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Polycyclic soils with Bt and Bw developed on mafic rocks in a forest cerrado transition environment in Roraima, northern Amazon, Brazil

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ABSTRACT: In the extreme north of Brazil, in Roraima, there is an important set of mafic, volcanic or plutonic rocks, associated with the Juro-Cretaceous magmatism, and one of the most extensive areas is the Colônia do Taiano region, the first agricultural colony of Roraima. In addition to basalts, many diabases and diorites occur, forming an extensive patch of soils with good agricultural suitability, in the cerrado-forest transition. Two soil profiles developed from diabase were studied, after selecting the most representative pedons of the area. P1, an *Argissolo Vermelho Eutrófico latossólico* (Ultisol) and P2 an *Argissolo Vermelho Eutrófico típico* (Ultisol), were described and collected. Morphological, physical, chemical, mineralogical analyses, and extraction of Fe, Al, Ti and Si oxides by sulfuric attack were carried out; Fe_2O_3, Al_2O_3, TiO_2, and SiO_2, by plasma emission spectrometry; and Fe-DBC (dithionite-citrate-bicarbonate) and Fe ammonium oxalate. The soils presented a typical latosolic morphology at the base of the profile, with the top of the B horizon showing waxiness varying from moderate to abundant, thus revealing a polycyclic genesis of Bt superimposed on Bw, formed in a previous cycle. The SiO_2 contents indicated a desilication process, and the low contents of trace elements and TiO_2 showed mafic materials poor in magnetite, and reworking of the parent material by pediment in a drier climate. The Feo/Fed ratio proved to be atypical for the Amazon region, consistent with the mafic lithology.

Key words: Amazon soils, basic rocks, tropical soils

Solos policíclicos com Bt e Bw desenvolvidos sobre rochas máficas em ambiente de transição floresta-cerrado em Roraima, norte da Amazônia, Brasil

RESUMO: No extremo norte do Brasil, em Roraima, há ocorrência de importante conjunto de rochas máficas, vulcânicas ou plutônicas, associadas ao magmatismo no Juro-Cretáceo, e uma das mais extensas áreas é a região da Colônia do Taiano, uma das primeiras colônias agrícolas do Estado de Roraima. Além de basaltos, ocorrem muitos diabásios e dioritos, formando extensa mancha de solos com boa aptidão agrícola, na transição cerrado-floresta. Estudou-se dois perfis de solos desenvolvidos de diabásios, após caminhamento e seleção de pedons mais representativos da área. Foram descritos e coletados P1, um ARGISSOLO VERMELHO Eutrófico latossólico, e P2 um ARGISSOLO VERMELHO Eutrófico típico. Foram realizadas caracterização morfológica, física, química, mineralógica e extração dos óxidos de Fe, Al, Ti e Si, por ataque sulfúrico; Fe_2O_3, Al_2O_3, TiO_2 e SiO_2, por espectrometria de emissão de plasma; e Fe-DBC (ditionito-citrato-bicarbonato) e Fe oxalato de amônio. Os solos apresentaram morfologia latossólica na base do perfil, com topo do horizonte B mostrando cerosidade variando de moderada a abundante, revelando assim a gênese policíclica de Bt superimposta ao Bw, formado num ciclo anterior. Os teores de SiO_2 indicaram processo de dessilificação, e a pobreza de elementos-traço e os teores de TiO_2 evidenciaram materiais máficos pobres em magnetita, e retrabalhamento do material de origem por pedimentação em clima mais seco. A relação Feo/Fed revelou-se atípica para a região amazônica, consistente com o material de origem máfico.

Palavras-chave: solos Amazônicos; rochas básicas, solos tropicais

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Introduction

The Amazon region presents a great diversity of soils, resulting from the most varied pedogenetic processes, which occurred under current and/or past bioclimatic conditions. In general, the nature of the source material and the geomorphological configurations of the Amazon, contribute to the formation of dystrophic, deep and highly weathered soils (Campos et al., 2012). However, extensive patches of eutrophic soils are found under the influence of Andean sediments, in floodplains or terraces, and low plateaus of the Acre and Alto Amazonas basins, or even in regions of outcrops of mafic rocks, in Roraima (Schaefer et al., 2017; Melo et al., 2010). Another case is portions of anthropogenic soils ('Terras Pretas de Índio'), in central Amazon (Schaefer et al., 2017; Trujillo et al., 2020).

Between the extreme north of Brazil and the periphery of the Amazon biodiverse forests, the State of Roraima is physiographically inserted under geomorphologic, geologic and climatic conditions contrasting and distinct from the entire Brazilian Amazon, composed of morphostructural units with extensive areas of hills, or even mountains, and isolated residual reliefs, formed over various lithologies, from gneisses and granites, to acid and basic volcanics, and igneous mafic rocks, object of the present study. The region is transitional, with rainfall concentrated in the months of May, June, and July (Franca & Mendonça, 2016). The climatic conditions of the transition zones, and the diverse lithologies present confer singular pedological diversity to the region.

The soils of Roraima have been intensively studied in recent decades (Schaefer et al., 2015; Barros, 2020), and the classes already identified are distinguished according to the various geological formations and existing bioclimatic conditions. *Latossolos e Argissolos Amarelos* and *Vermelho-Amarelos*, *Gleissolos Melânicos e Háplicos*, and *Plintossolos Pétricos e Háplicos* are associated with the pre-intemperate sediments of the Boa Vista formation (Benedetti et al., 2011); in the context of diverse mafic rocks, *Latossolos Vermelhos*, *Chernossolos Ebânicos*, *Cambissolos Háplicos e Nitossolos Vermelhos*, and *Vertissolos Órticos* were identified, developed by transported or in situ materials from the decomposition of basic rocks (Melo et al., 2010); *Neossolos Flúvicos*, formed from Holocene sediments of the Cauamé River (Benedetti et al, 2011); *Planossolos Nátricos e Háplicos*, developed from acidic volcanic rocks (rhyolites, dacites and rhyodacites) of the Surumu formation. In general, acidic, dystrophic, kaolinitic soils poor in exchangeable bases and iron oxides predominate; eutrophic soils with the presence of 2:1 type minerals and high calcium contents only occur associated with mafic rocks (Schaefer et al., 2015; Melo et al., 2010).

Mafic, volcanic or plutonic basic rocks have a strong representation in the Taiano region, where red soils are intensively cultivated in the first planned agricultural production area in Roraima. Pedogenesis represents the balance between the massive structure of the igneous rock, which increases physical resistance, and the climate, which tends to favor the deepening of the actual weathering.

As for importance, the soils of this region present a high value for the social, environmental, agricultural and economic context of the state (Alves et al., 2020). Besides the very relevant livestock production, the region also stands out in the agricultural sector, with great representation at the national level in the production of grains such as rice, soy, and corn (Souza et al., 2020). In addition, the region lies within the Amazon biome, which is highly diverse and is currently being modified by agricultural advances, altering the vegetation and, consequently, the atmosphere and soils (Condé & Tonini, 2013).

Although many studies have been conducted in Roraima, little is known about the genesis and characterization of soils from mafic rocks in the Taiano region, a pioneer agricultural colony in the State of Roraima. This study investigated the pedogenesis of soils developed from mafic rocks in the region by means of representative profiles.

Materials and Methods

Characterization of the study area

The study area is located in Colônia Agrícola Coronel Mota, Vila Taiano, municipality of Alto Alegre, in the northwestern portion of the State of Roraima, Brazil, at the geographical coordinates 3° 17' 26" N and 61° 05' 17" W, approximately 120 km from the capital, Boa Vista (Figure 1).

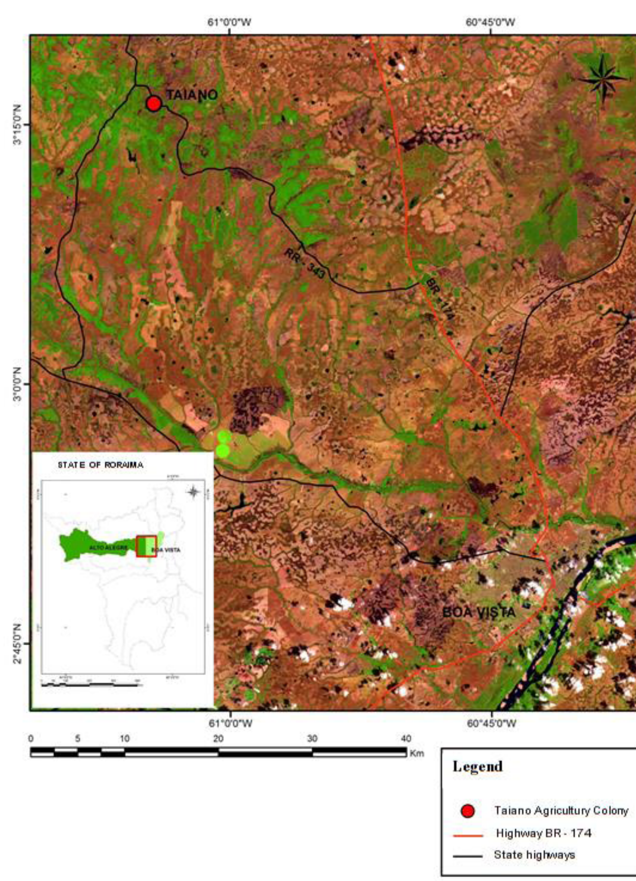


Figure 1. Location of the study area with emphasis on the agricultural community of Taiano.

The region has an annual rainfall of 1,688 mm, with a dry season from October to March. The average air temperature is 27.7 °C and the climate is classified as Tropical Rainy (Aw) and hot (Schaefer & Dalrymple, 1995). The typical vegetation is classified as submontane semidecidual seasonal forest, with a uniform canopy.

The lithology is represented by extensive outcropping of diverse mafic rocks (diabase and diorite, mainly), dating from the lower to middle Jurassic period, rich in iron-magnesian minerals (Brasil, 1974). The relief is smooth and wavy, with altitudes in the range 400 m and slopes around 8%, denoting structural control defined by embedded valleys. At the top of the landscape, sparse blocks of diabase occur, denoting a phase of aggressive erosion and pedimentation, exhuming the resistant rock cores.

Two representative profiles of the area of occurrence of mafic rocks were selected (P1 - cultivated for 2 years; P2 - cultivated for 10 years), in which the criterion for choosing the profiles to be studied came from the distinction of landscape components (Figure 2).

Field and laboratory analysis

In the field, after identifying and determining the horizons and/or layers, soil samples were collected for physical, chemical, morphological, and mineralogical analyses. The profiles were morphologically described according to Santos et al. (2005), comprising the horizons A, B and transitional AB and/or BC. As cores, matiz e croma foram identificadas conforme Munsell (2000). After collection, the samples were air dried, crushed and passed through a 2.00 mm sieve, thus obtaining the fine air-dried soil (FADS), material that was used for the analyses.

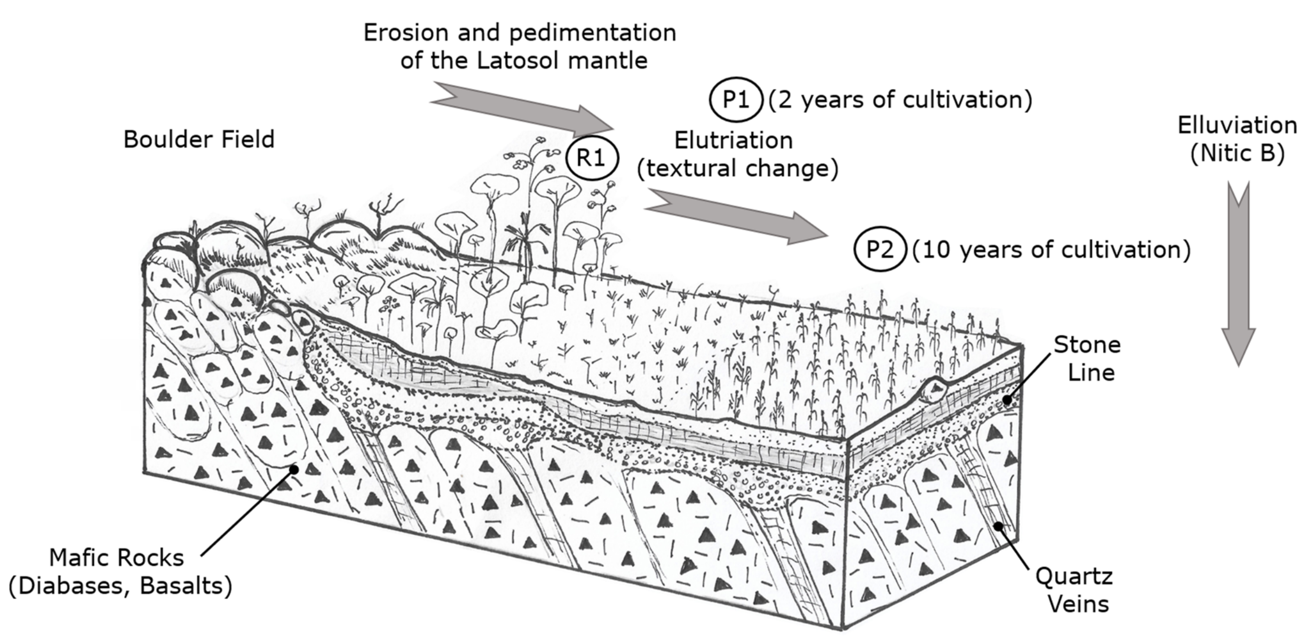
The textural analysis, the determination of pH values in water and in 1 mol L^{-1} of KCl solution, the contents of exchangeable cations (Ca^{2+} and Mg^{2+}), available P, exchangeable K and Na, exchangeable Al, potential acidity (H + Al) and total organic carbon were determined according to (Teixeira et al., 2017). The Fe, Al, Ti, and Si elements were obtained by sulfuric attack on the FADS after boiling and refluxing, followed by cooling, dilution, and filtration. The Fe_2O_3, Al_2O_3, TiO_2, and SiO_2 contents were determined by plasma emission spectrometry in both the sulfuric extraction filtrate and the alkaline extraction residue. The Fe oxide contents of high and low crystallinity were extracted by solutions of sodium dithionite-citrate-bicarbonate (Mehra & Jackson, 1960) and ammonium oxalate at pH 3.0, respectively. The Fe_{oxa}/Fe_{DCB} ratio was calculated from the Fe_2O_3 contents determined in the extracts by atomic absorption.

The mineralogy of the clay fraction was evaluated by X-ray diffractometry, rounds between 4 and 40° 2θ, according to Mehra & Jackson (1960), and rounds between 10 and 70° 2θ, according to Kämpf & Schwertmann (1982).

Results and Discussion

Morphological and physical properties

The soils developed from mafic rocks in the Taiano region are medium deep, well drained, with distinct morphological characteristics along the profile, showing typically latsolic morphology at the base (horizons Bt_2 and Bt_3 are actually Bw, Table 1). Towards the top, there is a change in structure, denoting the genesis of the Bt horizon superimposed over the Bw horizon (represented by the Bt_2 and Bt_3 horizons). The mineralogy of the clay fraction, dominated by kaolinite, followed by iron and aluminum oxides, favors the microgranular structure, formed from the intense biological activity of the mesofauna, notably termites and ants (Schaefer et al., 2001). The profiles also showed a consistency typical of very clayey soils, i.e. varying from slightly sticky to sticky.



Block diagram of Taiano soils and landscape features, illustrating the pedogeomorphological process

Figure 2. Follow-up free soil collection in the studied profiles in an agricultural area in the Bloco-Taiano.

Table 1. Morphological characteristics of the reference profiles in the Taiano region.

Horiz.	Depth (cm)	Color		Textural class	Structure	Cerosity	Consistency
		Dry	Humid				
P1 – *Argissolo Vermelho Eutrófico latossólico*, very clayey texture, A moderate – 2 years of cultivation							
Ap	0-15	10R4/3	10R3/4	Sandy-clay-loam	st., vsma., gran.	abun. mod.	ha., fir., plas., sli. sti.
A_1	15-25	10R4/3	10R3/6	Clayey	st., sma., gran.	abun. mod.	ha., fir., plas., sti.
BA	25-50	10R4/3	10R3/6	Clayey	mod., mea., sub. bl.	abun. mod.	sli. ha., fri., plas., sti.
Bt_1	50-60	10R4/6	10R3/4	Very clayey	mod., sma., sub. bl.	abun. mod.	ha., fri., plas., sti.
Bt_2	60-80	10R4/4	10R3/4	Very clayey	mod., sma. to mea., sub. bl.	abun. mod.	ha., fri., plas., sti.
Bt_3	80-100	10R4/6	10R4/4	Very clayey	fr., mea., sub. bl.	abun. mod.	ha., fri., plas., sti.
BC	100-130$^+$	10R4/6	10R4/3	Very clayey	fr., sma., sub. bl.	abun. mod.	mac., mfri., plas., sti.
P2 – *Argissolo Vermelho Eutrófico típico*, clayey texture, A moderate – 10 years of cultivation							
Ap	0-10	2,5YR3/4	2,5YR3/2	Sandy-clay-loam	st., vsma., gran.	abun. mod.	ha., fir., plas., sli. sti.
BA	10-15	2,5YR3/4	2,5YR3/2	Sandy-clay-loam	st., sma., gran.	abun. mod.	ha., fir., plas., sti.
Bt_1	15-40	2,5YR4/4	2,5YR3/3	Sandy-clay-loam	mod., sma. to mea., sub. bl.	abun. mod.	ha., fri., plas., sti.
Bt_2	40-60	10R4/4	10R3/6	Clayey	mod., sma. to mea., sub. bl.	abun. mod.	ha., fri., plas., sti.
Bt_3	60-80$^+$	10R4/4	10R3/4	Clayey	fr., mea., sub. bl.	abun. mod.	ha., fri., plas., sti.

abun.: abundant; mod.: moderate; we.: weak; st.: strong; sma.: small; mea.: mean; vsma.: very small; gran.: granulate; sub. bl.: subangular blocks; sof.: soft; sli. ha.: slightly harsh; ha.: harsh; vfri.: very friable; fri.: friable; fir.: firm; plas.: plastic; sli. sti.: slightly sticky; sti.: sticky.

The coloration presented hues ranging between 10R and 2.5YR, in accordance with the mafic nature of the source material, indicating the presence of material with high pigmenting power in the clay fraction, notably hematite (Resende et al., 2007), and without exhibiting the process of surface xanthization, common in soils from more humid Amazon regions. The red color is more pronounced in depth. Almeida et al. (2019) found similar coloration in soils derived from basic and ultrabasic rocks, associated with high Fe contents, ferromagnesian silicate minerals, and primary Fe oxides.

Clay contents indicate the presence of a textural gradient, characterizing abrupt textural change in the diagnostic horizons, according to criteria established by the Brazilian Soil Classification System (Santos et al., 2018) (Table 2). The silt content was relatively low, reflecting a low silt-clay^{-1} ratio (less than 0.17) in the diagnostic horizons and indicating a relatively high stage of weathering, comparable to Latosols. However, moderate and abundant cerosity was described, revealing an eluviation/illuviation process and a lower degree of weathering than in Latosols (Resende et al., 2007). The latosolic aspect evidenced by the morphology of the base of the profile suggests polycyclic genesis of Bt superimposed on Bw. The clay cation exchange capacity (CEC) values, on the other hand, showed soils with shrinking movements when dry, and expanding movements when wet.

Chemical properties and oxide contents

As for the acidity of these soils, pH values above 5.0 are observed for both profiles and in all horizons, with negative

Table 2. Physical characteristics and activity of the clay fraction of reference profiles and areas under shifting cultivation in the Taiano region.

Horizon	Depth (cm)	Granulometry				$T_{clay}$$^{(1)}$ ($cmol_c\ kg^{-1}$)	B/A$^{(2)}$	Silt/clay
		Thick sand	Fine sand	Silt	Clay			
		($dag\ kg^{-1}$)						
P1 – *Argissolo Vermelho Eutrófico latossólico*, very clayey texture, A moderate – 2 years of cultivation								
Ap	0-15	29	22	15	34	39.58	-	0.44
A_1	15-25	22	18	13	47	13.23	-	0.27
BA	25-50	16	14	12	58	10.24	-	0.20
Bt_1	50-60	15	13	10	62	8.32	1.82	0.16
Bt_2	60-80	14	12	8	66	8.00	1.94	0.12
Bt_3	80-100	14	11	13	62	8.45	1.82	0.21
BC	100-130$^+$	17	10	9	64	7.73	-	0.14
P2 – *Argissolo Vermelho Eutrófico típico*, clayey texture, A moderate – 10 years of cultivation								
Ap	0-10	28	27	19	26	38.69	-	0.73
BA	10-15	27	25	16	32	29.72	-	0.50
Bt_1	15-40	21	21	7	51	11.88	1.96	0.14
Bt_2	40-60	18	20	9	53	11.02	2.04	0.17
Bt_3	60-80$^+$	19	18	17	46	10.76	1.77	0.37

(1) Clay dispersed in water; (2) Clay fraction activity; (3) Textural relationship between the B and A horizons.

pH delta, indicating the predominance of net negative charge, favoring the CEC. Despite the basic nature of most of the rocks present, more acidic pH values may result from the higher levels of organic matter, which contributes to the lower pH values in the superficial horizons (Ciotta et al., 2003). The highest values of CEC were verified in the superficial horizons, with a predominance of the Ca^{2+} ion, and the highest values of base saturation (V%) were verified for P1. As for the subsurface diagnostic horizons, the V% values are above 50%, characterizing eutrophic soils (Santos et al., 2018) (Table 3) resulting from the high exchangeable base contents, related to the nature of the source material (diabase) and the low potential acidity. As for P, the values were lower than 6.6 mg kg^{-1}, being classified as very low, according to the availability criteria adopted by CFSEMG (1999).

The stable Ca contents at depth suggest soils developed in situ from the mafic rocks, with shallow weathering mantle, with nutrient cycling and current bioclimatic conditions favorable to a eutrophic condition, concentrating exchangeable cations at the surface, even with constant cultivation.

Soil carbon is active in the CEC that guarantees the fertility of the soils in the Taiano region, even in agriculture with little fallow and intensity of fire and cultivation. Soils in the Amazon region are generally “poor” chemically, and show high aluminum contents and low CEC (Butzke et al., 2020), in contrast to the soils under study. Furthermore, cultivation in these areas does not result in apparent soil degradation, and even the carbon is shown to be higher in the longer cultivated profile.

The lowest SiO_2 values were found in the superficial horizons and are the result of an advanced desilication process, that is, monosialytic alteration. Fe_2O_3 contents, in the subsurface horizons, were above 90.0 g kg^{-1}, characterizing mesoferic soils (Santos et al., 2018), arising from the richness in ferromagnesian minerals, especially pyroxene (augite, pigeonite and small lamellae of biotite) and epidote, present in the diabase of the region (Schaefer et al., 2000). The increase in Fe_2O_3 content at depth promoted red hues (10R), with larger chroma, being most evident at P2, indicating drier conditions during the formation of the latosolic mantle. Fernandes et al. (2004) found similar field values, with a significant correlation between soil reddening index and hematite content, with color saturation being near 150.0 g kg^{-1} of soil.

Despite the mafic nature, TiO_2 contents were relatively low and variable in P1, with total values among the profiles in the range of 4.84 to 7.18 g kg^{-1}. This indicates possible mixing and reworking of the materials by erosion and pedimentation during the past dry climate, corroborated by the line of rocks with the presence of milky veined quartz. Another evidence of reworking of the materials is the trace element poverty in the profiles, an uncommon pattern in soils derived from mafic rocks. In relation to these elements, only the Zn contents presented a value above the detection limit and were higher than those verified by Melo et al. (2010), in soils derived from mafic rocks, in the northeastern portion of the state of Roraima. Low trace element contents associated with low occurrence of magnetite in mafic rocks of Roraima were reported by Schaefer et al. (2000).

In P1, the subsurface horizons, except Bt_3, presented Ki values lower than 2.2, a diagnostic condition for latossolic B horizon (Santos et al., 2018), while in P2 they were above (Table 4). However, these values are close to the limit for 1:1 clayominerals, suggesting a kaolinitic nature in the clay fraction of this soil. P2 showed a less pronounced pedogenetic evolution, but with monosialitic character alteration. The Al_2O_3 values obtained in the alkaline extract determine the possibility of isomorphic Al substitution in the tetrahedral silica. The proportions of Al_2O_3 obtained by alkaline extraction, in relation to total Al_2O_3 (R1), with a tendency to increase in depth, together with the SiO_2 contents, besides high values in the superficial horizons and low in the transitional horizons, can be attributed to the isomorphic substitution of Si by tetracoordinated Al and, in the superficial horizons, to the presence of organomineral alumina constituents not effectively

Table 3. Chemical characterization of the reference profiles in the Taiano region.

Horizon	Depth (cm)	pH			Sortive complex									V (%)	P (mg dm^{-3})	OC	N
		H_2O	KCl	ΔpH	Ca^{2+}	Mg^{2+}	K^+	Na^+	Al^{3+}	H+Al	S	CTCe	CTCp			(%)	
					(cmol$_c$ dm^{-3})												
P1 – *Argissolo Vermelho Eutrófico latossólico*, very clayey texture, A moderate – 2 years of cultivation																	
Ap	0-15	6.2	5.7	-0.5	8.8	1.6	0.64	0.62	0.0	1.8	11.66	11.66	13.46	86.6	2.4	2.96	0.19
A_1	15-25	5.5	5.4	-0.1	2.4	0.9	0.21	0.31	0.0	2.4	3.82	3.82	6.22	61.4	0.5	1.79	0.10
BA	25-50	5.5	5.1	-0.4	2.4	0.7	0.23	0.21	0.0	2.4	3.54	3.54	5.94	59.5	0.3	0.97	0.09
Bt_1	50-60	5.5	5.1	-0.4	2.3	0.7	0.18	0.18	0.0	1.8	3.36	3.36	5.16	65.1	0.0	0.74	0.03
Bt_2	60-80	5.5	5.1	-0.4	2.3	0.8	0.19	0.19	0.0	1.8	3.48	3.48	5.28	65.9	0.0	1.07	0.04
Bt_3	80-100	5.6	5.1	-0.5	2.4	0.9	0.22	0.22	0.0	1.5	3.74	3.74	5.24	71.3	0.0	0.58	0.01
BC	100-130$^+$	5.6	5.0	-0.6	2.5	0.9	0.17	0.18	0.0	1.2	3.75	3.75	3.75	75.7	0.0	0.19	0.00
P2 – *Argissolo Vermelho Eutrófico típico*, clayey texture, A moderate – 10 years of cultivation																	
Ap	0-10	6.1	-	-	4.5	1.3	1.80	0.66	0.0	1.8	8.26	8.26	10.06	82.1	6.4	2.41	0.17
BA	10-15	6.0	5.6	-0.4	4.0	1.1	0.56	0.55	0.0	3.3	6.21	6.21	9.51	65.2	3.2	2.22	0.01
Bt_1	15-40	6.1	5.6	-0.5	3.5	0.5	0.13	0.13	0.0	1.8	4.26	4.26	6.06	70.2	0.0	1.17	0.01
Bt_2	40-60	5.9	5.7	-0.2	3.2	0.5	0.16	0.15	0.0	1.8	4.01	4.01	5.84	69.0	0.0	0.78	0.01
Bt_3	60-80$^+$	6.0	5.9	-0.1	3.1	0.4	0.13	0.12	0.0	1.2	3.75	3.75	4.95	75.7	0.0	0.66	0.01

S - sum of bases; CECe - Effective CEC; CECp - Potential CEC; V - Base saturation; OC - Organic carbon.

Table 4. Results of SiO_2, Al_2O_3, Fe_2O_3, TiO_2, and Zn obtained in the filtrate, by sulfuric attack on FADS and in the residue, by alkaline extraction and molecular ratio Ki and Kr, in soils developed from mafic rocks in the Taiano region.

Hor.	Depth (cm)	Acid attack					Alkaline attack					Total					Σoxides[1]	Ki	Kr	R_1
		SiO_2	Al_2O_3	Fe_2O_3	TiO_2	ZnO	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	ZnO	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	Zn				
		(g kg^{-1})																		
P1 – *Argissolo Vermelho Eutrófico latossólico*, very clayey texture, A moderate – 2 years of cultivation																				
Ap	0-15	1.07	104.3	69.4	4.51	0.16	160.3	12.35	1.14	0.84	0.01	161.4	116.7	70.5	5.34	0.14	354.1	2.35	1.70	10.59
A_1	15-25	1.07	191.9	95.8	6.35	0.18	288.9	12.73	1.86	0.50	0.01	290.0	204.6	97.7	6.85	0.15	599.3	2.41	1.85	6.22
BA	25-50	1.07	233.7	108.1	5.85	0.18	297.5	8.17	3.72	0.50	0.01	298.5	241.9	111.8	6.35	0.15	658.7	2.10	1.62	3.38
Bt_1	50-60	1.50	224.2	109.5	5.18	0.19	284.6	10.64	3.86	0.50	0.01	286.1	234.8	113.4	5.68	0.16	640.2	2.07	1.58	4.53
Bt_2	60-80	1.28	262.2	113.5	5.68	0.19	329.6	22.80	5.72	1.50	0.01	330.8	285.0	119.3	7.18	0.16	742.5	1.97	1.56	8.00
Bt_3	80-100	1.28	229.9	112.7	5.01	0.18	344.5	26.98	4.29	1.67	0.01	345.8	256.9	117.0	6.68	0.15	726.6	2.29	1.77	10.50
BC	100-130⁺	5.14	247.0	115.4	4.68	0.16	284.6	16.72	4.29	0.84	0.01	289.8	263.7	119.7	5.51	0.14	678.9	1.87	1.45	6.34
P2 – *Argissolo Vermelho Eutrófico típico*, clayey texture, A moderate – 10 years of cultivation																				
Ap	0-10	1.28	107.5	55.6	4.84	0.13	184.9	19.00	1.72	0.50	0.01	186.2	126.5	57.3	5.34	0.11	375.5	2.50	1.94	15.02
BA	10-15	1.28	127.3	76.9	4.51	0.18	202.4	11.02	1.14	0.50	0.01	203.7	138.3	78.1	5.01	0.15	425.3	2.50	1.84	7.97
Bt_1	15-40	1.50	152.6	90.4	4.34	0.18	237.5	11.02	0.86	0.50	0.01	239.0	163.6	91.2	4.84	0.15	498.8	2.48	1.83	6.74
Bt_2	40-60	1.71	173.1	96.2	4.34	0.18	280.3	16.34	1.29	0.50	0.01	282.1	189.4	97.5	4.84	0.15	574.0	2.53	1.90	8.63
Bt_3	60-80⁺	1.71	191.9	100.2	4.34	0.18	278.2	12.05	1.72	0.50	0.01	279.9	204.3	102.0	4.84	0.15	591.2	2.33	1.77	6.05

Hor. - Horizon; [1] Sum of oxides; Ki - calculated as a function of SiO_2 and Al_2O_3 values; Kr - calculated as a function of SiO_2 and Al_2O_3 + Fe_2O_3; R_1 = Al_2O_3 (alkaline extract)/Al_2O_3 (total).

attacked by sulfuric digestion. This substitution can generate an increase in the CEC of the secondary argillominerals, giving rise to kaolinite with a higher surface charge.

Iron levels extracted with dithiorite-citrate-bicarbonate (Fed) and with ammonium oxalate (Feo)

A low Feo/Fed ratio is observed (Table 5), revealing a higher proportion of Fed in the clay fraction of these soils, but high compared to the values found by Campos et al. (2012), in Amazon soils; as they are soils with *in situ* development and shallow weathering mantle, these results are consistent with their lower degree of evolution relative to more weathered Latosols.

The nature of the parent material (diabase), rich in ferromagnesian minerals, and the bioclimatic conditions of the region were determining factors for the crystallization of the iron oxides.

Table 5. Fe_2O_3 content in the clay fraction obtained by extraction with sodium dithiorite-citrate-bicarbonate (Fed) and ammonium oxalate (Feo), and Feo/Fed ratio.

Horizon	Depth (cm)	Fed	Feo	Feo/Fed
		(g kg^{-1})		
P1 - *Argissolo Vermelho Eutrófico latossólico*, very clayey texture, A moderate – 2 years of cultivation				
Ap	0-15	113.2	10.4	0.092
A_1	15-25	119.6	8.9	0.074
BA	25-50	101.1	8.7	0.086
Bt_1	50-60	120.3	6.7	0.056
Bt_2	60-80	116.5	9.8	0.084
Bt_3	80-100	119.6	5.8	0.048
BC	100-130⁺	140.3	7.3	0.052
P2 - *Argissolo Vermelho Eutrófico típico*, clayey texture, A moderate – 10 years of cultivation				
Ap	0-10	84.3	8.8	0.104
BA	10-15	84.2	8.2	0.097
Bt_1	15-40	127.1	7.4	0.058
Bt_2	40-60	101.4	4.6	0.045
Bt_3	60-80⁺	98.5	9.6	0.097

The Fe contents extracted with acid ammonium oxalate (Feo), were higher than those obtained by Campos et al. (2011), in Santo Antônio do Matupi, Manicoré, AM, Brazil; Campos et al. (2012), in a natural grassland-forest transition, in the region of Humaitá, AM, Brazil. However, the soils studied by these authors are characterized by relatively lower organic carbon values compared to the soils in this study. This evidence confirms the effect of organic matter in reducing the crystallinity of these oxides.

The increase in Feo values verified in the Bt_2 (9.8 g kg^{-1}) and Bt_3 (9.6 g kg^{-1}) horizons of P1 and P2, respectively, associated with the increase in organic carbon in these horizons, indicate current ferrite formation, from the dissolution of goethite and/or hematite. This pattern indicates movement of iron complexed with organic matter in the subsurface or *in situ* destruction of more crystalline oxides by organic matter, a result that may be reinforced by the higher Feo/Fed values in such horizons.

Mineralogical characterization

The mineral composition of the clay fraction of the soils revealed (Table 6), in all horizons, a wealth of silicate minerals, with kaolinite dominating, followed by illite and, in similar proportions, hematite and goethite. The profiles were differentiated by traces of anatase in P1 and ilmenite in P2. This mineralogical pattern shows a relatively high degree of weathering, where the minerals present in diabase, such as pyroxenes (augite, pigeonite and small lamellae of biotite) and epidote, presented a pedogenetic evolution characterized by the hydrolysis process with partial elimination of silica. Similar mineralogical pattern, for the soil class, were verified by Benedetti et al. (2011), in soils of pre-intemperate origin, in Roraima, Brazil, and by Campos et al. (2011), in soils originated from saprolites of rondonian granites, in Amazonas, Brazil.

The climatic conditions of the Amazon, characterized by hot and humid climate, as well as the free drainage, without

Table 6. Mineralogy of the clay fraction, in descending order of occurrence, of the soils developed in the Taiano region.

Reference	Soil class	Horizon	Main minerals present in the clay fraction	
			DCB[1] (4 and 40° 2θ)	5 mol L^{-1} of NaOH (10 and 70 ° 2θ)
P1	*PVe latossólico*	Ap	Kaolinite, ilita	Hematite/goethite, traces of anatase
		Bt_1	Kaolinite, ilita	
		Bt_2		
		BC	Kaolinite, traces of ilita	
P2	*PVe típico*	Ap	Kaolinite, ilita	Hematite/goethite, ilmenite
		Bt_1	Kaolinite, ilita	
		Bt_3		

[1] Sodium dithiorite-citrate-bicarbonate.

excessive leaching of silica from the system, and the acidic medium were determining factors for the genesis of kaolinite (Zaninetti et al., 2016). Other minerals present in the profiles, such as illite, from the 2:1 mineral group, have their genesis based on the transformation of micaceous argillominerals and, or, from the neoformation of pyroxene products, by the addition of K^+.

Hematite and goethite were the only iron oxides identified by treating the samples with 5.0 mol L^{-1} of NaOH. Possibly formed from the oxidation of minerals that have iron in their constitution. This reaction causes the destruction of the crystalline structure of the mineral with ferrous iron (Fe^{2+}), oxidizing it to ferric iron (Fe^{3+}), forming hematite. During hydration, under more humid conditions, water is incorporated into the hematite structure. The occurrence of these oxides, in similar proportions in the profiles, evidences alternating cycles of wetting and drying or a polycyclic genesis.

Conclusions

The soils developed from mafic rocks (diabase) are clayey, with low/clay ratio, of kaolinitic-oxidic nature, and relatively rich in nutrients even with prolonged cultivation. Its genesis is polycyclic, revealing the following distinct phases: (i) a long period of latosolization in a humid tropical climate, which deepened the weathering mantle in the mafic rocks; (ii) a very sharp dry phase followed, when erosion (morphogenesis) became more pronounced and exhumed more resistant diabase blocks on the tops, and partially removed the pre-intemperate mantle; and, (iii) finally, the current, wetter, transitional climate is responsible for the argilluviation, elutriation and genesis of Bt horizons, with blocky structure and cerosity, superimposed on the microstructured, latosolic, sotopposed soil materials.

From the chemical point of view, these are soils that present eutrophy (V > 60%) in the profile, negligible exchangeable Al^{3+} and high exchangeable base values, with predominance of the Ca^{2+} ion, making them differentiated in relation to the dominant pattern of dystrophic soils under cerrado in Roraima, Brazil. The oxide distribution pattern, extracted by the sulfuric attack, reveals monosialytic alteration, with an active desilication process, with comparable proportions of hematite and goethite, and magnetite poverty. In general, the soils of the Taiano region present a less advanced stage of weathering and much better physical and chemical conditions compared to the soils normally found in the Amazon over pre-intempered sediments and crystalline rocks, denoting the importance of the mafic substrates in the formation of higher fertility soils, even in the current humid climate. They are classified as *Argissolos Vermelho Eutróficos*, in the case of latosolic P1 and typical P2. They represent a classic example of soils with textural Bt developed from pre-existing latosolic mantle (Bt_2 and Bt_3 horizons of the profiles).

Compliance with Ethical Standards

Author contributions: Conceptualization: JFVJ, CEGRS; Formal analysis: JFVJ; Funding acquisition: JFVJ, CEGRS; Investigation: JFVJ, MILS; Project administration: JFVJ, CEGRS; Resources: JFVJ; Supervision: CEGRS; Writing – original draft: JFVJ, CEGRS; Writing – review & editing: MGP, MILS, MCC, EGBF.

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