Mercator - Revista de Geografia da UFC
ISSN: 1984-2201
edantas@ufc.br
Universidade Federal do Ceará
Brasil

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MAGALHÃES, Vanderlei Leopold; CUNHA, José Edézio; NÓBREGA, Maria Teresa
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Mercator - Revista de Geografia da UFC, vol. 16, no. 9, 2017
Universidade Federal do Ceará, Brasil
Available in: https://www.redalyc.org/articulo.oa?id=273652707003

PHYSICAL-HYDRIC DYNAMICS OF A PEDOLOGICAL LATOSOL-NITOSOL SYSTEM

Vanderlei Leopold MAGALHÃES
Federal Technological University of Paraná (UTFPR), Brasil
vlmagalhaes@utfpr.edu.br

José Edézio CUNHA
State University of West Paraná (UNIOESTE), Brasil

Maria Teresa NÓBREGA
State University of Maringá (UEM)., Brasil

Redalyc: https://www.redalyc.org/articulo.oa?id=273652707003

Received: 20 June 2017
Accepted: 04 September 2017
Published: 15 September 2017

ABSTRACT:

In order to comprehend the hydric dynamics of soils along the slopes, the research took place on a slope from Marechal Cândido Rondon, Paraná. Trenches were open to the macromorphological description, sample collection for physical, chemical and micromorphological analysis and quantification of hydraulic conductivity. In the top sector, Eutroferric Red Latosol was identified, and from the middle sector, the latosolic Distroferric Red Nitosol predominates. In micromorphological terms, the Ap and Bw horizons have presented two distinct types of arrangements: a continuous and/or discontinuous porphyric fabric with cavities and planar pores and other with enaulic fabric, with high connectivity - compound packing porosity. In the AB and nitic B horizons the enaulic fabric is less representative, prevailing the continuous porphyric fabrics, which make the pores less communicating. The Ap and Bw horizons have shown higher hydraulic conductivity, while AB and B nitic horizons had the lowest rates, reinforcing the notion that besides soil density, the pores arrangement directly interfereswith the hydric behavior of the pedological system.

KEYWORDS: Nitic horizon, Latosolic B horizon, Micromorphology, Hydraulic conductivity.

RESUMO:

Dinâmica Físico-Hídrica De Um Sistema Pedológico Latossolo-Nitossolo. Com o objetivo de compreender a dinâmica hídrica dos solos, realizou-se esta pesquisa em uma vertente, do platô da cidade de Marechal Cândido Rondon, Paraná. Foram abertas trincheiras para a descrição macromorfológica, coleta de amostras para as análises físicas, químicas, micromorfológicas e quantificação da condutividade hidráulica. No setor de topo, foi identificado o Latossolo Vermelho Eutroférrico e a partir da média baixa vertente, o Nitossolo Vermelho Distroférrico latossólico. Em termos micromorfológicos, os horizontes Ap e Bw apresentam dois tipos de arranjos distintos: um de trama enáulica, com alta conectividade – porosidade de empacotamento composto, e outro de trama porfírica contínua e/ou descontínua, com cavidades e os poros planares. Nos horizontes AB e B nítico a trama enáulica é menos representativa, predominando a trama porfírica contínua, que deixa os poros menos comunicantes. Em termos hídricos, os horizontes Ap e Bw indicaram maior condutividade hidráulica, enquanto o AB e B nítico apresentaram os menores índices, reforçando que além da densidade do solo, o arranjo dos poros interfere diretamente no comportamento hídrico do sistema pedológico.

PALAVRAS-CHAVE: B nítico, B latossólico, Micromorfologia, Condutividade hidráulica.

RESUMEN:

DINÁMICA FÍSICO-HÍDRICA DE UN SISTEMA PEDOLÓGICO LATOSOL-NITOSOL

AUTHOR NOTES

Address: Avenida Brasil, nº 4232. CEP: 85884-000, Medianeira (PR), Brasil. Tel: (+55 45) 32408000

Con el objetivo de comprender la dinámica hídrica de los suelos, se realizó investigación en una vertiente de la meseta de la ciudad de Marechal Cândido Rondon, Paraná. Se abrieron zanjas para la descripción macromorfológica, colecta de muestras para los análisis físicos, químicos, micromorfológicos y la cuantificación de la conductividad hidráulica. En el sector superior, fueron mapeados el Latosol Rojo Eutroférrico y a partir de la media y baja vertiente, el Nitosol Rojo Distroférrico latosólico. En los análisis micromorfológicos, los horizontes Ap y Bw presentan dos tipos de disposiciones distintas: una de trama enáulica, con poros inter- agregados con alta conectividad – porosidad de envoltorio compuesto, y otra de trama porfídica continua y descontinua, con cavidades y poros planeares. En los horizontes AB y B nítico la trama enáulica es menos representativa, predominando la trama porfídica continua, que deja los poros menos comunicantes. En términos hídricos, los horizontes Ap e Bw indicaron mayor conductividad hidráulica, mientras que el AB y B nítico presentaron los menores índices, reforzando que además de la densidad del suelo, la disposición de los poros interfiere en el comportamiento hídrico del sistema pedológico.
Palabras clave: B nítico, B latosólico, Micromorfología, Conductividad hidráulica.

INTRODUCTION

Integrated landscape study, especially its characteristics and operation, have presented themselves as vital for both rural and urban land-use planning. According to Ruellan and Dosso (1993), is necessary for understanding the landscape from macro to micro-scale. The knowledge of the pedological cover contributes, in this sense, to identify the arrangement of soil in the landscape in a bi-dimensional and tri-dimensional way, as a pedological continuum, since they undergo different actions and reactions in space and time.

The soil is a dynamic portion of the landscape, from a tri-dimensional nature that synthesizes, in its profile, many influences of the present and past. For Ruellan (1988) there is a need to comprehend the soil as an organized, structured, living medium, with its own dynamics even before its effective utilization. Such approach is deemed necessary since the man-made use and management of this natural element changes not only its structure but mainly its functioning, and according to the author, it causes widespread changes in other characteristics of the environment, be it natural (terrain, climate, vegetation) and/or anthropic (use and management methods).

Soil or pedological surveying generates information that allows the classification, monitoring, and evaluation of agricultural aptness, project productivity and establishes the best manner for land use. Such combined pieces of information can be organized in zoning maps as an essential part of regional agricultural planning for both rural and urban rural properties. There are a great number of projects that require spatial soil information in terms of surface and different depths, contributing along with the knowledge of spatial soil distribution in more detailed scales.

There is a consensus that land use for agriculture entails changes in its natural characteristics. Agricultural soils have been seeing great modifications, where soil compaction is identified as the main cause for such changes, due to the traffic of tractors and agricultural machines being inadequately used (RAPER, 2005). The changes caused by the physical properties are one of the first that appear, varying in their intensity according to the cultivation system used. The modifications occur mainly in the structure, affecting density, porosity, and aeration, causing changes in water flow and retention of that system (CARDOSO et al., 2006).

Water, sediments, and chemical elements transference on slope sectors occur via several flows that vary in space and time, in a superficial and sub superficial manner, resulting in differentiations and discontinuing of processes, not only in slope sectors forms but also in soil categories arranged on each topographic segment.

In order to comprehend the dynamics of water on soil, it is necessary to recognize some of its morphological characteristics, such as texture and structure, responsible for the organization of the porous system. According to Bertoni and Lombardi Neto (2005), it is the size and arrangement of porous spaces that directly influence water infiltration speed in soil. These movements are carried out by gravitational and capillarity forces. Gravitational force promotes water movement of large pores in saturated soils, whereas the capillarity force occurs on non-saturated soils (REICHARDT, 1990).

Reichardt (1990) defines the hydraulic conductivity as volume water that passes through, by time unit, a specific soil area driven by a difference in potential. It is concluded that conductivity coefficient expresses the facility for a fluid such as water to be transported through a porous medium such as soil, dependable both from the soil and water properties. Among soil properties, the following characteristics can be highlighted; size distribution and particles form, specific surface, and porosity, in other words, all properties that are reflected on the porous geometry of the soil.

Mesquita and Moraes (2004) corroborate that the saturated hydraulic conductivity of a soil is determined by the geometry and pores taken by water, therefore becoming dependent on shape, quantity, distribution, and above all, their continuity.

Thereby, studies about hydric behavior of pedological covers, aiming at understanding their morpho-pedological transformations on slope sector (toposequence) and on landscape (hydrographic basin), must prioritize the use of techniques that allow the distribution and redistribution evaluation of matters (silts and clays) on different topographic segments of slope sectors, such as micromorphology, highlighted by Castro (1989), Ruellan and Dosso (1993), Kertzman (1996), Castro et al. (2003), and Filizola and Gomes (2006).

According to Filizola and Gomes (2006), micromorphology corresponds to a scale of pedological cover observation, crucial for the understanding of its organization and functioning. The adequate use of micromorphology involves detailed information of the distribution of pedological horizons, both on the profile and on the landscape. Therefore, micromorphological observation is considered a zoom in into the pedological cover organization.

Micromorphology technique is considered efficient either on soil genesis and dynamics or on evaluation and monitoring of various agricultural practices. Micromorphology is capable of giving porosity and permeability results with precision (in two dimensions) with the aid of processing and digital image analysis techniques, as well as allowing the visualization of structural alterations caused by densification and compaction in accordance with Castro (1989), Ruellan and Dosso (1993), Kertzman (1996), Castro et al. (2003), and Filizola and Gomes (2006).

There is a consensus among researchers (DERPSCH et al., 1990; De MARIA et al., 1999; TAVARES FILHO et al., 2006) that different soil management systems have the purpose to create favorable conditions for the development of crops. However, a disregard for more favorable conditions for soil preparation and the use of larger and heavier machinery for that could cause structural modifications to the soil. That could cause either greater or lesser soil compaction interfering on soil density, porosity, water infiltration in the soil, and on the root development of crops, consequently reducing their productivity. It is also highlighted that studies of such nature could contribute towards the knowledge of physical-chemical, physical-hydrological, and micromorphological attributes, emphasizing the genesis and evolution of soils. Such studies are made evident, either separately or simultaneously, in works from Vidal-Torrado et al. (2005), Cunha et al. (2008), and Tavares Filho and Tessier (2010).

Learning about the porous arrangement and hydraulic conductivity of the soils on the slope sectors is crucial to establishing water flow on soils, and from a practical viewpoint, for the creation of irrigation and draining projects, as well as for quantification of chemical substances leaching and erosion.

Therefore, this studies aims at presenting the physical-hydric behaviour and micromorphological aspects of a Latosol/Nitosol pedological system in Marechal Cândido Rondon, West of Paraná state, Brazil, an agriculture-based economy.

MATERIALS AND METHODS

The municipality of Marechal Cândido Rondon is located on the far west of Paraná state, between parallels of latitude 24°26'and 24°46' South and longitude 53°57' e 54°20' West (Figure 1). It shows in its 748-sq.km area sectors of three morpho-sculptural sub-units of Third Paraná Plateau, on Paraná Sedimentary Basin: Cascavel Plateau, São Francisco Plateau, and Foz do Iguaçu Plateau (MINEROPAR, 2006).

The Cascavel Plateau morpho-sculptural sub-unit stretches through the North-eastern sector of the municipality, where the urban plot of Marechal Cândido Rondon is located, locally identified as a landscape unit - Plateau de Marechal - by Moresco (2007). On this plateau, there is a dominance of medium dissection terrain, characterized by hills with elongated and flattened summits, convex slopes with declivities, in general, lower than 12% and V- shaped valleys.

The Cascavel Plateau ends making way to a border zone carved by direct tributaries to Paraná and São Francisco rivers, which shape slopes with varied and pronounced declivities, quite often presenting steep segments on the summits and deep valleys. This carved border zone corresponds to the west side of the great interfluve, named Sao Francisco Plateau morpho-sculptural sub-unit. The western sector, characterized by wide low hills with long slopes and weak declivities, corresponds to Foz do Iguaçu Plateau.

The landscape unit Marechal Plateau (MORESCO, 2007), where the current research was done, is located on the North-eastern sector of the municipality, between 360 and 460 m altimetry quotas. The more elevated spurs keep the axis SE-NO and N-S. It is characterized by convex-straight slopes and V-shaped narrow valleys, with gradient ruptures on the peak to high slope passage and steep declivity (8 to 20 %).

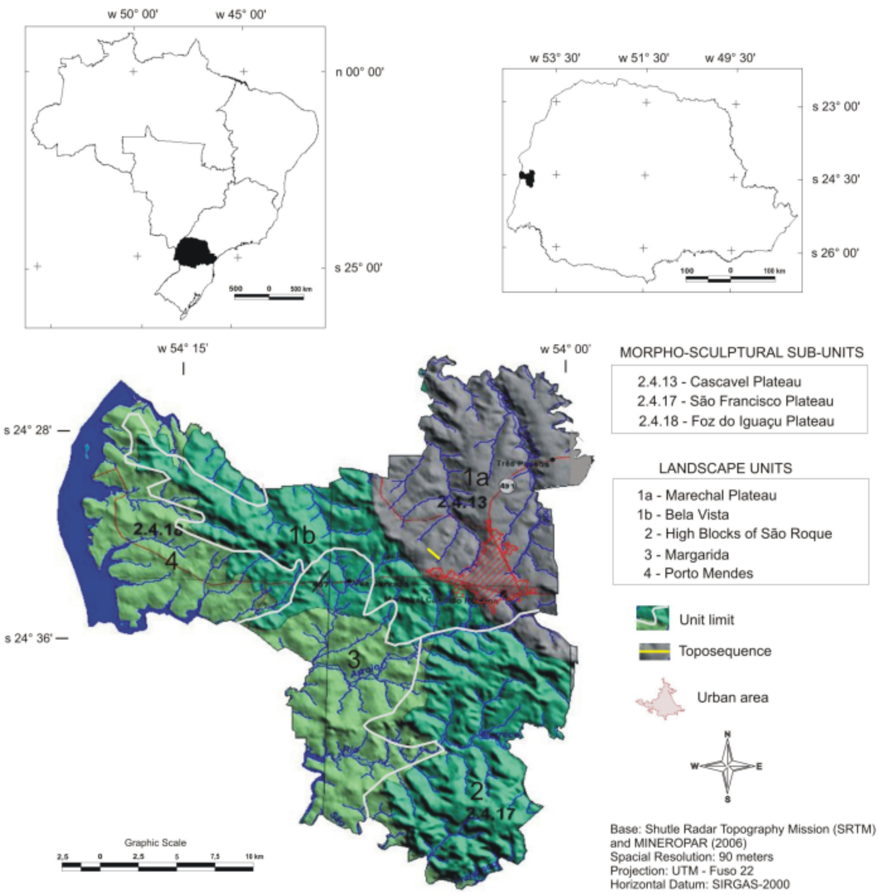

Figure 1

Location of Marechal Cândido Rondon municipality, the morpho-sculptural sub-units, and the landscape units.

In order to obtain the knowledge of the pedological cover on the Marechal Plateau systemic surveys were done along the slope, followed by the opening of two trenches, respectively on the top and medium low slope sectors for the macro-morphological description (SANTOS et al., 2015), sample collection for physical, chemical, and micro-morphological analyses, as well as tests for hydraulic conductivity quantification (constant load permeameter) and macro and microporosity. It is worth highlighting that since the valley floor area (covered by woods) is altered and coated by sediment material, it was not possible to carry out the investigation on the lower segment of the slope.

The chemical analyses followed the Agronomic Institute of Paraná (IAPAR) technique (PAVAN et al.,) in the laboratory. The phosphor was established by spectrophotometry (# = 360 nm) and potassium by flame photometry. Interchangeable acidity (Al) determination was done in KCl, and potential acidity (H + Al) with SMP buffer solution added to the sample used on the pH in CaCl2, with new pH reading with a potentiometer. Ca2+ and Mg2+ determinations were done by atomic absorption spectrophotometry (AAS), utilizing Ca2+ and Mg2+ standard solutions containing La and KCl at the same extract concentrations. The organic carbon was obtained using the Walkley-Black method with organic matter oxidation by K2Cr2O7 1N potassium dichromate in acid medium. The soil pH was established in CaCl2 and H2O solution, under calibrated potentiometer with buffer solutions at pH 7.0 and 4.0.

Soil granulometric fractions and clay dispersed in water were determined by the Bouyoucos densimeter method (EMBRAPA, 1997), both in triplicate. The determination of soil and porosity densities (macro and micro) followed the one proposed by Embrapa (1997), utilizing the mean of three soil samples collected in 147 cm3 stainless-steel volumetric rings on the diagnostic horizons. The hydraulic conductivity test established in these volumetric rings was done in the laboratory using constant load permeameter in three samples for each horizon, 8 readings totaling 8 h. For the hydraulic conductivity calculation the mean of the last three readings was used, applying the following formula:

$$Ko = Q.\ L / A.\ H.\ t$$

Where:
Ko = hydraulic conductivity of saturated soil in mm/h;
Q = water volume in mL percolated on the sample;
L = length (height) of sample in cm;
H = soil block and water column height;
A = soil cylinder area in cm2;
t = time in hours.

For results interpretation the following classes were employed according to Embrapa (1997) guidelines: very slow (< 1); slow (1-5), moderately slow (5-20), moderate (20-60), moderately fast (60-125), fast (125-250), and very fast (> 250).

The hydric dynamics study was done by micromorphological observation on thin sections obtained from non-deformed soil samples, collected in plastic containers measuring 6x10x5cm, dried in greenhouse at 38o C. The samples in dried state were impregnated with polyester resin, selecting thin slices between 2 and 4 mm in thickness, followed by the polishing of one of the sides using a polisher and assembling in a glass slide. After assembling, thinning was carried out until reaching 25 micrometers of thickness (CASTRO et al., 2003).

The thin sections observations were done with a petrography-type optical microscope, with 2.5 and 4X lenses, under natural light and crossed nicols (polarized light). Bullock et al. (1985) recommendations were followed on this stage for identification and classification of attributes and the soil components organizing (thin section) called micromass (< 2 µm), coarse material (from 2 to 2.000 µm diameter), and pores (from 30 to 500 µm).

The images obtained with the optical microscope were subjected to ArcGIS® 10.1 image classification software, in order to generate images showing pores geometry, shape, and connexion.

RESULTS AND DISCUSSION

Physical and chemical attributes

The toposequence of Marechal Plateau is located in one of the drainage riverbeds of the canals that conjoin with the Guavirá stream, the main water course of the urban site. This toposequence is 790 m long and it has 45 m of uneven topography dominated by convex shape (Figure 2). Temporary crops with direct planting system for over 20 years are found along its entire extension.

Due to the prevalence of basaltic rocks (BHERING et al., 2007), the pedological cover is quite clayey along the whole toposequence (Table 1), presenting variations in color and structure. For this same research field, Magalhães et al. (2015) presented such macromorphological characteristics in detail, which indicates Ap horizon with a weak structure, made of small granules of 1cm in diameter. AB horizon presents, due to the degree of compaction, the large subangular blocky structure of up to 5 cm in diameter, with strong levels of development. Such greater resistance of material could be due to compaction noted on the field and also by the soil density determined in the laboratory. Bw horizons showed that subangular blocky structures of up to 3 cm in diameter have moderate resistance, whereas B nitic of strong to the moderate structure is characterized by large subangular blocky structures of up to 5 cm in diameter. The presence of strong clay films was evidenced mainly on the walls of the blocks. Small variations of color were highlighted, for instance, dark-reddish-brown (2.5YR 3/4) on the surface and greyish-dark-red (10R 3/4) on Bw and B nitic.

Based on the variation of these morphological characteristics, along with the 320 m extension from the summit to the medium slopes (surveys 3 to 6 and trench 2), Ap, AB, Bw1, and Bw2 horizons were identified. On the remaining 470 m of extension from the medium slope to the valley bottom (surveys 2 to 6 and trench 2), Ap, AB, B nitic, and Bw horizons were identified.

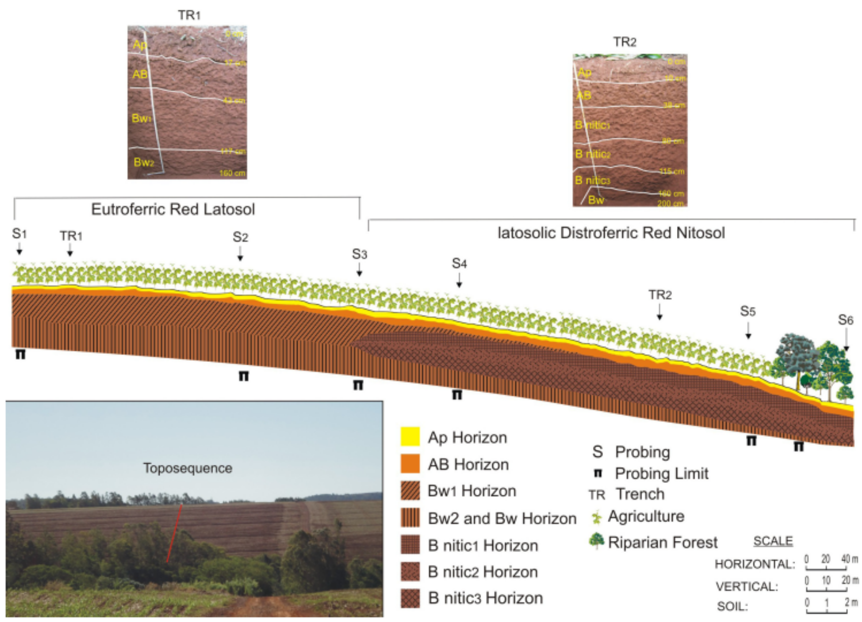

Figure 2

Toposequence of soils from Marechal Plateau.

Such sequence of horizons and their morphological characteristics allow classification this pedological system as Red Latosol / Red Nitosol and, also, taking into account that it is basalt rock creating soils with high levels of iron oxide (> 18%) it is identified with ferric quality, as done by Bhering et al. (2007), when updating the soil map of Paraná state.

Flocculation, as well as dispersion levels, presented a 64% range on the diagnosed horizons. On the summit sector, Ap and AB horizons presented 32% and 48% of flocculation, respectively. While on the medium slope, Ap horizon keeps values close to the summed ones, AB volume presented 96% flocculation, demonstrating a 50% increase laterally on the slope.

Bw sub surface horizon on slope summit showed more flocculated clay than on the surface, presenting values around 81%, which decreases laterally to 78%. B nitic volumes were more flocculated in terms of depth, initiating with 78% on B1 nitic and reaching 96% on B3 nitic. It can be determined in this case, that agricultural practices (use of organic manure) are interfering and increasing the values of clay dispersed on the surface, just as diagnosed by Barbosa et al. (2015) on Red Latosols from the North of Paraná state.

Table 1

Trench Horizon	Horizon Depth (cm)	Granulometry %			Natural Clay	Degree of Floccula-tion	Degree of Dispersion	Particle Density g cm^{-3}	Rela-tionship silt / clay
		Clay	Silt	Sand		%			
1- Ap	00-17	73.08	16.38	10.54	49.72	32	68	2.72	0.2
1- AB	17-43	83.08	9.54	7.38	43.08	48	52	2.73	0.1
1- Bw1	43-117	76.40	16.90	6.7	14.74	81	19	2.77	0.2
1- Bw2	117-160+	79.72	13.38	6.9	14.74	82	18	2.77	0.2
2- Ap	00-10	79.36	8.62	12.02	51.38	35	65	2.75	0.1
2- AB	10-38	81.02	7.14	11.84	3.08	96	4	2.70	0.1
2- B nitic 1	38-80	82.72	8.60	8.68	18.08	78	22	2.74	0.1
2- B nitic 2	80-115	86.04	5.54	8.42	13.08	85	15	2.75	0.1
2- B nitic 3	115-160	86.40	5.16	8.44	3.08	96	4	2.80	0.1
2- Bw	160-200+	86.40	5.72	7.88	19.36	78	22	2.80	0.1

Physical characteristics of soil profiles from Marechal Plateau toposequence.

According to Embrapa (1984), Latosols have a high flocculation level on Bw horizon that could reach 100%. Such contribution also occurs due to the degree of weathering that increase flocculation levels on tropical soils. The basic division of silt by clay contents, summarizing the relation silt/clay, generated values between 0.1 and 0.2, confirming the high evolution levels of soils from this toposequence. Silva and Castro (2015) after analyzing a clayey Distroferric Red Latosol of sugarcane cultivation in the state of Goiás, Brazil, noted that the flocculation level on most of the horizons reached 100%, and none of them were lower than 80%, reinforcing a typical condition of this type of soil.

In terms of chemical properties of these soils (Table 2), the pH values in H2O are always superior to the pH in CaCl2, demonstrating that on exchange complex, cationic-type reactions predominate over anionic ones. On the summit segment, represented by the Red Latosol with ferric characteristics (BHERING et al., 2007), the pH data in water were constant, presenting a predominantly neutral reaction (>6.6) on Ap, Bw1, and Bw2 horizons, and it presented a moderate acidity (6.5) only on AB volume, according to Embrapa (2013) classification.

The sum of bases (S) together with potential acidity (H + Al) indicate a relatively low cationic exchange capacity (CEC) on soil volumes of this toposequence, varying between 7.77 and 17.27 cmolc dm-3 meeting the chemical criteria established by Embrapa (2013) for Latosols and Nitosols.

Saturation by bases (V) (Table 2) presents values with an amplitude of up to 56% on the toposequence soil volumes. The higher values are concentrated in the pedological set of amount, that varied between 60.96% and 78.87%. These values are reduced on the transition to the lower slop since a substantial part of B nitic and Bw shows less than 50% of saturation by bases.

According to the third categorical level of soil classification in Brazil (EMBRAPA, 2013), such soils are characterized as eutrophic on the summit and dystrophic from the medium slope sector to the foothill.

Thus, the classification points to eutroferric and/or distroferric soils, an indication that the toposequence of the Marechal Plateau presents an pedological system organized on the top sector that correspond to the Eutroferric Red Latosol soil horizons, and laterally, it switches to the latosolic Distroferric Red Nitosol soil horizons.

Table 2

Trench Horizon	Horizon Depth (cm)	P	MO	pH	pH	H + Al	Al^{3+}	K^+	Ca^{2+}	Mg^{2+}	S	CEC	V	Al
		$mg\ dm^{-3}$	$g\ dm^{-3}$	$CaCl_2$	H_2O	$cmol_c\ dm^{-3}$							%	
1- Ap	00-17	37,28	37,59	5,99	6,64	3,65	0,00	1,09	8,91	3,62	13,62	17,27	78,87	0,00
1- AB	17-43	4,20	16,40	5,38	6,49	4,56	0,00	0,28	5,19	1,65	7,12	11,68	60,96	0,00
1- Bw1	43-117	1,38	6,15	5,92	6,57	3,05	0,00	0,08	4,79	0,62	5,49	8,54	64,29	0,00
1- Bw2	117-160+	1,48	2,05	6,19	6,66	2,96	0,00	0,08	4,24	0,49	4,81	7,77	61,90	0,00
2- Ap	00-10	22,30	33,05	5,17	6,45	4,2	0,00	1,02	8,32	3,02	12,36	16,56	76,23	0,00
2- AB	10-38	2,51	8,89	4,91	6,02	6,10	0,05	0,17	4,87	1,85	6,89	12,89	53,09	0,72
2- B nitic 1	38-80	2,77	10,25	5,81	6,43	3,57	0,00	0,13	3,99	0,62	4,74	8,31	57,04	0,00
2- B nitic 2	80-115	1,79	1,37	4,89	5,46	5,18	0,30	0,10	3,09	0,58	3,77	8,95	42,12	7,37
2- B nitic 3	115-160	1,59	2,05	4,37	4,88	6,48	0,65	0,10	1,42	0,86	2,38	8,86	26,86	21,45
2-Bw	160-200+	1,87	2,05	4,35	5,63	6,57	0,55	0,12	0,95	1,15	2,22	8,79	25,26	19,86

Chemical characteristics of Marechal Plateau soil profiles toposequence.

Micromorphological attributes

In order to maximize the presentation and generate subsidies for understanding the hydric dynamics of the slopes, all horizons of the Marechal Plateau pedological system are detailed. The Ap horizon (from both soils) presents itself with two different types of arrangements (coarse/fine-related distribution) in micromorphological terms; one of continuous porphyric fabric and the other of enaulic fabric. The porphyric zones that represent half the volume are surrounded by enaulic zones, in similar proportions (Table 3 and Figure 3-a).

The microaggregate that appear on enaulic fabric zones are essentially made of dark red soil material, ferruginous clay micromass, undifferentiated to speckled b-fabric, even under increased zoom and bright light, bordered by a narrow band of red-yellow, speckled micromass (Figure 3-a). They present different dimensions mainly between 0.5 and 2 mm in diameter, strong pedality, not accommodated with each other.

On porphyric fabric zones, the aggregates present subangular shapes with diameters higher than 3 mm. Such continuous zones are the result of the rounded microaggregates cluster, coalesced with each other by the red-yellow micromass.

The difference on the arrangements imply variations on porosity type, on enaulic zones, inter-aggregated pores of high connectivity – compound packing voids predominate. There is still a finer intra-aggregate porosity as emphasized by some authors (COOPER; VIDAL-TORRADO, 2005), not observable on this analysis scale. On porphyric zones, porosity consist of two different types of pores: cavities and planar pores. The larger cavities are policoncave (400 μm) and the smaller ones are oval shaped (205 μm), occasionally more elongated and curved presenting weak or null connectivity. On the other hand, planar pores are thin and accommodated (15 to 40 μm fissures), or wider and unaccommodated, dividing the larger continuous zones into smaller polyhedral aggregates. The wider planar pores (60 μm) are normally longer and interconnected with a close compound packing porosity. The thinner pores tend to be shorter and could be either interconnected or not with the general porous system. Some tubular voids filled by microaggregates were also observed, confirming biological activity.

Table 3

Horizons	Attributes					
	General	Microstructure	Micromass	Coarse Material	Pores	Fabric
Ap	Heterogeneous. Two types of arrangements: 1(50%) e 2 (50%).	1) Rounded microaggregates 2) Subangular blocky	1 e 2) Ferruginous clay, dark-red, undifferentiated to speckled b-fabric, and yellow-red speckled	1 e 2) Few dark minerals (ilmenite and magnetite), angular to subangular	1) Inter-aggregates, compound packing voids 2) Planes and poly-concave and oval vughs	1) Enaulic 2) Porphyric continuous
AB	Heterogeneous. Three types of arrangements: 1(30%), 2 (50%), 3 (20%)	1) Coalesced roundend microaggregates2) Rounded microaggregates and subangular blocky 3) Rounded microaggregates	1, 2 e 3) Ferruginous clay, dark-red, undifferentiated and yellow-red speckled	1, 2 e 3) Few dark minerals (ilmenite and magnetite), angular to subangular	1) Elongated or curved and poly-concave vughs elonged 2) Planes and oval vughs 3) Inter-aggregates, compound packing voids	1) Porphyric - discontinuous 2) Porphyric - continuous 3) Enaulic
Bw1/ Bw2	Heterogeneous. Three types of arrangements: 1(25%), 2 (25%), 3 (50%)	1) Subangular bloky 2) Subangular bloky 3) Rounded microaggregates	1, 2 e 3) Ferruginous clay, dark-red, undifferentiated and yellow-red speckled	1, 2 e 3) Few dark minerals (ilmenite and magnetite), angular to subangular	1) Long and open planes 2) Oval vughs 3) Compound packing voids	1) Porphyric - continuous 2) Porphyric - discontinuous 3) Enaulic
B nitic	Heterogeneous. Three types of arrangements: 1 (70%) e 2 (10%) e 3 (20%)	1) Subangular blocky 2) Rounded microaggregates 3) Agregados poliédricos subangurales	1, 2 e 3) Ferruginous clay, dark-red, mosaic-speckled and micromass red to yellow-red, striated b-fabric	1, 2 e 3) Few dark minerals (ilmenite and magnetite), angular to subangular	1) Planar and oval vughs 2) Compound packing voids 3) Planar, and vughs	1Porphyric - continuous 2) Enaulic 3) Porphyric - continuous
Bw	Heterogeneous. Three types of arrangements: 1(20%), 2 (10%), 3 (70%)	1) Subangular blocky 2) Subangular blocky 3) Rounded microaggregates	1, 2 e 3) Ferruginous clay, dark-red, undifferentiated and yellow-red speckled	1, 2 e 3) Few dark minerals (ilmenite and magnetite), angular to subangular	1) Long and open planes 2) Oval vughs 3) Compound packing voids	1) Porphyric - continuous 2) Porphyric - discontinuous 3) Enaulic - open

Micromorphological description of the pedological system of soil horizons from Marechal Plateau.

The AB sub superficial horizon (Figure 3-b) presents a dominant porphyric fabric encompassing small sectors of enaulic fabrics similar to those noted on the superior horizon. Porphyric zones are discontinuous and continuous at times. Similar to the superior horizon, these porphyrics are formed due to micro-aggregates grouping and the discontinuous or continuous porphyric variation reveals different agglutination stages: discontinuous porphyric - a stage where rounded volumes are noticeable with some vughs elongated and curved and others policoncave 150 μm around it; continuous porphyric - a stage where original rounded shapes are already deformed, showing some small oval vughs (~20 to 40 μm), aligned along welding plans resulting in a reticular distribution pattern.

On open enaulic and porphyric zones, micromass is dark-red, ferruginous clay, speckled, and undifferentiated, presenting on some sectors, aggregated or vughs edges, a clearer red-yellowish and speckled micromass. On continuous porphyric zones, the red-yellowish micromass appears striated on some sectors, in the contact bands between the originally rounded volumes of the microaggregates, now deformed and welded with each other. Corresponds to stress cutan in Brewer's classification (BREWER, 1976).

On the whole, the material is organized in aggregates of subangular polyhedral shape with around 1.000 μm in diameter. On zones of discontinuous porphyric fabric, the microaggregates coalescence that started it caused the closing of porosity, originally interaggregated of compound packing voids, and the appearing of a mainly vugh porosity – policoncave pores (25 μm) or elongated and curved – and planar, partially connected, presenting 40 μm width at the most. Such coalescence condition and porosity alteration were also checked by Cooper and Vidal-Torrado (2005), in Bw horizon.

In continuous porphyry zones, planar pores appear more frequently, consisting of short, thin (~ 25 μm) and accomodated, partially connected, when intra-aggregated, and wider and unaccomodated (45 μm) inter-aggregated cracks. Vugh pores are smaller, normally oval, and in small amounts. They can locally present a reticular distribution, as observed on Ap horizon. Some filling pedological features made of light yellow micromass in some pores can be noted.

The subjacent horizons of Latosol Bw1 and Bw2 are quite similar in physical, hydric, (Figure 3, Table 4), and micromorphological (Figure 3-c) terms. They show continuous porphyric fabric sectors cut by (long with 15 to 30 μm opening) planes, separating subangular polyhedral peds moderately accommodated and discontinuous porphyric fabric sectors with vugh porosity, similar to the ones observed on the AB horizon. These zones appear involved by longer sectors made of rounded-shaped microaggregates agglomerates (100 to 200 μm in diameter), non-accommodated, dominated by enaulic fabric described by Cooper (1999) in Bw horizon of a Eutroferric Nitosol. The prevalent micromass is dark-red undifferentiated to speckled, hemmed by narrow strips of speckled red-yellowish micromass.

As an example of what was noted on AB horizon, porphyric zones have reduced porosity made also by planar pores and policoncave and oval vughs. It is noted, however, an elevation on porosity due to the increase of enaulic fabric zones dominated by compound packing voids. Agglomeration of microaggregates often produces a reduction on porosity packing transforming it into policoncave vughs in certain places. Such condition was also verified by Silva and Castro (2015) when describing the Bw of a Red Latosol, prevalent of enaulic distribution, strong pedality (microaggregated) with small porphyric thickened zones in small sub rounded blocks. Indicating also, the prevalence of pilling inter-granular macroporosity, with channels, vughs, and/or millimeter chambers associated to the mesofauna, as well as filling features with material from the same horizon.

The micromorphological characteristics noted on summit soil (Latosol) for Ap and AB horizons remain along the entire toposequence, also appearing on Ap and AB horizons on trench 2 (Nitosol), on the low hillside.

B nitic horizon appears from the medium slope towards the foothill, right below AB horizon (Figure 2). As seen in Figure 3-d, such horizon presents a continuous porphyric fabric prevalent and some isolated enaulic fabrics sectors. The micromass is dark-red, mosaic speckled, appearing on the edges of the aggregates with lighter color – red to yellow-red.

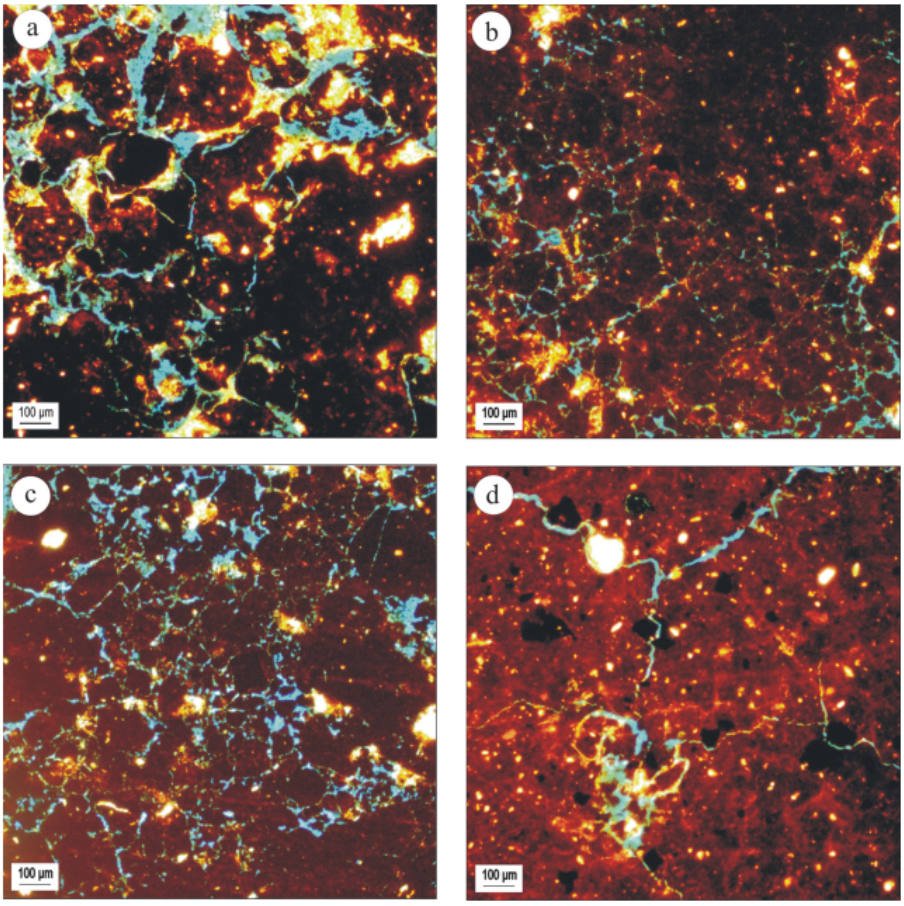

Figure 3

Soil horizons photomicrographs from the Marechal Plateau toposequence. a) Ap volume – Transition from discontinuous porphyric fabric and enaulic fabric zone with compound packing voids. b) AB volume – Red-yellowish micromass with "stress cutans" and highlight to coalescence of microaggregates. c) Bw volume – Porphyric fabric and agglomerates of microaggregates. d) Nitic volume – Porphyric fabric, subangular polyhedral aggregates, and inter-aggregated planar dominant porosity.

The structure is composed by subangular polyhedral aggregates varying from 1 to 4 mm, partially to totally accommodated, and blocks smaller than 500 µm. The prevalent porosity is connecting inter-aggregated planar, with openings of 10 to 30 micrometers.

Oval-shaped vugh porosity is prevalent inside the aggregates (~ 40 µm) and non-connected thin fissures. Oval section channels appear on some larger polyhedral blocks, filled by very small aggregates (160 and 300 µm), resulting from the biological activity.

On the field, B nitic horizon was subdivided into three volumes due to small morphological differences, confirmed by physical data (Tables 1 and 4). The B nitic summit is denser, whereas its center and base are less dense. That is micro morphologically represented by the increase of discontinuous porphyric fabric sectors in relation to the continuous porphyric fabric ones and by variations on the porous system, with the increase of vughs in relation to planar pores in the center and on the horizon's base.

Effects of biological activity evidenced by the presence of channels and pedofeatures of loose filling (microaggregates), more often on the central portion of B nitic horizon, are also responsible for physical variations noted on its interior (soil density and porosity).

This structure of aggregates in polyhedral and granular blocks is prevalent to up to 160 cm of depth on the toposequence; Bw appears again, in this slope segment below B nitic, with characteristics similar to the ones observed on the summit, yet with more discontinuous enaulic fabric sectors as indicated by the soil density data, significantly lower.

The coarse material (macromass) appears in small quantities along the entire pedological cover and on all horizons as confirmed by the granulometric data (Table 1). They are dark mineral grains (ilmenite and magnetite), normally angular to subangular, disperse and involved my thin material (micromass). Such material is seen in Figure 3-d.

Hydric attributes

The vertical and lateral variation of soil density data on Marechal Plateau (Table 4), evince a greater densification on superior horizons of the cover, more significant on AB horizon, followed by a reduction in porosity. It presents total porosity decreased by around 10% in relation to the superficial horizon on summit position, and by around 15% on the slope foothill. However, macroporosity is mainly affected by that decrease, which varies between 56% (summit) and 66% (foothill).

Table 4

Trench Horizon	Horizon Depth (cm)	Porosity %			Soil Density g cm^{-3}	Hydraulic Conductivity mm h^{-1}
		Macro	Micro	Total		
1- Ap	00-17	16.39	42.69	59.08	1.12	49.37
1- AB	17-43	7.21	46.20	53.41	1.27	0.93
1- Bw1	43-117	13.37	40.43	53.80	1.06	3.72
1- Bw2	117-160+	11.94	43.34	55.28	1.09	3.39
2- Ap	00-10	13.89	41.73	55.62	1.10	45.15
2- AB	10-38	4.76	42.79	47.55	1.37	0.15
2- B nitic 1	38-80	9.80	43.10	52.89	1.14	0.32
2- B nitic 2	80-115	16.02	39.74	55.76	1.06	4.40
2- B nitic 3	115-160	11.87	44.98	56.85	1.08	2.04
2- Bw	160-200+	17.31	42.83	60.14	0.98	36.03

Porosity, soil density and hydraulic conductivity of soil profiles from Marechal Plateau toposequence.

On subjacent horizons, soil density decreased sharply on transitions to Bw and B nitic. The values are close, be it on Bw (Bw1 and Bw2) from the high sector of the slope or be it on B nitic (B1 nitic, B2 nitic, B3 nitic). Nevertheless, Bw, on the low slope, presents the lowest soil density values of the entire toposequence (Figure 4).

That behavior is also reflected in the total porosity data, which is similar on Bw and B nitic. Using AB horizon as a reference, it can be noted, however, that the total porosity values on the upward sector of the toposequence have a slight increase in depth (3.5%) on Bw2. This increase is more significant on the low slope (around 11%) for B1nitic, right below AB, gradually increasing, reaching 26.5% on Bw, below B3 nitic. The substantially reduced macroporosity on AB horizon increases on B horizons (Bw and B nitic), more than 85% on summit Bw1 and 105% on B1 nitic on the low slope sector. While macroporosity is generated by structural arrangements of soil materials, microporosity is restricted by the texture of the material. Macroporosity allows free hydric circulation and microporosity acts mainly on water retention and its storage. Thus, as the structure is transformed, the balance between macro and microporosity changes, as noted along this toposequence, both vertically and laterally, hence able to produce hydrological behavior variations of the pedological cover.

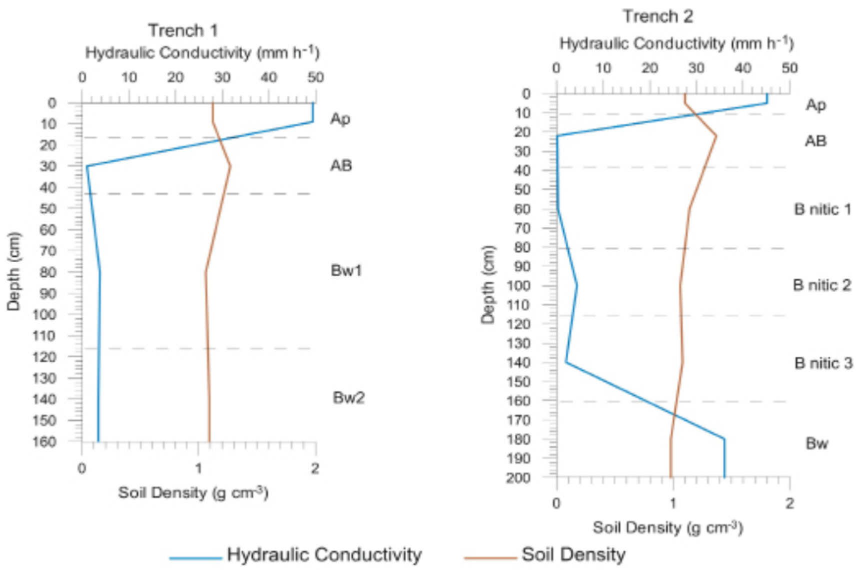

Figure 4
Hydraulic conductivity and soil density correlation of Marechal Plateau toposequence.

As shown by the data (Table 4), microporosity prevails on this pedological cover, representing 72% to 79% of poral system on the toposequence summit, showing that it reaches 86% on AB horizon due to densification and on its foothill there are variations between 71% and 82%, reaching 90% on AB horizon. Textural porosity is prevalent, favoring water retention. The data from hydraulic conductivity tests (Table 3 and Figure 5) confirm a correlation between porosity (macro and microporosity) and the hydric behavior of the pedological cover.

In hydric terms, Ap superficial horizon along the entire toposequence presents moderate hydraulic conductivity (49.37 mm h-1 upstream and 45.15 mm h-1 downstream) favoured by greater porosity; very slow on AB horizon (values below 1.00 mm h-1 with greater reduction on low slope); slow on Bw volumes on summit (3.72 mm h-1 for Bw1 and 3.39 mm h-1 for Bw2). From the medium slope, it turns laterally very slow on B nitic summit (0.32 mm h-1 on B1 nitic), remaining slow on B2 nitic (4.40 mm h-1) and B3 nitic (2.07 mm h-1). Hydraulic conductivity only increases from the medium slope on Bw, subjacent to B nitic, still moderate (36.03 mm h-1).

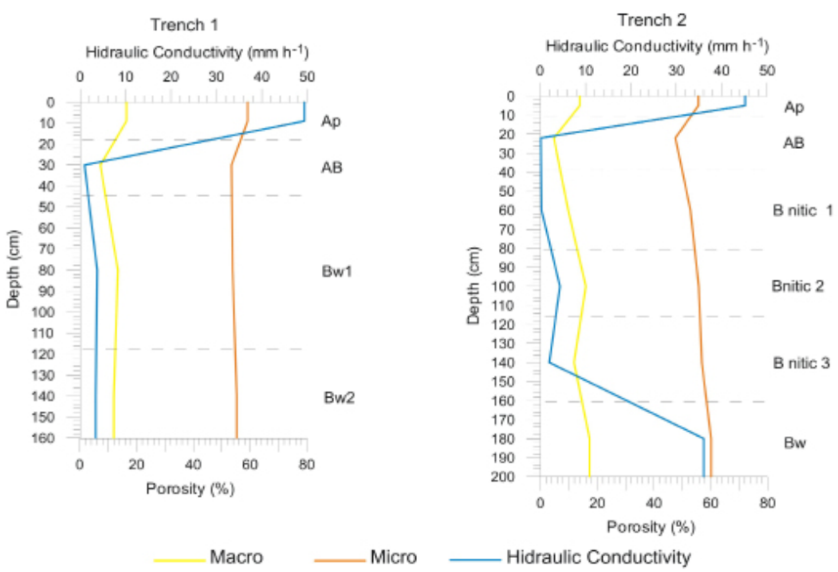

Figure 5
Hydraulic conductivity correlation with macro and microporosity of soils from Marechal Plateau toposequence.

Despite a hydraulic conductivity growth trend with the increase of total porosity and macroporosity, as seen on data, total porosity or macroporosity increase is not followed by hydraulic conductivity with the same intensity. More elevated total porosity and macroporosity on Bw were not able to restrict the same hydraulic conductivity rates as on Ap horizon, likewise, similar porosity values, or more specifically, macroporosity ones do not correspond to rates close to hydraulic conductivity.

Similar behavior can be noted when correlating soil density data with hydraulic conductivity (Figure 4). The close relation between total porosity and soil density does not extend to hydraulic conductivity.

The study from Tavares-Filho et al. (2006) corroborates with this discussion, where the hydraulic conductivity achieved with infiltrometer at 15 cm in depth in a dystrophic Red Latosol in the North of Paraná state, Brazil, under direct planting after 20 years, generated an average of 2.15 10-5 m s-1 (77 mm h-1), that is to say, a moderately fast hydraulic conductivity. Those authors concluded that nonsoil inversion in conjunction with agricultural machinery traffic has caused an increase in soil density in Ferralsols and Nitosols from the North of Paraná state, reaching values close to 1.50 g cm-3 and they could decrease significantly after scarification, reaching values of 0.99 g cm-3.

For the Marechal Plateau soils, balance interferences between macro and microporosity on the hydric behavior of this pedological cover must be considered as well as pore types, their degree of connectivity, and distribution, especially with regards to macroporosity, the general agent for hydric circulation. The micromorphological observations contribute to understanding the poral system configuration and its operation.

Figure 6 shows type, distribution, and size variations of pores observed on thin sections of soil volumes typical of this toposequence. As indicated by the micromorphological analysis, a porous system transformation occurs from the surface to the base of the studied soils, seen along the entire toposequence, with some lateral differences related to Bw transformation into B nitic, from summit to the slope foothill.

Vertically, it can be noted that the superficial volume (Ap horizon) of the pedological cover shows a significant porosity part (macroporosity) of compound packing voids type, generated by the enaulic arrangement of approximately half the horizon's groundmass. On continuous arrangement zones (porphyric fabric), porosity is very small and of vugh and fissural type. The ratio between the two types of arrangements and their distribution ensure pores connectivity, mainly for the compound packing ones. However, below the superficial horizon, as seen in Figure 5, the material is dense (AB horizon), the enaulic zones are drastically reduced, the arrangement type is predominantly porphyric and the macroporosity is preferably of vugh and planes types with weak or null connectivity. Such poral space transformation implies the closing of a substantial part of structural porosity where the free hydric flows circulate and the microporosity responsible for water retention – textural porosity - increases. Hydraulic conductivity rates obtained (Table 3) confirm hydric behavior alteration.

Silva and Castro (2015) draw attention to the porphyric structure prevalence on A and AB superficial horizons, caused by heavy surface compaction in areas affected by crops changes, from grazing and soybean to sugarcane.

Similarly, Kertzman (1996) using binary images to represent the organization of microaggregates and their poral space, noted that from 10 to 35 cm depth on area cultivated with direct planting, soil porosity is much more reduced than woods-covered soils. Such compaction reduces water infiltration rates by over 20 times. For the author, such infiltration decrease was caused by the reduction of inter-aggregated pores and mainly by low connectivity.

Despite the increase of macroporosity and total porosity on Bw horizon (Bw1 and Bw2) on the superior slope stretch and on B (B1 nitic, B2 nitic, B3 nitic), the low hydraulic conductivity values confirm the weak connectivity of porosity. Even with the increase of enaulic fabric zones and compound packing porosity in relation to porphyric zones on Bw1 and Bw. Upstream, the tendency to the agglomeration of such microaggregates transforms a significant part of compound packing porosity in vugh porosity, decreasing its connectivity, hence the reduced hydraulic conductivity rates. Downstream, the predominantly fissural and vugh porosity typical of B nitic is responsible for low conductivity. The subjacent Bw horizon, on medium and low slope, presents inter-aggregated porosity zones (compound packing voids) more enlarged and inter-connected, containing porphyric zones with lightly connected vugh porosity, but causing less interference on hydric circulation, making moderate hydric circulation similar to the one observed on the Ap superficial horizon possible, as per the obtained values.

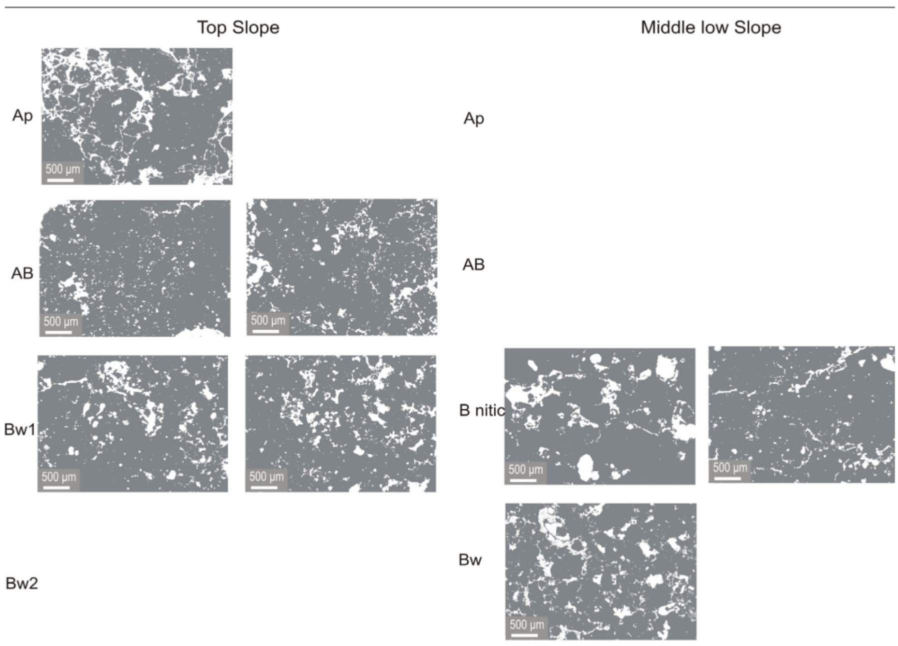

Figure 6
Binary images of soils horizons porous systems from Marechal Plateau. Poroids are shown in white and solid phase in gray.

The micromorphological analysis confirms that pore type, its organization, and distribution on the soil groundmass condition porosity connectivity and, consequently, hydraulic conductivity, justifying also the variations and relations between this analysis and the total porosity, macro, and microporosity data seen on the horizons.

Final Considerations

On the pedological system, made of Eutroferric Red Latosol and latosolic Distroferric Red Nitosol, the soils present a high degree of evolution confirmed by the low silt/clay relation rates, however, the diagnostic Bw and B nitic horizons do not present 100% clay-fraction flocculation.

In micromorphological terms, the pedological system presents particular structural characteristics for each horizon, sometimes repeated on the others. On the Ap horizon, the microstructure of rounded, subrounded, and granular aggregates under prevalent enaulic fabrics is well-noticed. On the AB horizon, the porphyric fabrics are formed by the grouping of microaggregates and vary from discontinuous to continuous porphyric fabric, according to different agglutination stages. Notoriously, the coalescence of these microaggregates imply the closing of the porous system, originating vugh pores (policoncave or elongated and curved), and planes, partially connected.

On latosolic B horizon, the enaulic fabric characteristics – rounded and subrounded microaggregates (crumb microstructure) and compound packing voids – is only common on deeper Bw. Porphyric fabric sectors cut by planes are frequent, distinguishing moderately accommodated subangular polyhedral blocks, discontinuous porphyric fabric sectors with vugh porosity, similar to the ones observed on AB horizon, and more extensive sectors made of round-shaped, non-accommodating microaggregates agglomerations ruled by enaulic fabric.

B nitic horizon presented a prevalent discontinuous porphyric fabric and its structure is composed of subangular polyhedral aggregates, partially to totally accommodated, with some isolated enaulic fabric sectors. It is worth mentioning that field and micromorphological observations on Bw, below B nitic, infer a possible transformation of this horizon into polyhedral structures, taking B nitic characteristics.

In hydric terms, despite the tendency for hydraulic conductivity growth with the increase of both total porosity and macroporosity as shown by data, it is noted that total porosity and macroporosity increase is not followed by hydraulic conductivity with the same intensity. The highest total porosity and macroporosity on Bw were not capable of conditioning the same hydraulic conductivity rates as seen on Ap horizon. Likewise, similar macroporosity values do not correspond to rates close to hydraulic conductivity.

The same behavior can be noted when comparing soil density data and hydraulic conductivity. The close relation between total porosity and soil density does not extend to hydraulic conductivity. The micromorphological observation contributed to the understanding of the porous system and its operation. Then, balance interferences between macro and microporosity on this pedological cover's hydric behavior must be considered in the same way as pores types, their distribution, and degree of connectivity, mainly regarding macroporosity, as it is the general agent for hydric circulation.

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