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Artigo de Pesquisa

Relationship between soil, relief, and parental material in the Devonian Escarpment – Ponta Grossa – Southern Brazil

Relações entre solo, relevo e material de origem na região da Escarpa Devoniana em Ponta Grossa – Sul do Brasil

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Abstract: The Devonian Escarpment (South Brazil) has developed in a very peculiar area, in the transition between the First (basement) and Second (Paraná Sedimentary Basin) Paranaense Plateaus. Considering this complex geological-geomorphological framework, this study aims to understand the relationship between soil, relief, and lithology in a sector of this area, in Ponta Grossa (Paraná State). Together with geological information, Copernicus elevation data were interpreted in order to divide the study area into morphopedological units, for which the probable soil cover could be inferred. Subsequently, field work was carried out to describe soil profiles and collect samples to perform granulometric and chemical analyses. On the top of the Second Plateau, *Neossolos Litólicos Húmicos* and *Hísticos* [Leptosols (Histic, Humic)] dominate due to the presence of headwaters and closed depressions, whose origin is related to mineral dissolution caused by organic acids. *Cambissolos Háplicos* [Cambisols] and *Latossolos Vermelho-Amarelos* [Clayic Ferralsols (Ferritic, Rhodic)] occur in interfluves where there are no headwaters and closed depressions. In the First Plateau, *Argissolos Vermelho-Amarelos* [Acrisols (Ferric)] associated with *Cambissolos Háplicos* [Cambisols] dominate on the slopes, while in the flat-bottomed valleys, *Gleissolos Háplicos* [Gleysols] associated with *Cambissolos Háplicos* [Cambisols] occur. In the Escarpment Front, *Neossolos Litólicos* [Loamic Leptosols (Cambic)] with low concentration of organic matter dominate over metamorphic rocks due to the presence of very steep relief.

Keywords: Geomorphology; Closed Depressions; Morphopedology; Paraná Plateaus.

Resumo: A interação solo, relevo e material de origem é complexa na chamada Escarpa Devoniana, em Ponta Grossa (PR), situada na transição entre o Primeiro (embasamento cristalino) e o Segundo Planalto (Bacia do Paraná) Paranaenses. Considerando esse particular arcabouço geológico-geomorfológico, este trabalho buscou compreender a relação entre essas três variáveis em um setor da área em questão. Com base nos dados de elevação Copernicus (30 m) e na litologia, a área foi dividida em compartimentos morfopedológicos, para os quais foi inferida a provável cobertura pedológica. Em campo, foram realizadas descrições de perfis de solo e coletadas amostras, submetidas a análises granulométricas e químicas para fins de classificação. Os resultados mostram que no reverso da escarpa dominam Neossolos Litólicos Húmicos e Hísticos, cuja gênese é possibilitada pela presença de depressões fechadas, as quais evoluem por processos de dissolução associados aos ácidos orgânicos. Cambissolos Háplicos e Latossolos Vermelho-Amarelos ocorrem nos interflúvios sem feições pseudocársticas. No Primeiro Planalto, dominam Argissolos Vermelho-Amarelos associados a Cambissolos Háplicos nas vertentes, enquanto que nos Vales de Fundo Plano ocorrem Gleissolos Háplicos associados a Cambissolos Háplicos. Na Frente Escarpada, em função do relevo declivoso, dominam Neossolos Litólicos, sobre rochas metamórficas, mas com baixa concentração de matéria orgânica.

Palavras-chave: Geomorfologia; Depressões Fechadas; Morfopedologia; Planaltos Paranaenses.

1. Introduction

Since the classical studies by Fallou (1862) and Dokuchaev (1879), it has been established that climate, relief, parental material, organic activity, and time are the factors that control the formation of soil, a concept later recapitulated by Jenny (1941). Although the relevance of these five factors is consensual, a special particular relationship between soil and relief can be verified, such that the genesis and evolution of one affects the genesis and evolution of the other, making it difficult to dissociate the two (QUEIROZ NETO, 2000, 2002, 2011). Such an association has been confirmed by several more recent studies carried out in Brazil (e.g. FURIAN et al., 1999, VILLELA et al., 2013, FURQUIM et al., 2017; PINHEIRO et al., 2020; SANTOS et al., 2024). Beyond relief and climate, bedrock lithology is one of the most evident factors that impact soil formation. Therefore, knowing the geomorphology and pedological cover of an area is a valuable tool that can be used to infer information about lithologies and geological structures existent in areas with few rock outcrops.

In this context, the technique of morphopedological mapping, developed by Castro and Salomão (2000), stands out as a tool for studying the relationship between soils, landforms, and parent material (rocks, sediments, and other soils). This technique involves the compartmentalization of the terrain in relation to soil and lithology, based on aerophotogrammetry surveys or digital elevation models, pre-existing geological mappings, and further detailing through fieldwork. The technique is widely used in the scientific community, with more than 90 publications utilizing this methodology (FIGUEIREDO and SALOMÃO, 2023).

In this context, the region known as the Devonian Escarpment, located at the transition from the Second Paraná Plateau—sculpted in the sediments of the Paraná Sedimentary Basin—to the First Paraná Plateau—formed on the Precambrian crystalline basement —uniquely displays the relationships between forms, soils, and lithologies. However, data on these components of the physical environment in the area are still scarce or are part of broader regional studies, making them unsuitable for use in larger-scale research (e.g., EMBRAPA, 1984; BOGNOLA et al., 2003; PARANÁ, 2004). Therefore, the objective of this work is to understand the interaction between landforms, soil, and parent material in a transition sector between the Second and First Paraná Plateaus, in order to understand how these three variables mutually influence one another, thereby contributing to explaining the landscape evolution of the area.

2. Study Area

The study area covers the regions of Abranches and Palmitalzinho, two localities situated in the municipality of Ponta Grossa, in the state of Paraná (southern Brazil), approximately 30 km southeast of the urban zone of the city (Figure 1). These locations are notable for lying at the boundary between the First and Second Paraná Plateaus, known as the Devonian Escarpment (MAACK, 1968).

The escarpment is the result of the erosional retreat of the Furnas Formation—of the Devonian age and part of the Paraná Sedimentary Basin—over the crystalline basement (MAACK, 1968). In the selected region, this erosional retreat is particularly illustrative, expressed through an asymmetrical relief composed of a higher area (Second Plateau – approximately 1,050 m in elevation) supported by the Furnas Formation, while the lower zone (First Plateau – approximately 600 m in elevation) is carved into the Precambrian basement. Between these two units, a heavily dissected landscape is formed by the fluvial system, marking the escarped zone. Although morphologically similar to *cuestas*, the most appropriate term to describe this feature is "glint," which, according to Peulvast and Varney (2001), refers to an aclinal escarpment formed at the unconformable contact between sedimentary lithologies and the crystalline basement.

The study area is situated not only between two major geomorphological units, but also between two morphostructural domains: The Atlantic Orogenic Belt and the Paraná Sedimentary Basin (SANTOS et al., 2006). The Paraná Basin is one of the main geotectonic units of South America, having formed between the Ordovician and the Late Cretaceous periods (MILANI, 2004). According to this author, this basin corresponds to an intracratonic syneclise and passed through six supersequences: Rio Ivaí, Paraná, Gondwana I, Gondwana II, Gondwana III, and Bauru. The Furnas Formation, which supports the escarpment relief (Figure 2), was formed during the Paraná Supersequence and consists of medium-grained sandstones of fluvial origin (MILANI, 2004), showing a high degree of cementation by silica and kaolinite (DE ROS, 1998). This formation also includes a basal layer of conglomerates (MILANI, 2004) and pelitic layers at the tops of the depositional cycles (DE ROS, 1998).

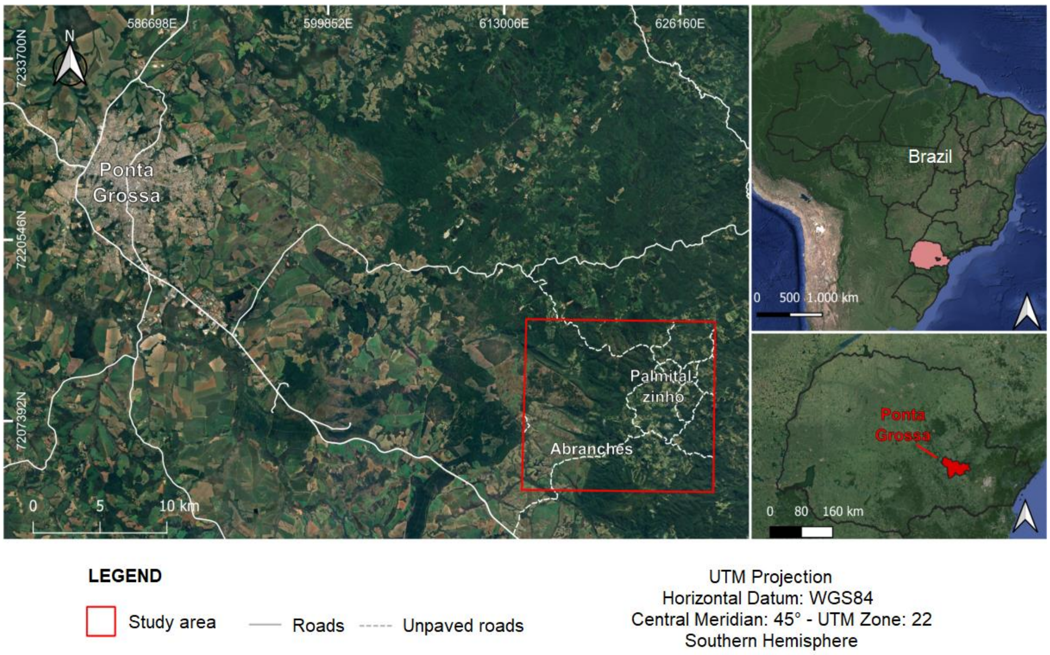

Figure 1. Map showing the study area. Source of the Satellite image: Google Earth. 2024.

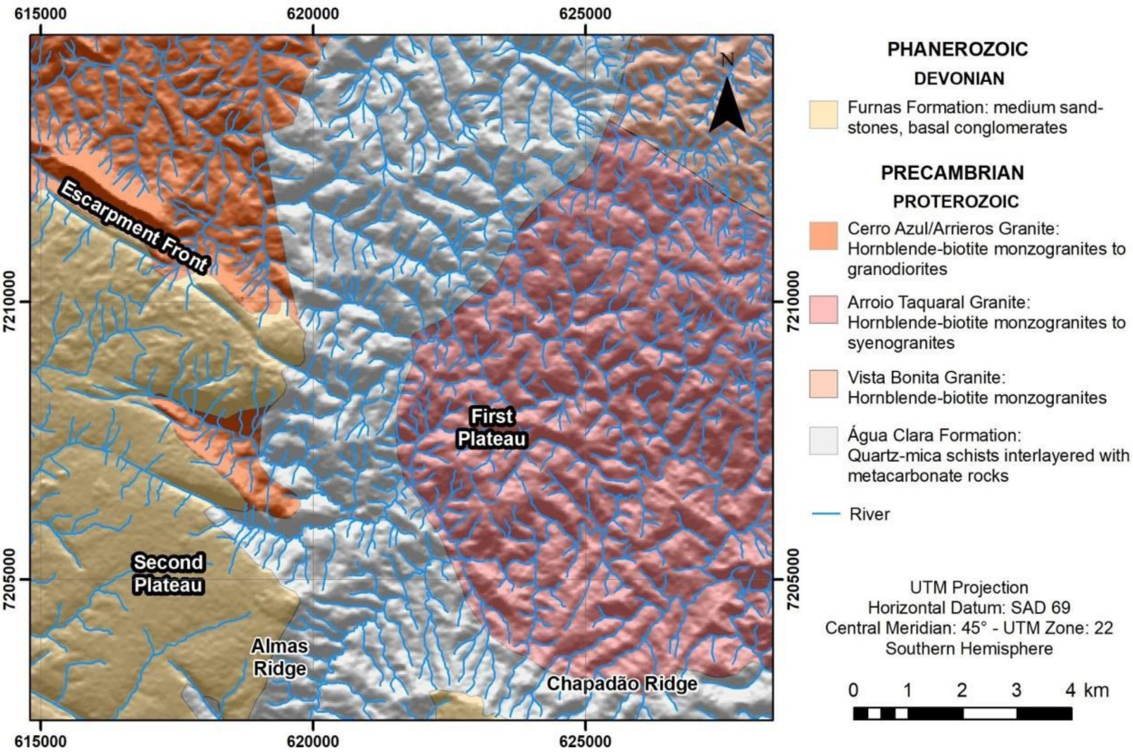

Figure 2. Geological map of the study region. Adapted from Besser et al., (2021). DEM: SRTM/NASA (2000).

The Atlantic Orogenic Belt is part of the crystalline basement of the region, which forms the most dissected relief and corresponds to the First Paraná Plateau. In the study area, this morphostructure is expressed as the Ribeira Belt, a result of the Brasiliano Orogeny, which dates back to the Neoproterozoic era (BESSER et al., 2021). The Ribeira Belt is a complex geotectonic unit, part of the Mantiqueira Province, and contains different terranes. Among them, the Apiaí Terrane stands out as the foundation of the crystalline basement in the study region.

According to Hasui et al. (1975), the Apiaí Terrane is composed of the Açungui Supergroup, the São Roque and Serra do Itaberaba Groups, and several granitic batholiths and stocks. Within the Açungui Supergroup, the Água Clara Formation is notable, as it outcrops in the study area. Two significant granitic batholiths are the BTC (Três Córregos Batholith) and the BCP (Cunhaporanga Batholith). The BTC forms the remaining terrain in the study area, where the Arrieros/Cerro Azul and Conceição subunits outcrop. The Conceição Unit is subdivided into the Arroio Taquaral and Vista Bonita facies, both of which outcrop in the eastern portion of the study area (Figure 2).

Dated to the Mesoproterozoic according to Weber et al. (2002), the Água Clara Formation shows a medium degree of metamorphism, between greenschist and amphibolite facies. According to these authors, the original deposition is interpreted as having occurred in a deep platform environment. This formation exhibits a great variety of lithologies and is divided into two members: The Lower Member and the Upper Member. The Lower Member, which outcrops in the central and north-central region of the study area, is predominantly composed of quartz-mica schists with chlorite, biotite, and muscovite, along with intercalations of metabasalts, quartzites, metamarl, metacherts, and marbles. The Upper Member is predominantly carbonate in composition, consisting of marbles and calcareous schists interbedded with quartzites and quartz-mica schists.

The Arrieros/Cerro Azul Granitic Unit, which outcrops in the northwest of the area, consists of grayish hornblende-biotite monzogranites to porphyritic granodiorites (PRAZERES FILHO, 2003). These are I-type granitic rocks, high in potassium, and classified as calc-alkaline and metaluminous. According to the same author, the Conceição Unit is also calc-alkaline, metaluminous, and of I-type typology. The Arroio Taquaral facies are comprised of reddish hornblende-biotite monzogranites with medium texture, while the Vista Bonita facies consist of pink hornblende-biotite monzogranites. This unit is also rich in potassium.

Various soil types have formed over these lithologies. According to Paraná (2004), the area includes *Cambissolos Háplicos* [Cambisols], *Latossolos Brunos* [Ferralsols], *Nitossolos Háplicos* [Nitisols], *Argissolos Vermelho-Amarelos* [Acrisols] and *Neossolos Litólicos* [Leptosols], as well as rock outcrops.

Finally, it is worth noting that the region's climate, according to the Köppen classification, is Cfb (CRUZ, 2007): mesothermal (mild summers with the average temperature of the warmest month below 22 °C), with no defined dry season. According to Moraes and Galvani (2012), the average annual precipitation in the municipality of Ponta Grossa (from January 1954 to December 2001) is 1,553.2 mm, while the average air temperature is 18 °C. These authors also report that evapotranspiration (ETP) reaches 821.6 mm, with a water surplus (EXC) of 733.4 mm.

3. Materials and Methods

The methodological approach of this study follows the principles of the Morphopedological Cartography, structured by Castro and Salomão (2000), based on the classical work of Tricart and Kilian (1979), and later simplified by Pinheiro (2009). In this context, a digital elevation model (DEM) of the study area was first generated using the QGIS software, based on topographic data from Copernicus, with a spatial resolution of 30 m (3 arc-seconds). Based on this DEM, hypsometry, slope, and topographic profiles were derived, which were essential for recognizing the relief patterns of the area.

From the visual interpretation of these data, the study area was divided into homogeneous units according to landform patterns, using hypsometry and surface roughness as the classification criteria. Based on this topographic information and geological data from Besser et al. (2021), the probable soils covering each unit were inferred, which guided the field survey. In the field, soil profiles were described in all these homogeneous zones, following the methodology of Santos et al. (2015). Information about the local lithology and the general geomorphological characteristics (slope and slope morphology) of each unit were also verified, enabling a more accurate determination of soil-relief-lithology relationships.

Additionally, 23 soil samples were collected for laboratory analysis, prioritizing profiles considered key to the understanding of soil genesis and their relationships with landforms and parent material. These samples were sent to the Soil Science Department of the "Luiz de Queiroz" College of Agriculture (ESALQ-USP), where chemical analyses were carried out (pH in H_2O, pH in KCl 1 mol L^{-1}, organic carbon content, levels of P, K, Ca, Mg, and Al, H+Al, base saturation, cation exchange capacity, V% and m%) along with grain-size analyses for classification purposes. The soils analyzed were classified according to the Brazilian Soil Classification System (SANTOS et al., 2018), but the correspondence with the World Reference Base for Soil Resources (IUSS Working Group - WRB, 2022) are indicated.

When the preliminary results were compared with field observations, it became clear that the complexity of the relationship between soil, landforms, and lithologies was greater than initially assumed. Therefore, a detailed geomorphological mapping of a sample section of the 2nd Plateau was conducted to better understand how these three variables interact on the reverse slope of the scarp. This mapping followed the legend proposed by Queiroz Neto and Journaux (1978), modified by Pinheiro and Queiroz Neto (2016), and was based on the interpretation of 1:25,000 scale panchromatic aerial photographs (ITC-PR, 1980).

All of the aforementioned data were then compared with the preliminary morphopedological information, allowing for (1) the establishment of the final boundaries of the morphopedological units, (2) the correction of soil, geological, and geomorphological data inferred during the preliminary analysis, and (3) an understanding of how the relationships between relief, lithology, and soil cover occur in the studied region—thus achieving the objective of the present study.

4. Results

The first stage of morphopedological compartmentalization involved the identification of the three major first-order geomorphological units (First Plateau, Escarpment Front, and Second Plateau) present in the area. These features are recognized in the Geomorphological Map of the State of Paraná (SANTOS et al., 2006). These large compartments were subdivided into seven morphopedological units (Figure 3): First Plateau: Flat-Bottomed Valleys with hydromorphic soils, Dissected Hills and Knolls covered by *Cambissolos* [Cambisols] and *Neossolos Litólicos* [Loamic Leptosols (Cambic)], Gently rounded Hills covered by *Cambissolos* [Cambisols] and *Argissolos* [Acrisols (Ferric)], and Knolls covered by *Cambissolos* [Cambisols]; Escarpment Front with shallow soils; Second Plateau: Smoothly convex interfluves covered by *Neossolos Litólicos* [Leptosols (Histic, Humic, and Cambic)] and Flat-Bottomed Valleys with rocky beds. The geomorphological characteristics of each unit, as well as their geological and pedological data, will be described below.

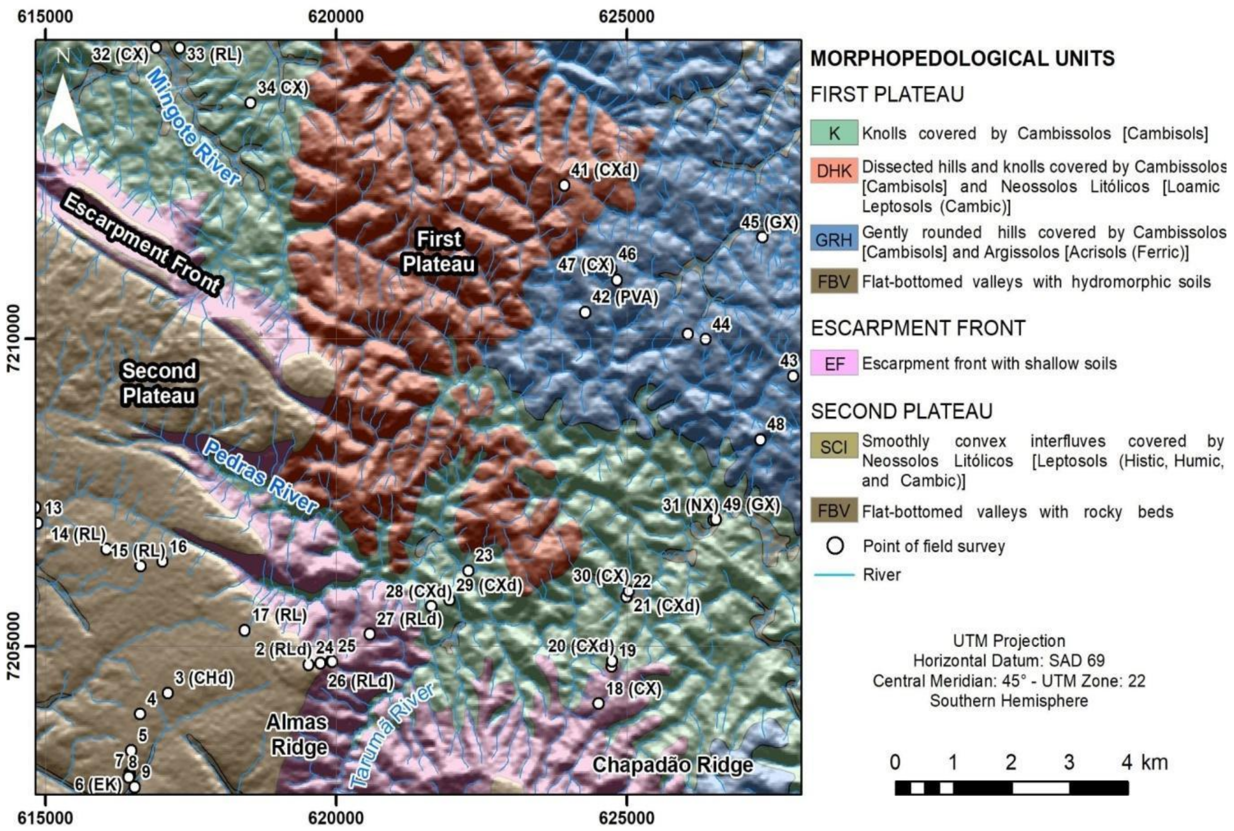

Figure 3. Map showing the morphopedological compartments of the study area. DEM: SRTM/NASA (2000).

• First Plateau (1P)

This unit encompasses the entire area below the escarpment, belonging to the so-called First Plateau of Paraná, subdivided into the compartments shown in Figure 3. The unit of Knolls (K) covered by *Cambissolos* [Cambisols] presents altitudes ranging from 700 to 900 meters and corresponds to regions with gently convex topography, with predominant slopes of 10 to 20°, reaching up to 30° only in occasional breaks (*cornijas*). Due to the gentle topography, this compartment presents a low drainage density, which follows a dendritic pattern.

The Dissected Hills and Knolls covered by *Cambissolos* [Cambisols] and *Neossolos Litólicos* [Loamic Leptosols (Cambic)] present an altimetric range exceeding 100 meters and can feature very steep slopes, surpassing 45° in inclination. The elevation ranges from 850 to 1,080 meters, a value consistent with that of the Second Plateau, making this the highest altimetric unit within the First Plateau. It presents a high drainage density, predominantly dendritic, although the pattern is occasionally subparallel. These geomorphological characteristics represent an undulating to strongly undulating relief, primarily supported by schists from the Água Clara Formation.

The Gently rounded hills (GRH) covered by *Cambissolos* [Cambisols] and *Argissolos* [Acrisols (Ferric)], like the DHK unit, present slopes with an altimetric range greater than 100 meters. However, their elevation is slightly lower, ranging from 790 to 960 meters. The hilltops and slopes are gently convex, while the drainage network is organized in a dendritic pattern. This landscape, carved into monzogranites and syenogranites, appears to represent an intermediate level between the more dissected relief of the DHK unit and the more subdued modeling of the Knolls compartment.

The Flat-Bottom Valleys with hydromorphic soils (FBV) occur at elevations ranging from 690 to 810 meters and also include floodplains and fluvial terraces, especially those along the main drainage channels that cross the area—namely the Rincão, Pedras, Tarumã, and Santa Cruz rivers. These wide valleys are zones with very gentle slopes, generally from 0 to 3°, not exceeding 12° in the steepest areas. Due to their flat bottoms and exposure to river dynamics, they are considered poorly drained environments and are likely composed of alluvial material, even though the geological maps (e.g. BESSER et al., 2021) covering the area—typically on a small scale—have not mapped these deposits.

Regarding the soil cover of the First Plateau, a general predominance of *Cambissolos* [Cambisols] and *Argissolos* [Acrisols (Ferric)] was observed, typically with clay to clay-loam textures (Table 1). These soils are highly acidic, with pH values ranging from 4.89 (point 31) to 5.26 (point 20), leached (with an average base saturation of less than 20%), and derived from the weathering of schists and granites (Table 2). *Argissolos* [Acrisols (Ferric)] are especially present on the hilltops of the GRH and DHK units. These soils exhibit a clear increase in clay content from the A horizon to the Bt horizon, where clay illuviation is evidenced by the presence of clay coatings. Some profiles contain a horizon with characteristics similar to a Bw horizon (friable soil, weak blocky structure that breaks into granular form, and few visible weatherable minerals) beneath the Bt horizon. Considering these features, along with their color (5YR 5/6; 7.5YR 4/3) and low saturation of exchangeable bases (Table 2), these soils were classified as *Argissolos Vermelho-Amarelos Distróficos* [Acrisols (Ferric)]. A notable feature is the frequent presence of granite saprolite within these profiles, especially in the C or BC horizon, as well as the presence of coarse sand enriched with quartz and feldspar throughout all horizons.

The *Cambissolos* [Cambisols] found in the K, GRH, and DHK units can be deep, with the C horizon reaching over 2 meters in depth. However, the A and Bi horizons are thin and poorly developed, as evidenced by the presence of rock fragments, high silt content (Table 1), and abundance of weatherable primary minerals (micas and feldspars, in addition to quartz)—all indicators of low degree of soil development. The C or CR horizons of these soils exhibit pinkish tones, while the B horizons display more brownish and red-yellow colors (7.5YR 4/6), as shown in Figure 4A.

All the described *Cambissolos* [Cambisols] are haplic and dystrophic (V%: <20%), but they show substantial differences depending on their parent material. Soils formed from the Cerro Azul granite are generally more incipient than those derived from the Arroio Taquaral granite. In the Cerro Azul granite, which contains feldspar phenocrysts, there is a high concentration of this minimally weathered mineral even in the surface horizon, forming angular gravel fragments. Under the Arroio Taquaral facies, with a monzogranitic to syenogranitic composition, the soils are slightly thicker and contain more quartz in the coarse fraction. In contrast, the *Cambissolos* [Cambisols] and *Argissolos* [Acrisols] (Figure 4B) derived from the schists of the Água Clara Formation present a finer texture, with clay (35 to 48% at point 41 – Table 1) predominating over silt and sand. These soils also clearly exhibit muscovite flakes from the R horizon up to the B horizon.

Table 1. Granulometric data of the soils of the 1st Plateau.

Point	Soil	Horizon	Sand (%)						Silt (%)	Clay (%)
			VCS	CS	MS	FS	VFS	TS		
20	CXd	Ap	14.8	15.5	9.6	5.6	2.1	47.7	17	35.3
		BA	15.3	13.2	9.4	5.8	2	45.7	11.4	42.8
		Bi	17.8	9.1	5.6	3.7	1.5	37.9	14	48.1
		C1	14.6	8.3	4.2	3.2	2	32.4	30.1	37.5
		C2	12.7	7.9	4.8	4.4	3.5	33.5	41.4	25.1
26	RLd	A	4.7	5.8	7.9	14.4	22.6	55.3	32.1	12.6
31	NB	A	0	0.2	0.6	1.8	2.4	5.1	54.1	40.8
		Bni	0	0.2	0.4	1.27	2.1	4.1	55.2	40.7
		120 cm*	0	0.4	0.7	2	3.2	6.4	42.4	51.2
41	CXd	Ap	0.7	1.7	3.3	10.4	17.1	33.3	31.4	35.3
		Bi1	0.9	1.9	2.9	10.6	18.6	35.1	29.3	35.6
		Bi2	1	1.7	2.7	9.5	18.9	33.8	26.5	39.7
		CB	1.3	1.7	2.3	8.3	18.8	32.3	19.8	47.8

Legend: VFS: Very Fine Sand (0.053 – 0.125 mm); FS: Fine Sand (0.125 – 0.250 mm); MS: Medium Sand (0.250 – 0.5 mm); CS: Coarse Sand (0.5 – 1 mm); VCS: Very Coarse Sand (1 – 2 mm); TS: Total Sand (0.053 – 2 mm). *Sample collected at a depth of 120 cm using a Dutch auger.

Table 2. Chemical data of the soils of the 1st Plateau.

Unit			-	-	g.kg^{-1}	mg.kg^{-1}	mmolc.kg^{-1}							%	
Point	Soil	Horizon	pH H_2O	pH KCl	O.M.	P	K	Ca	Mg	Al	H+Al	SB	CEC	V	m
20	CXd	Ap	5.26	4.13	42	<1.2	1.61	25.6	2.9	9,2	82	30.1	112.1	27	33
		BA	5.25	4.23	23.5	<1.2	0.69	12	1.5	11	56.6	14.2	70.8	20	44
		Bi	5.23	4.15	16.6	<1.2	0.51	7.1	1.1	14.5	42.6	8.7	51.3	17	62
		C1	5.1	4.11	12.4	<1.2	0.41	3.1	0.1	17.9	25.4	3.6	29	12	83
		C2	4.93	4.08	10.4	<1.2	0.56	0.8	<0.1	22.4	35.3	1.4	36.7	4	94
26	RLd	A	4.99	4.13	13	1.4	0.61	<0.5	<0.1	13	21.7	0.8	22.5	4	94
31	NB	A	4.89	3.88	22.2	3	1.15	6.6	4.9	26.8	58.5	12.7	71.2	18	68
		Bni	4.85	3.91	16.1	4.2	0.74	4.6	4.1	27.2	72.8	9.4	82.2	11	74
41	CXd	Ap	5	4.15	39	1.4	1.13	8.8	3.1	8.4	76.5	13	89.5	15	39
		Bi1	4.9	4.37	26.4	<1.2	0.59	4.9	0.5	3.7	44.9	6	50.9	12	38
		Bi2	4.9	4.57	17	<1.2	0.49	2.3	<0.1	2	39.3	2.8	42.1	7	42
		CB	5.05	4.83	10.6	1.7	0.43	3	<0.1	0.4	31.3	3.4	34.7	10	10

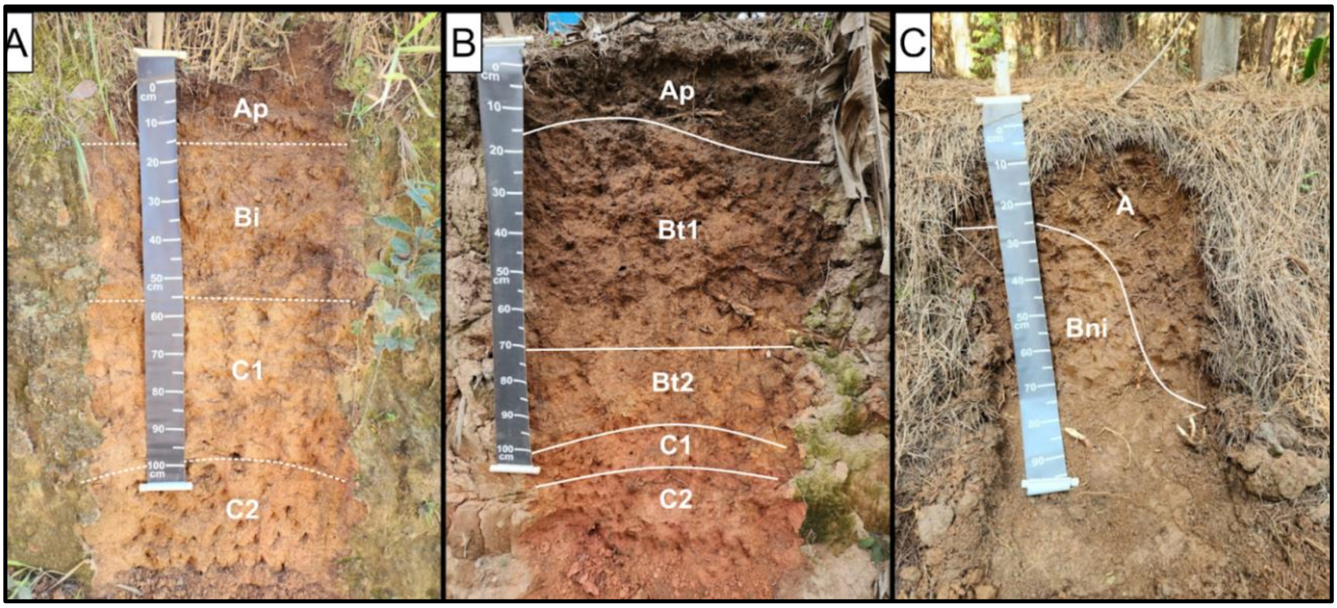

Figure 4. Soils of the First Plateau. A) *Cambissolo Háplico* [Cambisol], point 21. B) *Argissolo Vermelho-Amarelo* [Acrisol (Ferric)], point 42. C) *Nitossolo Bruno* [Nitisol], point 31. Continuous lines show clear transitions between horizons, whereas dotted lines show diffuse transitions. Each division on the scale is 5cm long.

In the FBV (Flat-bottomed valleys with hydromorphic soils), the presence of *Gleissolos Háplicos* [Gleysols] is notable, which aligns with the poor drainage conditions of these areas, as indicated by mottled colors associated with redoximorphic features. These soils are dominated by neutral and grayish colors (10Y 5/1; Gley 1 6/N), with textures ranging from silty clay loam to silty loam, high moisture content, and water table at the contact between soil and its parent material, usually fluvial deposits. *Cambissolos Háplicos* [Cambisols] were also found in these broad valleys, occasionally associated with the *Gleissolos Háplicos* [Gleysols], but occupying slightly higher positions such as low fluvial terraces and accretion bars. Additionally, a typical profile of *Nitossolo Bruno Distrófico* [Nitisols] was encountered (Figure 4C) at the transition between the footslope of a hill and the valley bottom.

• Escarpment Front (EF)

The Escarpment Front marks the transition between the First and Second Plateaus, delineating the boundary between the Paraná Sedimentary Basin and the crystalline basement. It corresponds to the steepest relief sector in the area, with slope inclinations ranging from 12° to over 45°. Although it is classified as an escarpment, the current morphology of this feature has been considerably softened due to the prolonged erosive action of the fluvial system on the edge of the basin (Figure 5). Rock faces are limited to the outcrops of the Furnas Formation and the large amphitheaters that emphasize the scalloped appearance of the escarpment.

The Escarpment Front is supported by the Furnas Sandstone, which hosts ruiniform relief features, and in certain sectors, by schists of the Água Clara Formation. The soils here are more incipient than those of the First Plateau, generally acidic and leached. The area is dominated by *Neossolos Litólicos* [Loamic Leptosols (Cambic)], which are silty and pinkish in color (5YR 4/4), and are derived from the weathering of schists (Figure 6).

Figure 5. Landscape view from the border of the 2nd Plateau, from which can be observed, in the background, crests and promontories highlighting the escarpment front roughness. In the first plane, a Furnas sandstone outcrop is shown.

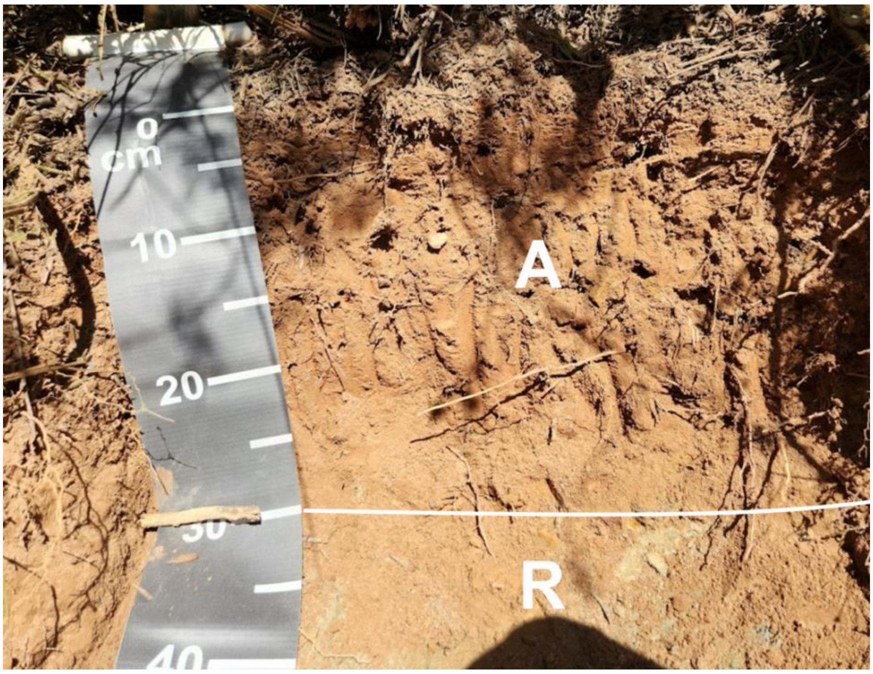

Figure 6. *Neossolo Litólico* [Loamic Leptosol (Cambic)] of the escarpment front. Horizon A in lithic contact with Horizon R (schists). Point 26.

•Second Plateau (2P)

The Smoothly convex interfluves (SCI) covered by *Neossolos Litólicos* [Leptosols] are features entirely carved into the Furnas Formation and present an altimetric range of less than 100 meters, with elevations varying from 1,060 to 1,130 meters. They exhibit extremely gentle slopes on both hilltops and hillsides, with boundaries that are difficult to define (Figure 7). Frequently, the relief in this compartment appears flat, and its drainage network presents a very low density. Among these broad, gentle interfluves are Flat-bottomed valleys (FBV), with elevations ranging from 940 to 1,060 meters and slopes below 12°.

Figure 7. Typical landscape of the 2nd Plateau, showing flat-bottomed valleys with rocky beds dissected by drainage that flow directly above the Furnas sandstone.

On the Second Plateau, soils were identified only in the smoothly convex interfluves, while the flat-bottom valleys appear as rocky riverbeds. The soils in the SCI are predominantly *Neossolos Litólicos* [Leptosols] with loamy-sandy texture, in association with *Cambissolos* [Cambisols] that present clay to clayey-sandy textures (Table 3). These soils feature a thick, very dark A horizon (5YR 3/1), containing up to 154.7 g.kg^{-1} of organic matter (Figure 8A – Table 4). In this context, these soils are classified as *Cambissolos Húmicos* [Cambisol (Humic)] (Figure 8B – Point 3), while the *Neossolos Litólicos* [Leptosols (Cambic)] occur in an association with *Neossolos Litólicos Hísticos* [Leptosols (Histic)] (Figure 8A – Point 2) and *Neossolos Litólicos Húmicos* [Leptosols (Humic)]. As in the First Plateau, these soils are dystrophic and highly acidic, with pH values ranging from 4.71 to 5.87, with high aluminum concentrations in the exchange complex (Table 4), generally exceeding 70%.

Although the previously mentioned soils are dominant, an *Espodossolo Humilúvico Órtico típico* [Arenic Umbrisol (Cambic)] (Figure 8C) was also described in the middle third of a gentle slope (Point 6). The Bh horizon, characterized by the accumulation of organic matter, presents a 10YR 3/4 color, loamy-sandy texture, and massive structure. The BA horizon displays a lighter color (7.5YR 4/6) and contains vertical fissures filled with organic matter. While the parent material in other SCI profiles is sandstone, at this point the parent material is a pelitic rock, where water emerges at the contact with the overlying soil.

In addition to the *Espodossolo* [Umbrisol], a *Latossolo Vermelho-Amarelo Distrófico petroplíntico* [Clayic Ferralsol (Ferritic, Rhodic)] (Figure 8D) with a clayey-sandy texture was also found, though sporadically, at the top of a very gentle slope. These *Latossolos* [Ferralsols] feature an A horizon with a color (7.5YR 4/3) that is much lighter than that of the surface horizon of other soils in this geomorphological compartment. In the C horizon, there is a layer of pebbles (stone-line) composed of petroplinthite/laterite, marking the transition from the altered material to the sandstone. The soil cover progressively becomes thinner farther down this slope, giving rise to a *Neossolo Litólico* [Leptosol] (Figure 8E) at the break that marks the transition to the valley bottom, where the Furnas sandstone outcrops.

Table 3. Granulometric data of the soils of the 2nd Plateau.

Point	Soil	Horizon	Sand (%)						Silt (%)	Clay (%)
			VCS	CS	MS	FS	VFS	TS		
2	RLi	Ap	1	3.4	17	39.6	3.2	64.2	25.5	10.3
		H	0.7	5.5	24.9	33.8	8.3	73.2	16.4	10.4
		CR	5.8	14.5	12.4	11.6	35.5	79.8	10.3	9.9
3	CHd	Ap	3.5	14.8	21.1	14.7	3	51.1	13.1	35.8
		A2	2.9	8.9	17	23.4	1.3	50.9	2.7	46.4
		BC	1.1	2.1	3.9	11.6	25.7	44.4	5	50.6
		C	2.5	9.7	24.8	29.6	26.5	40.1	2.1	57.9
10	LVAd	Ap	3	10.1	25.5	24.4	4.7	67.8	1.9	30.3
		Bw	7.2	9.4	19.8	20.5	3.8	61	3.9	35.4
		BC	8	9.4	19.9	20.2	4.6	62.2	2.9	35
		C					-			

Legend: VFS: Very Fine Sand (0.053 – 0.125 mm); FS: Fine Sand (0.125 – 0.250 mm); MS: Medium Sand (0.250 – 0.5 mm); CS: Coarse Sand (0.5 – 1 mm); VCS: Very Coarse Sand (1 – 2 mm); TS: Total Sand (0.053 – 2 mm).

Table 4. Chemical data of the soils of the 2nd Plateau.

Chemical data of the soils of the 2nd Plateau															
Units			-	-	$g.kg^{-1}$	$mg.kg^{-1}$	mmolc.kg-1							%	
Point	Soil	Horizon	pH H_2O	pH KCl	O.M.	P	K	Ca	Mg	Al	H+Al	SB	CEC	V	m
2	RLi	Ap	5.87	3.91	53.6	5.3	5.63	10.9	8.7	54.1	282.7	25.2	307.9	8	68
		H	5.53	4.27	154.7	<1.2	1.3	<0.5	0.1	30.3	164.7	1.5	166.2	1	95
		CR	5.67	4.52	20	5	0.28	<0.5	0.1	6.8	53.3	0.4	53.7	1	95
3	CHd	Ap	5.12	4.04	68.8	1.6	2.28	6.6	4.9	33.3	167.3	13.8	181.1	8	71
		A2	5.18	4.25	53.1	<1.2	0.54	1.5	0.6	28.2	156.3	2.6	158.9	2	91
		BC	4.86	4.37	18.4	<1.2	0.33	<0.5	<0.1	6.3	40.1	0.4	40.5	1	94
		C	4.8	4.48	13.6	<1.2	0.26	<0.5	0.1	3	32	0.4	32.4	1	89
10	LVAd	Ap	4.71	4.31	16.9	<1.2	0.36	1.2	<0.1	4.9	38.2	1.6	39.8	4	76
		Bw	4.84	4.07	24.8	<1.2	0.82	0.9	<0.1	11.2	49.3	1.7	51	3	87
		BC	5.12	4.8	12.8	<1.2	0.2	<0.5	<0.1	0.4	51.8	0.5	52.3	1	44
		C							-						

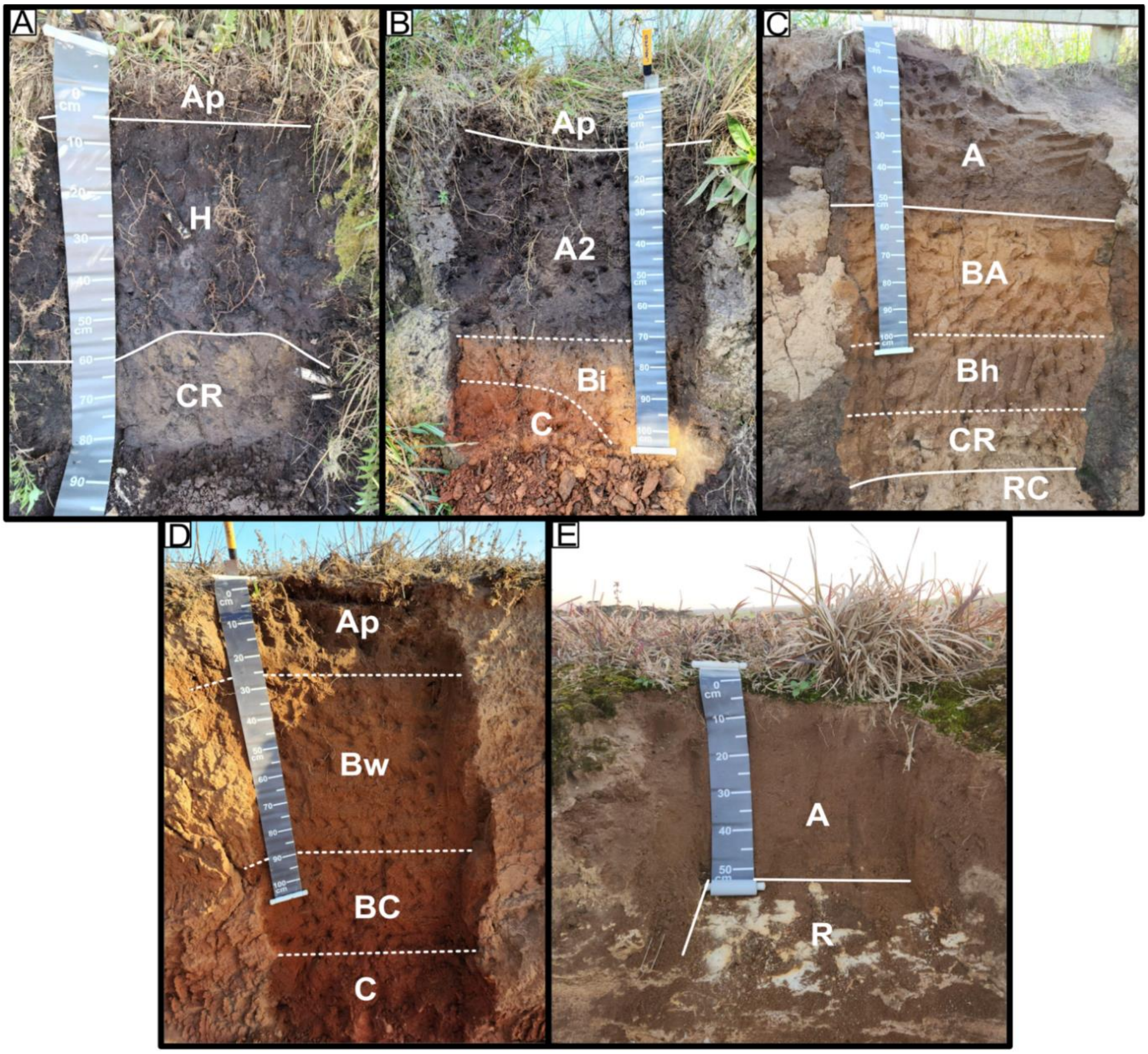

Figure 8. Soil profiles of the Second Plateau. A) Point 2, *Neossolo Litólico Hístico típico* [Leptosol (Histic)]. B) Point 3, *Cambissolo Húmico Distrófico latossólico* [Cambisol (Humic)]. C) Point 6, *Espodossolo Humilúvico Órtico típico* [Arenic Umbrisol (Cambic)]. D) Point 10, *Latossolo Vermelho-Amarelo Distrófico petroplíntico* [Clayic Ferralsol (Ferritic, Rhodic)]. E) Point 11, *Neossolo Litólico Distrófico típico* [Loamic Leptosol (Cambic)]. Continuous lines show clear transitions between horizons, whereas dotted lines show diffuse transitions. Each division on the scale is 5 cm long.

During fieldwork, the possible occurrence of closed depressions on the interfluves was observed (Figure 9). Since the elevation difference between the bottom of these depressions and their edges is subtle, and anthropic activity has altered part of these features, a morphopedological and geological profile was constructed (Figure 10). A detailed geomorphological map of part of the scarp's reverse slope was also assembled, as shown in Figure 11, to examine the morphology and spatial distribution of the depressions in relation to the relief and materials. The map confirms that there is not only a large number of closed depressions in the interfluves, but also many drainage headwaters. Additionally, the map shows that the Furnas sandstone outcrops at various points, especially near the scarp (Figures 5 and 7), and the main valleys are accompanied by abrupt breaks in the slopes (cornices). The map also highlights the clear NW-SE and NE-SW alignment of the main drainage lines, as well as of the principal break in the scarp. The profile (Figure 10), in turn, shows the clear control of landforms over soil types: *Neossolos Litólicos* [Leptosols] and *Cambissolos* [Cambisols], both with high organic matter content, are concentrated on the interfluve tops, particularly in closed depressions and near drainage headwaters, always over the Furnas Formation. In contrast, in the scarp zone, *Neossolos Litólicos* [Leptosols] and *Cambissolos* [Cambisols] alternate depending on changes in slope gradient.

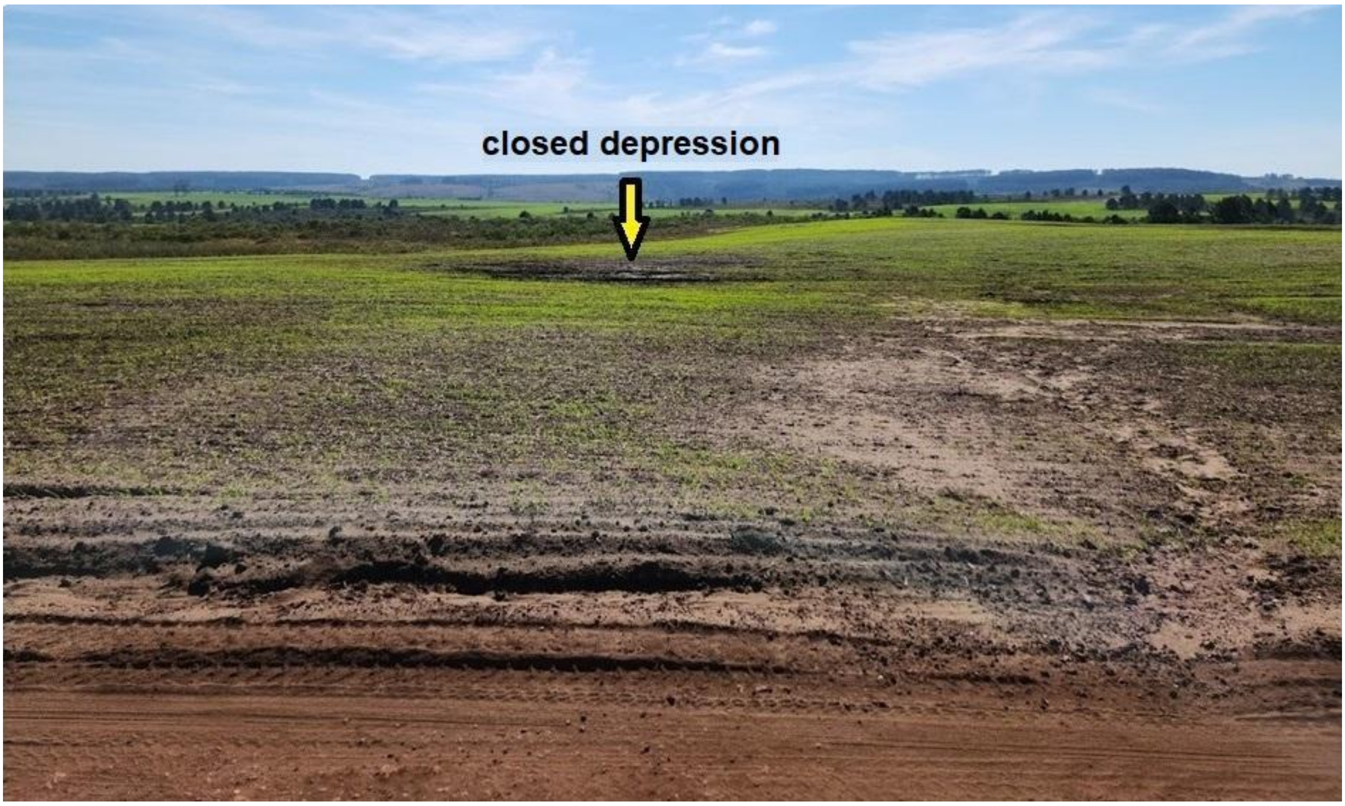

Figure 9. Closed depression on top of a gentle interfluve in the Second Plateau.

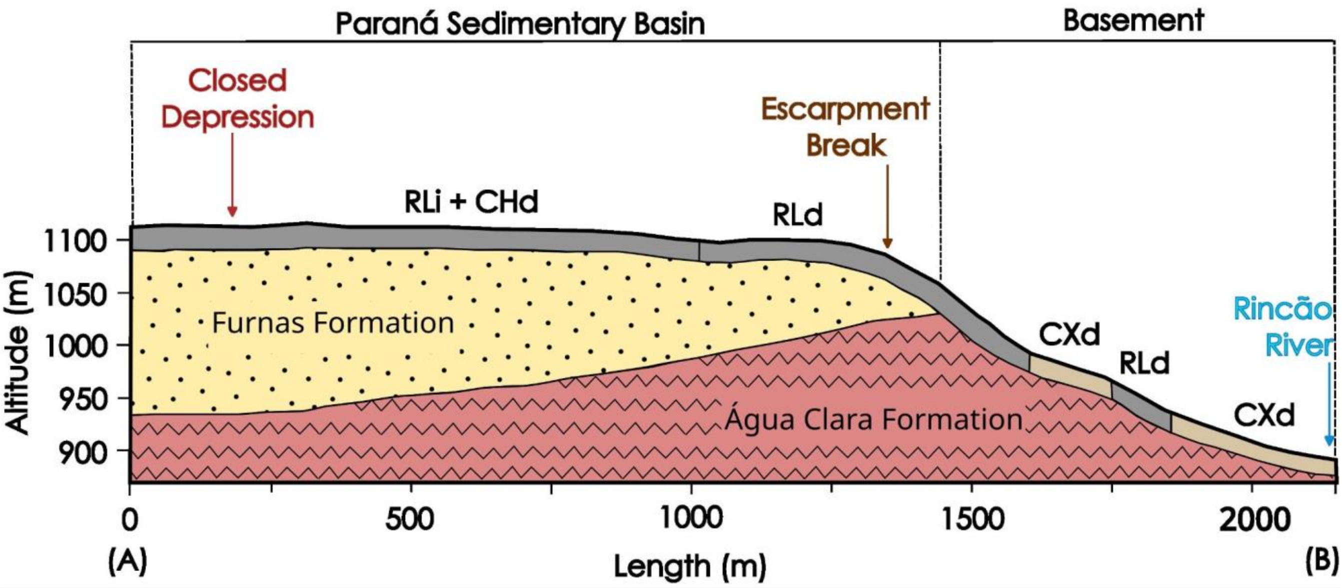

Figure 10. A-B morphopedological and geological profile showing the variations in soils as a function of changes in relief and geological substratum. The location of this profile is shown in Figure 11.

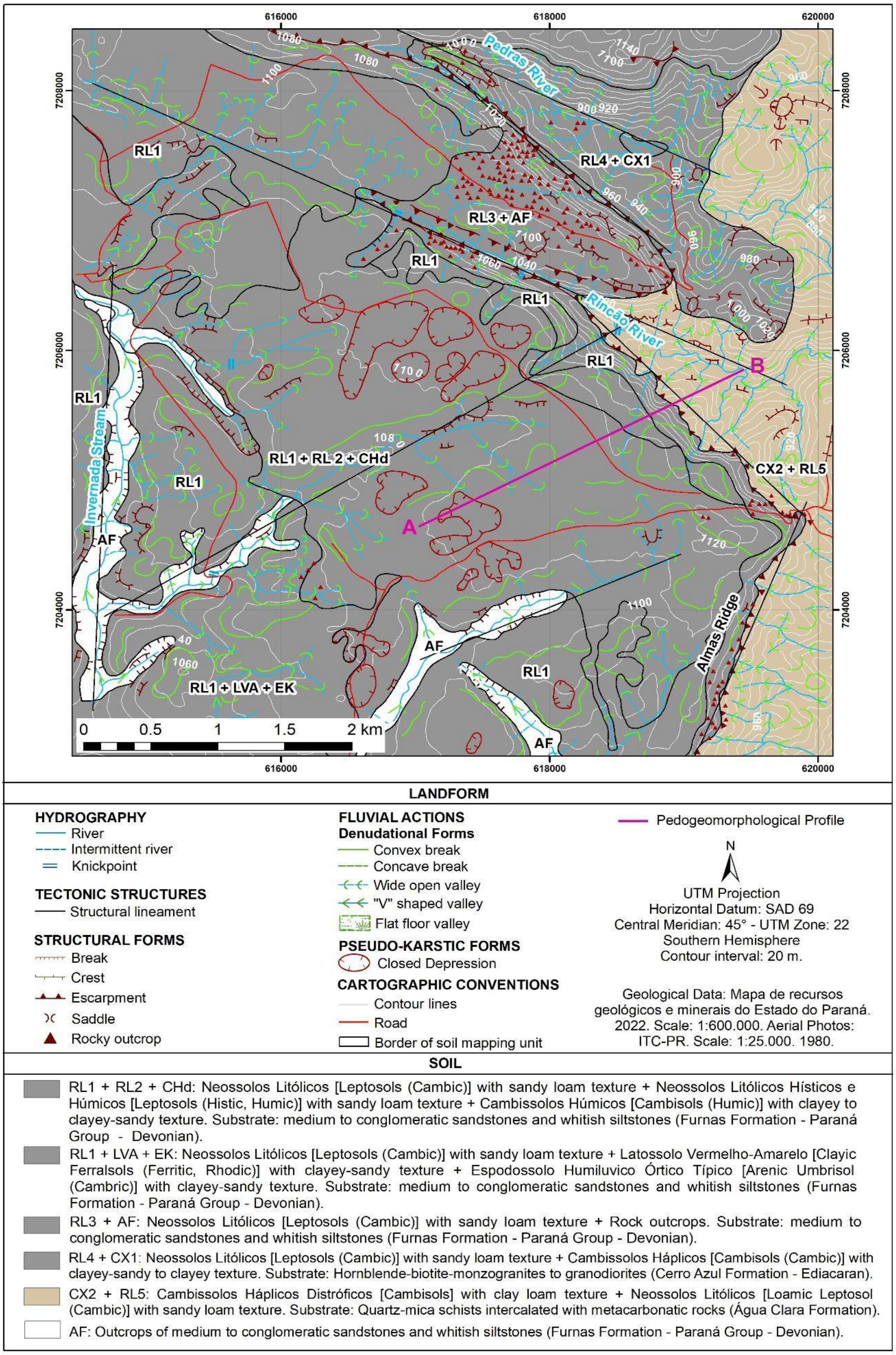

Figure 11. Geomorphological map showing the relations between landforms and materials (soils and rocks) in the sector in which the closed depressions occur in the Second Plateau.

4. Discussion

In the First Plateau, the relief and underlying lithology directly influence the characteristics of the soils, although the degree of importance of these factors varies depending on the specific features of each area. The soils, both on hills and on hillocks, are poorly developed—generally *Cambissolos* [Cambisols]—even in the summit areas, where the slope and, consequently, morphogenesis are less intense. The most substantial difference is that in areas with gentler relief, regardless of lithology, the *Cambissolos* [Cambisols] exhibit latosolic characteristics (textural homogeneity and weak blocky structure that disintegrates into microaggregates), whereas in the steeper areas, characteristics commonly found in *Argissolos* [Acrisols] (abrupt textural gradient, blocky structure, and clay illuviation features), although incipient, are more frequent.

Although the variations in the rocks that underlie these hills and hillocks are not sufficient to generate other types of soils besides the aforementioned *Cambissolos* [Cambisols], changes in the morphology of these soils are observed due to variations in the mineralogy of the granites. In the Cerro Azul/Arrieros facies, which consists of porphyritic-textured granitoids, slightly weathered centimeter-sized feldspar crystals occur (Figure 3 - Point 33) even in the A horizon, even at the hilltops, where a thicker and more developed weathering mantle would be expected. This is unexpected, since feldspars are more susceptible to weathering than quartz, and therefore one would not expect to find feldspar phenocrysts even in the surface horizon. However, the classic Goldich (1938) weathering series suggests that potassium feldspars, which constitute the grains in question, weather more slowly than other types of feldspar, which may explain why these phenocrysts are more resistant to alteration. In any case, further studies are needed to clarify this issue.

In the FBVs (flat-bottomed valleys), geomorphological characteristics greatly influence soil distribution, as small variations in landform significantly alter water dynamics. In these broad valleys, more grayish soils dominate, primarily *Gleissolos* [Gleysols], resulting from the absence of iron or its presence in a reduced form (e.g., GRIGOROWITSCHS and RODRIGUES, 2014), due to the reducing conditions of these poorly drained environments. Even in completely silted-up abandoned meanders, *Gleissolos* [Gleysols] are more common, whereas in accretion bars and fluvial terraces, *Cambissolos Háplicos* [Cambisols] are predominant (Figure 12).

In the Escarpment Front, the soils are also incipient, as in the First Plateau, but they are shallower, with *Neossolo Litólico* [Loamic Leptosol (Cambic)] predominating (Figure 3 – Point 26). This aligns with what is commonly reported in studies exploring pedogeomorphological interactions (e.g., CASTRO and SALOMÃO, 2000; ROSSI and QUEIROZ NETO, 2001; VILLELA et al., 2015; ROSSI, 2017; PINHEIRO et al., 2020; FIGUEIREDO and SALOMÃO, 2023), which associate steep slopes with a low degree of soil development. In such cases, the balance between morphogenesis and pedogenesis is not favorable for the development of the soil cover—a classic issue in Pedology (e.g., JENNY, 1941) and Geomorphology (e.g., TRICART, 1977).

The soil cover of the Second Plateau differs almost entirely from the inferences made prior to the field surveys, in which we predicted the predominance of *Neossolos Quartzarênicos* [Arenosols] and occasional medium-textured *Latossolos* (Ferralsols) in this area, similar to what is observed on the top of cuesta areas in the Paraná Basin, such as in the Serra de São Pedro/SP region (e.g., OLIVEIRA and PRADO, 1989; LADEIRA and SANTOS, 2006; PINHEIRO et al., 2016) and in the Chapada dos Guimarães (ROSS, 2014). The dominant soils in the area are, however, *Neossolos Litólicos* [Leptosols], with the A horizon lying immediately above the consolidated sandstone in lithic contact. Additionally, another unforeseen characteristic of these soils is the presence of thick, dark-colored A or H horizons (Gley 1 2.5/N – greenish-black), whether or not capped by an Ap horizon. These features indicate a high concentration of organic matter, which was confirmed by the analytical data in Table 4, showing 154.7 g.kg^{-1} of organic matter in the H horizon and 53.6 g.kg^{-1} in the Ap horizon of a typical *Neossolo Litólico Húmico* [Leptosols (Humic)].

The accumulation of organic matter in this area occurs especially on the interfluve summits (Figure 13) due to a combination of geomorphological, lithological, and climatic factors, as explained: (1) the high concentration of drainage headwaters and closed depressions in the area, along with the very low local slope gradient, hinders water runoff, creating poorly drained environments. These conditions, according to Brady and Weil (2013) and Zenero et al. (2016), slow down the degradation of organic matter by reducing microbial activity; (2) the mesothermal climate of the area, with a relatively low average temperature of about 22 °C in the warmest month, reduces the rate of organic matter mineralization, considering that the intensity of this process increases with rising temperature (HU et al., 2024), with the optimal range for mineralization being between 25 and 35 °C; (3) the Furnas

Formation acts as a limiting factor for infiltration, causing accumulation of water at the soil–rock contact. Supporting this hypothesis, De Ros (1998) points out that the Furnas Formation presents a high degree of cementation, reducing its permeability. Furthermore, according to this author, the tops of the depositional cycles of this Formation are composed of pelites, which present very low permeability.

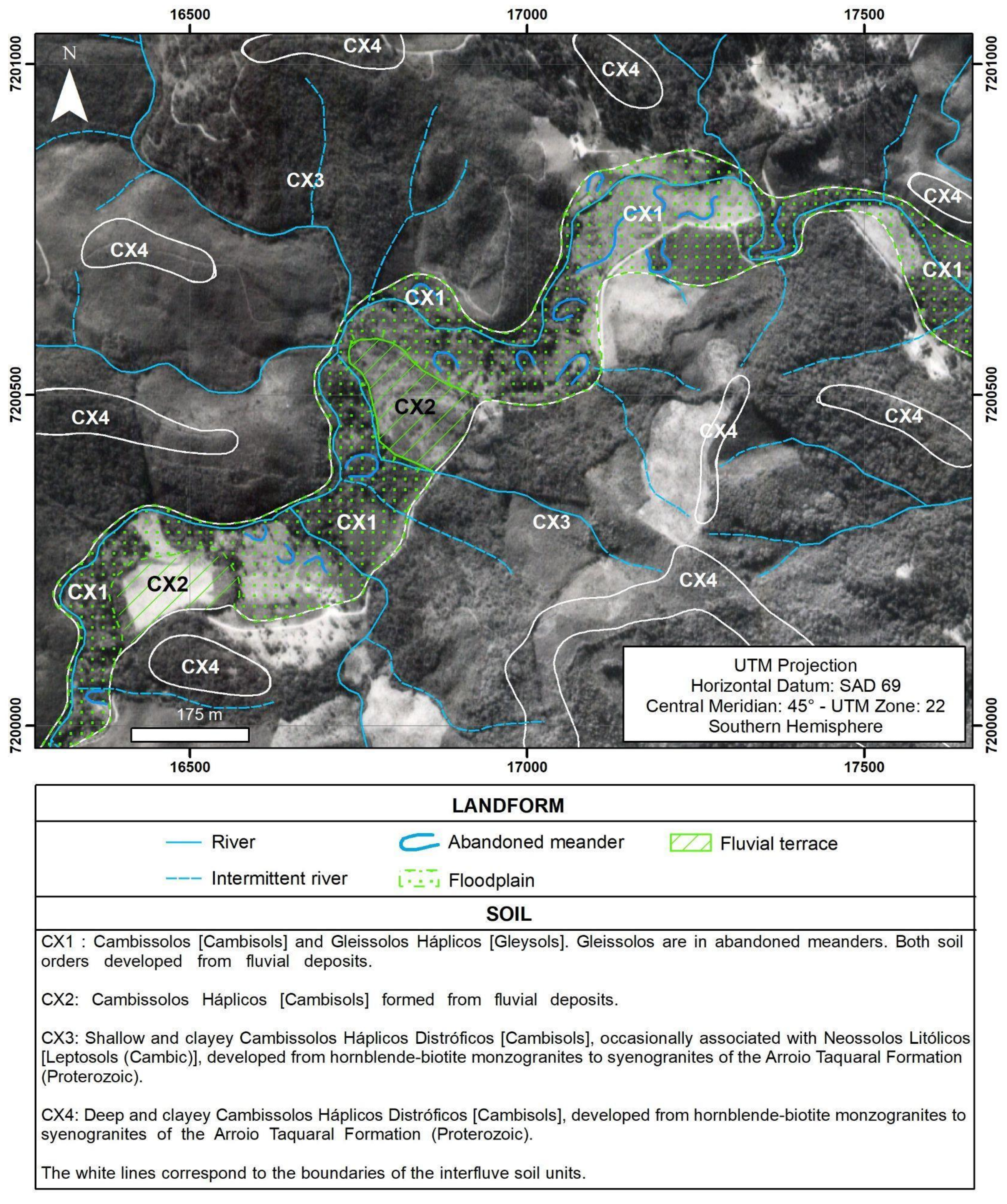

Figure 12. Example of fluvial morphologies in a subset of the Santa Cruz River floodplain (First Plateau), showing the corresponding soils and their parent materials. Background image: vertical panchromatic aerial photograph, scale 1:25,000 (ITC-PR, 1980).

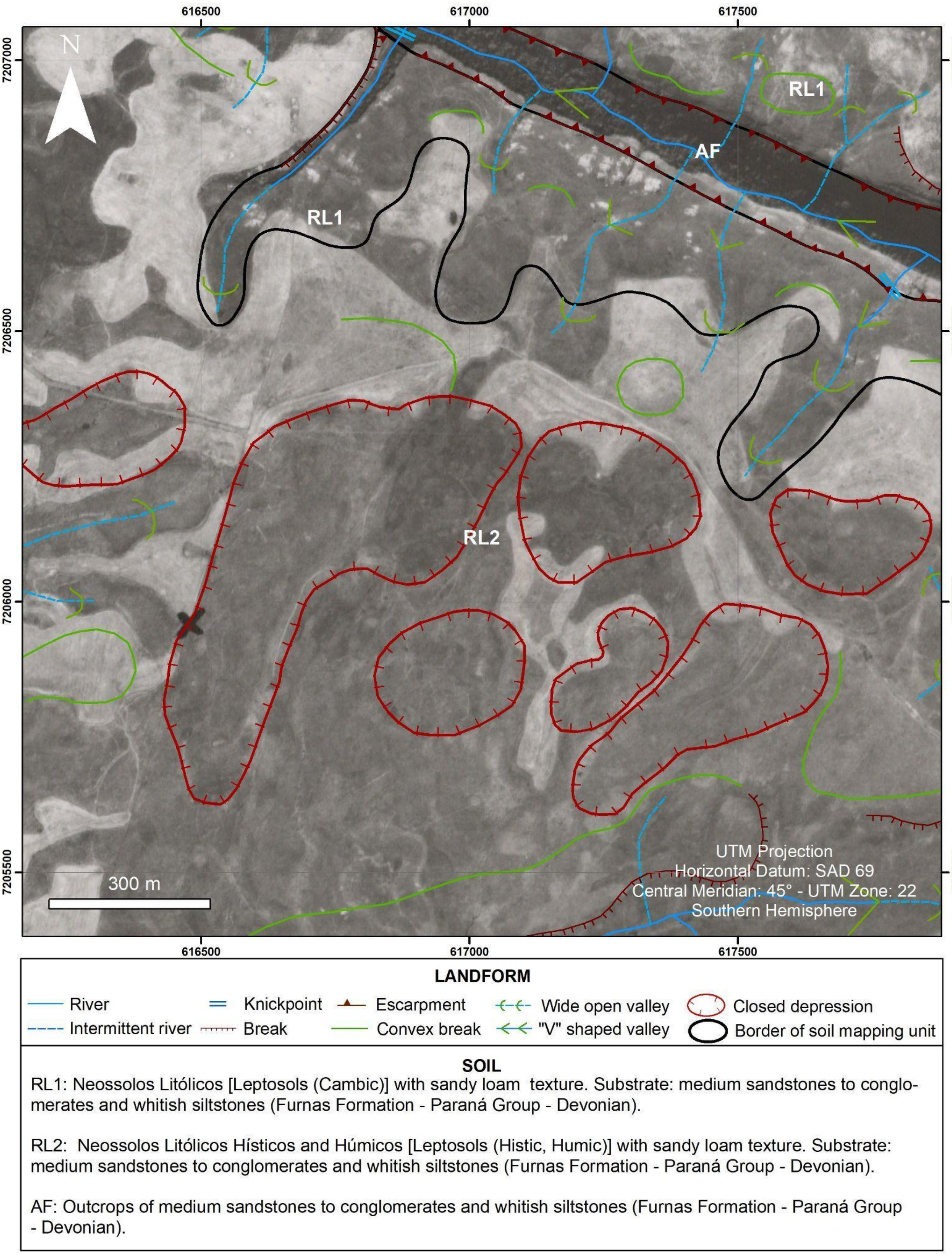

Figure 13. Example of closed depressions in the Second Plateau and their position in relation to drainage headwaters, soil cover, and geological substrate. Background image: vertical panchromatic aerial photograph, scale 1:25,000 (ITC-PR, 1980).

On the other hand, the presence of *Latossolos Vermelho-Amarelos* [Clayic Ferralsols (Ferritic, Rhodic)] without histic horizons was observed on the broad interfluve summits (SCI) where there are no closed depressions or drainage headwaters (Figure 3 – Point 10). This fact reinforces the argument that there is a close relationship between geomorphological, lithological, and pedological characteristics. Just as the closed depressions and drainage headwaters enabled the deposition and accumulation of organic matter and the formation of organic matter-enriched horizons, it is plausible to assume that the pedological characteristics also influenced the genesis and evolution of the depressions, mainly through the loss of material in solution. Although the very acidic pH of the depression soils, ranging from 5.7 to 4 (Table 4), is not particularly favorable for silica alteration—since silica is most unstable at pH ≥ 9 (e.g., WEAST et al., 1986; PALMER and PALMER, 2003)—we considered that the accelerated leaching of Al^{3+}, Fe^{3+}, and $Fe(OH)_3$, which are quite unstable under highly acidic conditions (FORMOSO, 2006), may be associated with the genesis of pseudokarst features in this area. Although still underexplored, the hypothesis that the genesis of these depressions is linked to dissolution processes had already been suggested in the classic studies by Maack (1946 and 1956), and was later revisited by Melo et al. (2011) and Pontes et al. (2022), who classify the closed depressions as true karst landforms, based on Wray's concept (1997a and b).

It is also considered that some of the drainage headwaters on the Second Plateau may possibly be remnants of former closed depressions that have already been captured by the fluvial system—a hypothesis similar to that proposed by Alves (2014) regarding the genesis of closed depressions in areas underlain by sandstones of the Caiuá Formation, in the Maracaí region (Southeast Brazil). This idea is quite compelling when observing, both in the field and in Figures 11 and 13, the proximity between the drainage headwaters and the current, to the still uncaptured closed depressions of the Second Plateau.

Finally, it is noteworthy that in the flat-bottomed valleys of the Second Plateau, contrary to previous assumptions, no hydromorphic soils formed in fluvio-colluvial deposits or typical fluvial plain morphologies were found. No deposition was observed in these valleys, even though they are broad and present a low slope gradient. Instead, rocky beds were being dissected by the current drainage, presenting waterfall-like levels and rocky slabs, which prevent soil formation. Only at the foot of the slopes, adjacent to these valley bottoms, *Neossolos Litólicos* [Leptosols (Histic, Humic] are found, typically consisting of a thick and dark A horizon in lithic contact with the Furnas sandstone.

5. Conclusions

As discussed throughout this study, the control of the underlying lithology on the soils is evident, such that particular or local conditions also govern the development of the soil cover, influencing variations in soils that are difficult to predict solely based on prior studies of relief and parent material. This lithological control is prominent in the First Plateau, where silty soils with more pinkish tones are developed over schists, while sandy, red-yellow soils with angular gravel of quartz and feldspar are developed over granitic lithologies. Thus, the color and granulometry of the soils prove to be powerful indicators of the parent material.

In the Escarpment Front, the geomorphological control over the soil cover, expressed through the slope, is highlighted and seems to be the most important factor for soil formation. Intense morphogenesis only allows for the development of thin and incipient soils, such as *Neossolos Litólicos* [Loamic Leptosol (Cambic)], regardless of the parent material.

The lithology of the Second Plateau gives the soils a high sand content, as expected. However, despite the gentle relief, the soils are predominantly incipient, shallow, and exhibit poor drainage conditions, facilitated by the high concentration of drainage headwaters and numerous closed depressions, adding complexity to the geomorphological configuration and soil cover of the area. The accumulation of organic matter is enabled by the poorly drained environment induced by the low permeability of the Furnas sandstone. In this context, just as the accumulation of water in the depressions influences the formation of organomineral soils, the presence of these soils creates favorable conditions for the accelerated dissolution and leaching of Al^{3+}, Fe^{3+}, and $Fe(OH)_3$. This process accentuates the development of the closed depressions, demonstrating that the evolution of relief and soil cannot be dissociated.

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References

1. ALVES, G.B. **Estudo da cobertura pedológica e sua relação com a formação e evolução de depressões no sudoeste de Macaraí (SP)**. 2014. Tese (Doutorado) – Universidade de São Paulo, São Paulo, 2014. Disponível em: http://www.teses.usp.br/teses/disponiveis/8/8135/tde-26052015-095108/. Acesso em: 13 dez. 2024.
2. BESSER, M. L., BRUMATTI, M., SPISILA, A. L. **Mapa geológico e de recursos minerais do estado do Paraná**: CPRM. 2021.
3. BOGNOLA, I.A., FASOLO, P.J., CARVALHO, A. P. DE, POTTER, R.O., BHERING, S.B., Levantamento de reconhecimento de solos da Região Centro-Leste do Estado do Paraná, Rio de Janeiro: **Boletim de Pesquisa Embrapa Solos**. 2003.
4. BRADY, N.C.; WEIL, R. R. **Elementos da natureza e propriedades dos solos**. Bookman Editora, 2013. 716 p.
5. CASTRO, S. S., SALOMÃO, F. D. T. Compartimentação morfopedológica e sua aplicação: considerações metodológicas**:** **Revista GEOUSP**, São Paulo, v. 7, p. 27-37. 2000.
6. CRUZ, G. C. F. D. **Alguns aspectos do clima dos Campos Gerais**. Editora UEPG, 23, 23-31. 2007
7. DE ROS, L. F. Heterogeneous generation and evolution of diagenetic quartzarenites in the Silurian-Devonian Furnas Formation of the Paraná Basin, southern Brazil. **Sedimentary Geology**, v. 116, p. 99-128. 1998.
8. DOKUCHAEV, V.V. **Short description and critical analysis of the more important soil classifications**: Trav. Soc. Nat. St. Petersburg, v. 10, p. 64-67. 1879.
9. EMBRAPA. **Levantamento de reconhecimento de solos do Estado do Paraná**: Serviço Nacional de Levantamento e Conservação dos Solos. 1984.
10. FALLOU, F.A. **Pedologie oder allgemeine und besondere Bodenkunde: Schönfeld's Buchlandlung**, Dresden, 487 p. 1862.
11. FIGUEIREDO, D. M., SALOMÃO, F. X. T. Morfopedologia: abordagem metodológica para estudos ambientais: **Revista Brasileira de Geomorfologia**, 24(00). 2023.
12. FORMOSO, M. L. Some topics on geochemistry of weathering: a review. **Anais da Academia Brasileira de Ciências**, 78, 809-820. 2006.
13. FURIAN, S., BARBIÉRO, L.; BOULET, R. Organisation of the soil mantle in tropical southeastern Brazil (Serra do Mar) in relation to landslides processes: **Catena**, v. 38, n. 1, p. 65–83. 1999.
14. FURQUIM, S. A. C., SANTOS, M. A., VIDOCA, T. T., BALBINO, M. A., CARDOSO, E. L. Salt-affected soils evolution and fluvial dynamics in the Pantanal wetland, Brazil. **Geoderma**, 286, 139-152. 2017.
15. GOLDICH, S. S. A Study in Rock-Weathering". **The Journal of Geology**. 46 (1): 17–58. 1938.
16. GRIGOROWITSCHS, H., RODRIGUES, C. Graus de Hidromorfia de Solos Situados em Planície Fluvial e em Setores de Interface Vertente-Planície na Bacia Hidrográfica do Rio Cotia/SP. **Revista Geonorte**, 5(21), 93-99. 2014.
17. HASUI, Y., CARNEIRO, C. D. R., COIMBRA, A. M. The Ribeira folded belt: **Revista Brasileira de Geociências**., v. 5, n. 4, p. 257-266. 1975.
18. HU, A., JANG, K. S., TANENTZAP, A. J., ZHAO, W., LENNON, J. T., LIU, J., ... & WANG, J. Thermal responses of dissolved organic matter under global change. **Nature Communications**, 15(1), 576 (2024). DOI:10.1038/s41467-024-44813-2
19. ITC-PR. **Levantamento aerofotogramétrico do Estado do Paraná**. Escala 1:25.000. 1980.
20. IUSS Working Group WRB. **World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps**. 4th edition. International Union of Soil Sciences (IUSS), Vienna, Austria. 2022.
21. JENNY, H. **Factors of soil formation, a system of quantitative pedology**: McGraw-Hill, New York, 281 p. 1941.
22. LADEIRA, F. S. B., SANTOS, M. Tectonics and Cenozoic paleosols in Itaqueri's Hill (São Paulo-Brazil): implications for the long-term geomorphological evolution. **Zeitschrift für Geomorphologie**, Supplementbaende, v. 145: 37-62. 2006.

23. MAACK, R. Geologia e geografia da região de Vila Velha e considerações sobre a glaciação carbonífera do Brasil. Curitiba, **Arquivos do Museu Paranaense**, v.5, 1946, 305p.
24. MAACK, R. Fenômenos carstiformes de natureza climática e estrutural de arenitos do Estado do Paraná. **Arquivos de Biologia e Tecnologia**, v. 11, p. 151–162, 1956.
25. MAACK, R. **Geografia Física do Estado do Paraná**. CODEPAR, Curitiba, 350p. 1968.
26. MELO, M.S.; GUIMARÃES, G.B.; PONTES, H.S.; MASSUQUETO, L.L.; PIGURIM, I.; BAGATIM, H.Q.; GIANNINI, P.C.F. Carste em rochas não-carbonáticas: o exemplo dos arenitos da Formação Furnas, Campos Gerais do Paraná/Brasil e as implicações para a região. SBE – Campinas, SP, **Espeleo-Tema**, v. 22, n. 1, p. 81-97, 2011.
27. MILANI, E.J. Comentários sobre a origem e a evolução tectônica da Bacia do Paraná. **In**: Mantesso-Neto, V., Bartorelli, A., Carneiro, C.D.R., Brito Neves, B.B. (Eds.), Geologia do Continente Sul-americano, Beca, Brasil, pp. 265–280. 2004.
28. MORAES, S. L., GALVANI, E. Balanço hídrico climatológico no município de Ponta Grossa, PR: aportes para o planejamento agrícola e hidrológico: **Revista Geonorte**, 3(9), 987-999. 2012.
29. OLIVEIRA, J.B; PRADO, H. **Carta pedológica semi-detalhada do Estado de São Paulo: folha Piracicaba**. São Paulo, IA – Instituto Agronômico / IGC – Instituto Geográfico e Cartográfico, escala 1:100 000.1989.
30. PALMER, A. N., PALMER, M. V. Geochemistry of capillary seepage in Mammoth Cave. **Speleogenesis and Evolution of Karst Aquifers**, 1(4), 1-8. 2003.
31. PARANÁ. Plano de manejo da área de proteção ambiental da Escarpa Devoniana. 2004
32. PEULVAST, J.P., VANNEY, J.R. **Géomorphologie Structurale: Relief et structure**. Paris/Orléans: Gordon and Breach et BRGM, 1, 505. 2001.
33. PONTES, H. S., FERNANDES, L. A., DE MELO, M. S., GUIMARÃES, G. B., MASSUQUETO, L. L. Características litofaciológicas e aspectos genéticos de feições cársticas da Formação Furnas e Arenito Vila Velha no município de Ponta Grossa (Paraná, Brasil). **Revista Brasileira de Geomorfologia**, 23(1), 1207. 2022.
34. PRAZERES FILHO, H. J., HARARA, O. M., BASEI, M. A. S., PASSARELLI, C. R., SIGA JR, O. Litoquímica, geocronologia U-Pb e geologia isotópica (Sr-Nd-Pb) das rochas graníticas dos batólitos Cunhaporanga e Três Córregos na porção sul do Cinturão Ribeira, Estado do Paraná. **Geologia USP. Série Científica**, 3, 51-70. 2003.
35. PINHEIRO, M.R. **Técnicas Cartográficas e Aerofotogramétricas para o Estudo da Erosão: Alta bacia do ribeirão Araquá - São Pedro e Charqueada/SP** [Dissertação de Mestrado]: Departamento de Geografia da Faculdade de Filosofia, Letras e Ciências Humanas da Universidade de São Paulo. 2009.
36. PINHEIRO, M. R., COSTA, J. R., SCIGLIANO, B. F., FERREIRA, R. P. D., CIANFARRA, P., MANFREDINI, S. Interações solo, relevo e material de origem na região do Alto Estrutural do Pau D'Alho–Sudeste do Brasil. **Revista do Instituto Geológico**, 41, 49-67. 2020.
37. PINHEIRO, M. R., QUEIROZ NETO, J. P. D. Geomorphology of the São Pedro Ridge and lower Piracicaba river region, southeastern Brazil**. Journal of Maps**, 12 (sup1), 377-386. 2016.
38. QUEIROZ NETO, J. P. Geomorfologia e pedologia. **Revista Brasileira de Geomorfologia**, 1, 59-67. 2000.
39. QUEIROZ NETO, J.P. Análise estrutural da cobertura pedológica: uma experiência de ensino e pesquisa. **Revista do Departamento de Geografia**, 15: 77-90. 2002. DOI: 10.7154/RDG.2002.0015.0008
40. QUEIROZ NETO, J. P. Relações entre as vertentes e os solos: revisão de conceitos. **Revista Brasileira de Geomorfologia**, v.12, n.3, p.15-24, 2011.
41. QUEIROZ NETO, J. P., JOURNAUX, A. **Carta geomorfológica de São Pedro, SP**. [Escala 1:50.000]. Laboratório de Sedimentologia e Pedologia do Departamento de Geografia-FFLCH-USP-Brasil and Centre de Géomorphologie du CNRS-Caen-France. São Paulo: Terrafoto e Instituto de Geografia da USP. 1978.
42. ROSS, J. L. S. Chapada dos Guimarães: borda da bacia do Paraná. **Revista do Departamento de Geografia**, 28, 180-197. 2014.
43. ROSSI, M. **Mapa pedológico do Estado de São Paulo: revisado e ampliado**. Escala 1:750.000. 2017.
44. ROSSI, M., Queiroz Neto, J. P. Relação solo/paisagem em regiões tropicais úmidas: o exemplo da Serra do Mar em São Paulo, Brasil. **Revista do Departamento de Geografia**, 14, 11-23. 2001.
45. SANTOS, H.G., JACOMINE, P.K.T., ANJOS, L.H.C., OLIVEIRA, V.A., LUMBRERAS, J.F., COELHO, M.R., ALMEIDA, J.A., ARAÚJO, J.C., OLIVEIRA, J.B., CUNHA, T.J.F., **Sistema brasileiro de classificação de solos**. Embrapa, Brasília, 5ª edição revisada e ampliada., 353 p. 2018.
46. SANTOS, L. G., PINHEIRO, M. R., MANFREDINI, S. Relação solo-vegetação em campos de altitude na Mata Atlântica: o caso do Núcleo Curucutu do Parque Estadual da Serra do Mar–sudeste do Brasil. **Boletim Paulista de Geografia**, 1(112), 101-125, 2024.
47. SANTOS, L. J. C., OKA-FIORI, C., CANALI, N. E., FIORI, A. P., SILVEIRA, C. T., SILVA, J. M. F., ROSS, J. L. S. Mapeamento geomorfológico do Estado do Paraná. **Revista Brasileira de Geomorfologia**, 7(2), 3-12, 2006.

48. SANTOS, R. D., SANTOS, H. G., KER, J.C., ANJOS, L. H. C., SHIMIZU, S. H. **Manual de descrição e coleta de solo no campo**. SBCS, Viçosa, 7ª.ed. rev. e ampl., 102 p. 2015.
49. TRICART, J. **Ecodinâmica**. Secretaria de Planejamento da Presidência da República, Fundação Instituto Brasileiro de Geografia e Estatística, Diretoria Técnica, Superintendência de Recursos Naturais e Meio Ambiente. 1977.
50. TRICART, J., KILLIAN, J. **La Eco-Geografia y la Ordenación del médio natural**: Barcelona. Editora Anagrama, 288 p. 1979.
51. VILLELA, F.N.J., ROSS, J.L.S., MANFREDINI, S. Relief-rock-soil relationship in the transition of Atlantic Plateau to Peripheral Depression, São Paulo, Brazil: **Journal of Maps**, v. 9, p. 343-352. 2013.
52. VILLELA, F. N. J., ROSS, J. L. S., MANFREDINI, S. Análise geomorfopedológica na borda leste da Bacia Sedimentar do Paraná, sudeste do Brasil. **Revista Brasileira de Geomorfologia**, 16(4). 2015.
53. ZENERO, M. D. O.; SILVA, L. F. S. D.; CASTILHO, S. C. D. P.; VIDAL, A.; GRIMALDI, M.; COOPER, M. Characterization and classification of soils under forest and pasture in an agroextractivist project in Eastern Amazonia. **Revista Brasileira de Ciência do Solo**, v. 40, p. 1-17, 2016. DOI: 10.1590/18069657rbcs20160165
54. WEAST R.C., ASTLE W.J. AND BEYER W.H. (Eds.). **CRC handbook of Chemistry and Physics**. Boca Raton, FL, CRC Press. 1986.
55. WEBER, W., SIGA JÚNIOR, O., BASEI, M. A. S., SATO, K. A formação Água Clara na região de Araçaiba-SP, registro de uma bacia mesoproterozóica: **Geologia USP, Série Científica**, 346. 2002.
56. WRAY, R. A. A global review of solutional weathering forms on quartz sandstones. **Earth-Science Reviews**, 42(3), 137-160. 1997a.
57. WRAY, R. A. Quartzite dissolution: karst or pseudokarst. **Cave and karst Science**, 24(2), 81-86. 1997b.