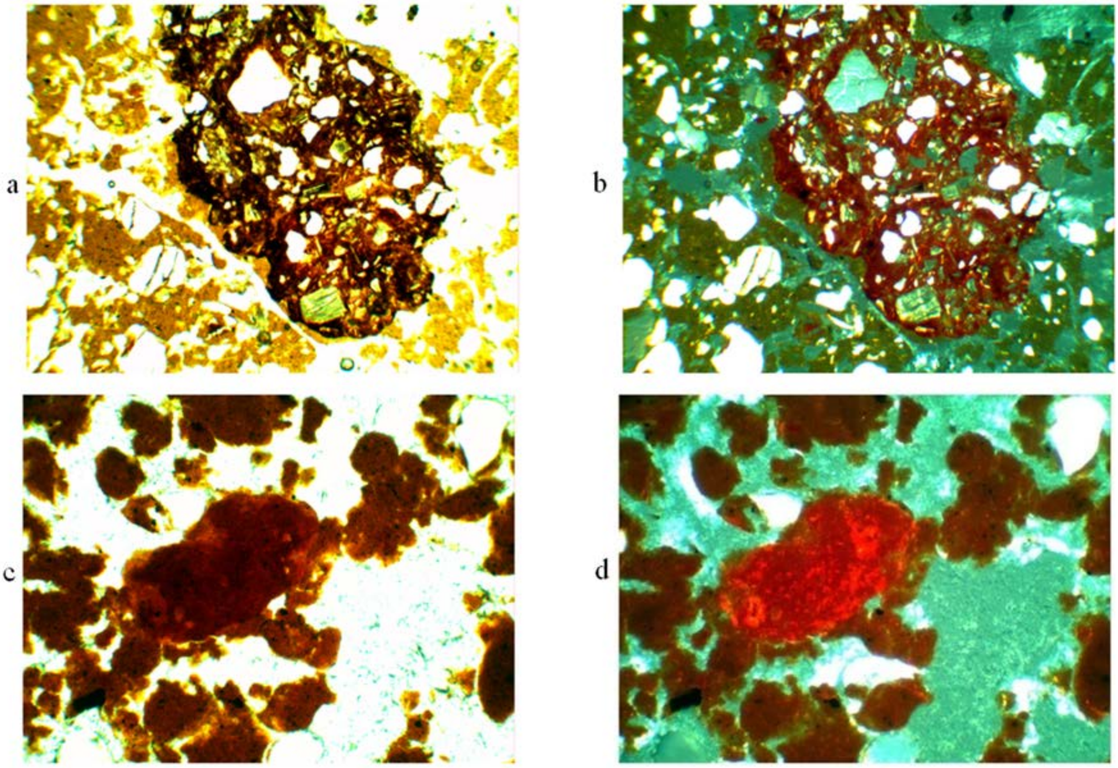

Figure 3: Images of the Cr horizons: a, b) Xanthic Acrudox, showing the contact of yellowish ground mass and red mottle, with biotite grain; c, d) Rhodic Acrudox, showing banded distribution pattern of quartz and the micromass, marked by micaceous domains with differential Fe oxide impregnation. Images are 0.9 mm wide, a and c in plane polarized light, b and d in crossed polarizers to highlight voids.

Internal drainage and micromorphology of soils

There are few studies on the effect of strata dip angle on soil properties, and they typically focus on saproliths, which are composed by soil materials that preserve the original rock structure. For instance, Ogunsanwo (1986) noted that saprolith strength was maximal for horizontal strata, and minimal for vertical strata inclination, with drastic implications for building purposes. In the present work, the Cr horizons can be considered as saproliths, which were more studied due to their geotechnical aspects than on Pedology and especially Micromorphology purposes (Nascimento et al., 2013; Pedron et al., 2015).

Soil thin sections were very useful in explaining hydropedological properties of the soils. In both soils, the low macroporosity and saturated hydraulic conductivity were associated with the predominance of planar voids (Figures 2 and 3) and vughs of limited connectivity. Such features suggest that the Cr horizon in the Xanthic Acrudox can act more as bedrock than as a porous aquifer, promoting considerable lateral flow of groundwater on the B/C horizon boundary, as proposed by McKay et al. (2005). This idea is supported by the current plinthite in the Cr horizon of the Xanthic Acrudox (Figures 2, 3a and 3b), suggesting that water saturating the Cr horizon is less oxygenated. This process is not as apparent in the Rhodic Acrudox, probably due to the pronounced dip angle and fractures parallel to the strata (McKay et al., 2005). The Cr horizon of this soil presented a groundmass largely composed by silt (Table 2), difficult to visualize due to the Holmes effect (Stoops, 2003), and indicative of textural differentiation among the metapellitic strata (Figure 1c). Silicate clays and oxides appear to have intruded this silty matrix via preferential flow along planar voids (fissures), forming coatings on the pore surface and beneath it (hypocoating, see Figure 5b in the following section), and even between cleavages of micas (Figures 3c and 3d).

The degree of silica removal can be also evidenced in soil thin sections. The less desilicated, moderately drained Xanthic Acrudox presents not only a blocky structure but also coarse mica and a limpid, birrefringent micromass. Even the impregnation of Fe oxides generating nodules in the A and B horizons preserves the optical anisotropy of the groundmass, caused by a dominant face-to-face arrangement of kaolinitic clay domains (Figures 4a and 4b). In contrast, the strongly drained, highly desilicated Rhodic Acrudox shows fine granular microstructure and undifferentiated b-fabrics of the micromass, typical of optical isotropy influenced by higher contents of fine-grained gibbsite and Fe oxides. Coarse and fine micas are less frequent in the Rhodic Acrudox, suggesting their instability in a highly weathering and Si-leaching environment. Also, quartz morphology supports the idea that parent material is the same, varying only in the dip angle.

Soil color differentiation processes

Lucas and Chauvel (1992) proposed that pedogenetic processes depend on factors external to the soil (climate, parent material and time), but also internal factors such as topography, organisms and profile hydrodynamics, which co-evolve with time. In the present work, internal drainage is controlled by the spatial arrangement of the same parent material, with no effect of topography, and with marked consequences on soil properties. It is well known that red hues in soils, such as in the Rhodic Acrudox studied here, are due to clay-sized hematite, which forms in environments with lesser water activity (Schwertmann, 1993). Conversely, goethite forms in a wider range of conditions and is stable in moister environments where hematite is unstable or absent, resulting in yellow colors, as in the Xanthic Acrudox studied here. However, Fe oxide concentration is also relevant to soil color. Both soils in the present work showed similar Fe_2O_3 contents of ca. 15% (Chagas et al., 1997), a value that is more commonly associated with red colors, which was not the case for the Xanthic Acrudox.

The former Brazilian Soil Classification recognized Fe-rich yellow Oxisols as Latosol Una, which contrasted

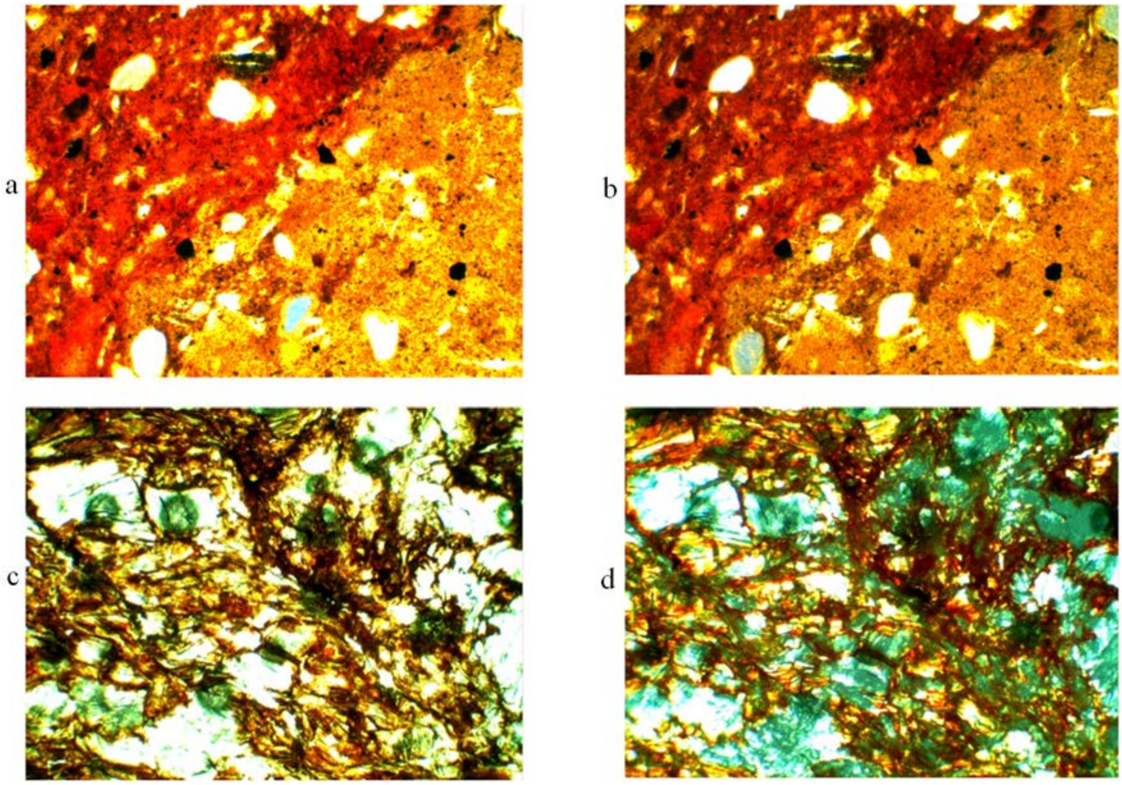

Figure 4: Images of the B horizon: a, b) Xanthic Acrudox, showing the difference of b-fabrics of a nodule (center) and the soil matrix; c, d) Rhodic Acrudox, showing a weathering nodule between granular peds. Images are 0.9 mm wide, a and c in plane polarized light, b and d in partly crossed polarizers to highlight voids.

with typical Yellow Latosols with low Fe contents (Chagas et al., 1997) that were generally associated with Fe-poor parent materials, such as in Coastal Plains and Amazonian regions, a distinction that was not included in the current classification (Embrapa, 2013). In the present case, the xanthization process was effective upon a soil material with ca. 15% Fe_2O_3, which was residually concentrated as silica and bases were leached by the latolization processes. As most of this Fe was part of biotite and magnetite in the schist, their weathering resulted in goethite as a final product, due to a internal drainage limited by horizontal rock strata acting as a slowly pervious layer, inhibiting hematite formation. Where strata dip angle was pronounced (45 °), faster drainage has favored hematite (rubefication) and strong Si leaching. Similar cases of xanthization were reported for Fe-rich mafic rocks even under ustic soil moisture regimes. In a toposequence of Oxisols developed from basalt in the Central Plateau of Brazil, B horizon hues changed from 2.5YR in upper slopes to 10YR in lower slopes, where hematite was absent, a case in which moister conditions resulted from topography (Curi; Franzmeier, 1984).

Part of the Fe oxides in both soils is comprised within the fabric of nodules of sand and coarser particle sizes, which have a less clear role in the overall soil color. This color effect is due to the type of oxide minerals present in the nodules, their crystal size (Schwertmann, 1993) and the current stage of nodule formation or destruction. In the Xanthic Acrudox, many nodules were described as orthic, i.e. currently in formation, since their internal fabric matches that of the surrounding soil (Stoops, 2003), which is consistent with a moderate internal drainage (Table 2). However, this soil also presents nodules described as anorthic, i.e. generated earlier within a different soil environment, which is indicated by an internal fabric presenting a greater content of micas than the soil matrix (Figures 4a and 4b). Such nodules are probably unstable as the current environment is moister, and can represent part of the lithic or saprolithic relics (Lucas and Chauvel, 1992) preserved by Fe oxide impregnation.

In the Rhodic Acrudox, orthic nodules were not observed and both anorthic translucent and opaque types appear to be unstable. The translucent fabric of the first type (Figures 4c and 4d) probably reflects a siliceous microcrystalline matrix impregnated with iron oxides, currently weathering into soil material, as interpreted by Zinn, Carducci and Araujo (2015). Duarte et al. (2000) reported similarly translucent hematitic nodules in process of hydration into goethite, promoting xanthization in A and B horizons under humid climate in soils of Coastal Plains, in Brazil. The opaque nodules show weathering rinds and their fragments are incorporated within the soil peds (Figure 5a). In addition, the multiple pores within these nodules were probably due to dissolution as their outlines are irregular in shape and fabric, contrasting with the linear outlines of stable Fe nodules found by Zinn and Bigham (2016) in the Brazilian Cerrado biome. Since this soil is strongly drained, these nodules are unstable probably because of fast, intense gravitational water flow rather than the action of anoxic pore water. In both soils, the presence of anorthic nodules can be interpreted as direct evidence of polygenesis, since nodules formed and were stable in past soil environments are being dissolved under current conditions.

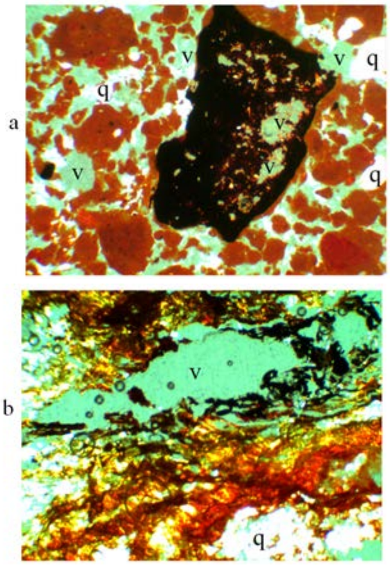

Figure 5: Dissolution of pedological features in Rhodic Acrudox: a) porous, opaque hematite nodule (Mn absent) in B horizon; b) planar void (fissure), where Mn and Fe oxides were deposited in Cr horizon. The Mn coating is currently dismantling, and the subjacent silty matrix shows hydration of the hematite hypocoating into goethite. Images are 0.9 mm wide; q: quartz; v: void.

Other evidence of the dissolving action of percolating water is observed in the Cr horizon of the Rhodic Acrudox, where nodules were not observed, but preferential water and air flows around fissures has resulted in deposition of Fe- and Mn-coatings (Figure 5b). Coatings of Fe- and Mn-oxides are known to form around fissures and pores of preferential flow in saproliths of layered sedimentary rocks (McKay et al., 2005). In the present work, the Mn coatings are currently being dissolved, probably due to a moister condition in that zone, considering that Mn is first reduced and later oxidized in comparison with Fe. Accordingly, the Fe coatings immediately below the Mn coatings are yellow, suggesting hydration of the hematite hypocoatings that impregnated the matrix (Table 2). Conversely, nodules in the Xanthic Acrudox show few or no dissolution features in the B and Cr horizons, suggesting their current formation and stability, consistent with their description as orthic, formed in place. These interpretations corroborate Kubiena (1964), who wisely stated that micromorphological studies add form to the substance determined from other types of analyses.

CONCLUSIONS

The studied Xanthic- and Rhodic-Acrudoxes had contrasting saturated hydraulic conductivity and color, due to the presence of hematite in the red soil. In addition, differences in composition of coarse and fine particles, including pedological features such as Fe nodules were detected using soil micromorphology. Thus, the hypothesis proposed was accepted, suggesting that internal drainage, independently from topography, influences properties which were reflected on soil micromorphology. The soil and nodule colors in thin sections effectively express the different pedogenic processes predominant in each soil environment.

ACKNOWLEDGMENTS

The authors thank the Brazilian funding agencies Fapemig, Capes and CNPq for financial support and scholarships that made this work possible. Thanks are due to the Capes/Fapemig PACCSS for the post-doctoral grant to the first author.

REFERENCES

BUOL, S. W. et al. **Soil genesis and classification**. New York: John Wiley and Sons, 2011. 543p.

CHAGAS, C. S. et al. Orientação das camadas de rochas metapelíticas pobres na gênese de Latossolos sob Cerrado. **Pesquisa Agropecuária Brasileira.** 32(5):539-548, 1997.

CURI, N.; FRANZMEIER, D. P. Toposequence of Oxisols from the Central Plateau of Brazil. **Soil Science Society of America Journal.** 48:341-346, 1984.

DUARTE, M. N. et al. Mineralogia, química e micromorfologia de solos de uma microbacia nos tabuleiros costeiros do Espírito Santo. **Pesquisa Agropecuária Brasileira**. 35(6):1237-1250, 2000.

EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA-EMBRAPA. **Sistema Brasileiro de Classificação de Solos**. Brasília: Embrapa, 2013. 353p.

FERREIRA, M. M.; FERNANDES, B.; CURI, N. Mineralogia da fração argila e estrutura de Latossolos da região sudeste do Brasil. **Revista Brasileira de Ciência do Solo**. 23(1):507-514, 1999.

FERREIRA, C. A. et al. Genesis and classification of Oxisols in a highland toposequence of the upper Jequitinhonha Valley (MG). **Revista Brasileira de Ciência do Solo**. 34(1):195-209, 2010.

GEE, G. W.; OR, D. Particle-size analysis. In: DANE, J. H.; TOPP, G.C. (eds.) **Methods of soil analysis part 4: physical methods**. Madison: American Society of Agronomy, 2002. p.255-293.

GIAROLA, M. F. B. et al. **Solos da região sob influência do reservatório da hidrelétrica de Itutinga/Camargos (MG): perspectiva ambiental**. Belo Horizonte: CEMIG, 1997. 101p.

GOMES, J. B. V. et al. Mineralogia, morfologia e análise microscópica de solos do bioma cerrado. **Revista Brasileira de Ciência do Solo**. 25:679-694, 2004.

JENNY, H. **Factors of soil formation – a system of quantitative pedology**. New York: Dover unabridged edition, 1941. 281p.

KÄMPF, N.; CURI, N. Óxidos de ferro: Indicadores de atributos e ambientes pedogênicos e geoquímicos. In: NOVAIS, R. F.; ALVAREZ, V. H.; SCHAEFER, C. E. G. R. (eds.). **Tópicos em ciência do solo**. Viçosa: Sociedade Brasileira de Ciência do Solo, 2000. p.107-138.

KLUTE, A.; DIRKSEN, C. Hydraulic conductivity and diffusivity: laboratory methods. In: KLUTE, A. (ed.). **Methods of soil analysis part 1: physical and mineralogical methods**. Madison: American Society of Agronomy, 1986. p.687-734.

KUBIENA, W. L. The role and mission of micromorphology and microscopic biology in modern soil science. **Soil micromorphology**. In: JONGERIUS, A. (eds.). New York: Elsevier, 1964, p.1-13.

LIMA, J. M. et al. Dispersão do material de solo em água para avaliação indireta da erodibilidade de Latossolos. **Revista Brasileira de Ciência do Solo**. 14:85-90, 1990.

LIMA NETO, J. A. et al. Atributos químicos, mineralógicos e micromorfológicos de horizontes coesos de Latossolos e Argissolos dos Tabuleiros Costeiros do Estado de Alagoas. **Revista Brasileira de Ciência do Solo**. 34:473-486, 2010.

LUCAS, Y.; CHAUVEL, A. Soil formation in tropically weathered terrains. In: BUTT, C. R. M.; ZEEGERS, H. **Handbook of exploration geochemistry**, v. 4: Regolith exploration geochemistry in tropical and subtropical terrains. Amsterdam: Elsevier, 1992. p. 57-77.

MCKAY, L. D. et al. Hydrogeology and pedology of saprolith formed from sedimentary rock, eastern Tennessee, USA. **Geoderma**. 126:27–45, 2005.

NASCIMENTO, A. F. et al. Genesis of textural contrasts in subsurface soil horizons in the Northern Pantanal-Brazil. **Revista Brasileira de Ciência do Solo**. 37:1113-1127, 2013.

OGUNSANWO, O. Influence of angle of inclination of schistosity planes on the geotechnical properties of a schist saprolith. **Engineering Geology**. 23:137-143, 1986.

PEDRON, F. A. et al. Boundary between soil and saprolite in Alisols in the South of Brazil. **Revista Brasileira de Ciência do Solo**. 39:643-653, 2015.

RESENDE, M. et al. **Mineralogia de solos brasileiros: interpretação e aplicações**. 2nd ed. Lavras: Editora UFLA, 2011. 206p.

RIBEIRO, A. et al. **Mapa geológico - Folha Lavras SF 23-X-C-I**. escala 1:100.000. Belo Horizonte, Codemig, 2003. Available in: <http://www.codemig.com.br/site/content/parcerias/levantamento_aerogeofisico.asp?id=30&idSubPrj=50&filhoId=54>. Accessed in: November 1st, 2015.

RICHARDSON, J. L.; DANIELS, R. B. Stratigraphic and hydraulic influences on soil color development. In: BIGHAM, J.M.; CIOLKOSZ, E. J. **Soil Color**. Madison: SSSA, 1993. p.109-125.

SCHWERTMANN, U. Relations between iron oxides, soil color, and soil formation. In: BIGHAM, J. M; CIOLKOSZ, E. J. **Soil Color**. Madison: SSSA, 1993. p.51-69.

SIMONSON, R. W. Outline of a generalized theory of soil genesis. **Soil Science Society of America Proceedings.** 23:152-156, 1959.

SOIL SURVEY STAFF. **Keys to Soil Taxonomy**. Washington: USDA/NRCS, 2010. 346p.

STOOPS, G. **Guidelines for analysis and description of soil and regolith thin sections**. Madison: SSSA, 2003. 184p.

WALD, J. A.; GRAHAM, R. C.; SCHOENEBERGER, P. J. Distribution and properties of soft weathered bedrock at <1 m depth in the contiguous United States. **Earth Surface Processes and Landforms**. 38(6):614-626, 2013.

ZINN, Y. L.; CARDUCCI, C. E.; ARAUJO, M. A. Internal structure of a vermicular ironstone as determined by x-ray computed tomography scanning. **Revista Brasileira de Ciência do Solo**. 39(2):345-349, 2015.

ZINN, Y. L.; BIGHAM, J. M. Pedogenic and lithogenic gravels as indicators of soil polygenesis in the Brazilian Cerrado. **Soil Research**. 54(4), 2016. Available in: <http://www.publish.csiro.au/paper/SR15142.htm>. Access in: June 9, 2016.