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MORPHOSTRATIGRAPHY OF FERRUGINOUS DURICRUSTS IN THE NORTHWEST OF PARANÁ

MORFOESTRATIGRAFIA DE DURICRUSTS FERRUGINOSO NO NOROESTE DO PARANÁ

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Resumo:

Solos são importantes meios para estudos dos processos condicionantes da evolução do relevo, considerando que neles pode ocorrer a preservação de materiais correlatos a eventos modeladores do relevo. Na região Noroeste do Paraná, observa-se ocorrência de *duricrus*t ferruginoso correlatos à esculturação do relevo, porém não há estudos detalhados sobre esses depósitos. Nesse sentido, este trabalho visa analisar esses materiais ferruginosos presentes na área de estudo, por descrição morfológica de perfis com *duricrusts*, bem como estudar esses materiais por difração de raio-X e micromorfologia, buscando compreender a organização atual dos materiais ferruginosos em topo de morrotes e colinas. Assim, utilizou-se o mapeamento de feições de relevo, sustentado por *duricrusts* ferruginoso, previamente, identificado por Fumiya *et al.*, (2016). A descrição morfológica de perfis com *duricrust* ferruginoso em 14 feições de relevo demonstrou que 11 feições apresentam truncamentos entre horizontes e camadas coluviais, indicando que, provavelmente, *duricrusts* são paleopavimentos rudáceos, que foram cobertos por colúvio.

Abstract:
Soils constitute an important mean for studying the conditioning processes of the evolution of the relief, considering that in them materials related to events modeling the relief can be preserved. In the Northwest region of Paraná, a manifestation of ferruginous duricrust related to relief sculpture is observed, but there are no detailed studies on these deposits. In this sense, this work aims to analyze these ferruginous materials present in the study area, through the morphological description of profiles with duricrusts, as well as to study these materials by X-ray diffraction and micromorphology, seeking to understand the current organization of ferruginous materials on top of hillocks and hills. Therefore, a mapping of relief features supported by ferruginous duricrusts, previously identified by Fumiya *et al.*, (2016) was used. A morphological description of profiles with ferruginous duricrust in 14 relief features showed that 11 features present truncations between horizons and colluvial layers, indicating that probably the duricrusts are rudaceous paleopavement, that were covered by colluvium.

Introduction

Analyzing landforms and the processes responsible for their evolution are fundamental for understanding the past and present configuration of the landscape (RIBEIRO *et al.*, 2012).

The study of the origin and evolution of the relief by correlative deposits allows us to identify evidence related to the relief-forming processes, since these deposits can be testimonies capable of elucidating which geomorphological processes were responsible for the modeling sculpture (MISSURA, 2005). Thus, correlative deposits are crucial in geomorphological research, and may indicate the disturbances and / or transformations through which the different landscapes were submitted, especially during the events that were triggered by changes in the flow of energy and matter in the system (RIBEIRO *et al.*, 2012).

In the Northwestern region of Paraná (Figure 1), correlative deposit records exist, as in the study by Justus (1985), that prove the occurrence of ferruginous duricrust[1] fragments, mobilized along slopes, and which are currently organized in stone lines. Still, according to the aforementioned author, these fragments are products resulting from planation processes and sustain morphological features of small elevations, such as hillocks and knocks, that differ from the low-relief landscape, characteristic of the region.

Despite the allusion of the presence of ferruginous duricrust fragments on top of prominent relief feature in the Northwest of Paraná, there is only a profile description in "Serra dos Dourados" (JUSTUS, 1985), located in the interfluve between the Ivaí and the Piquiri river basins. In this sense, no detailed study has been carried out in an attempt to understand the meaning of the presence of duricrust in the landscape.

Thus, the present work aims at the analysis of the organization and characterization of the mineral and micromorphological composition of these deposits, composed mainly of ferruginous duricrust, in the Northwest of Paraná, preserved in knocks and residual hillocks. In this way, these deposits will be used as part of the preserved records of landscape sculpturing processes in the addressed area.

Characterization of the study area (geology and relief)

The study area covers the extent of occurrence of the sandstones of the Caiuá Group, in the Northwest region of Paraná (Figure 1), which corresponds to approximately 13% of the state of Paraná (Southern Brazil). The Caiuá Group is composed of three geological formations sedimented in a desert environment: Paraná River (sandsea), Goio-Erê (peripheral eolian deposits) and Santo Anastácio (sandbanks plain) (FERNANDES and COIMBRA, 1994).

In the sandstones of the Caiuá Group, there are also occurrences of silicified sandstones whose origin is attributed to hydrothermalism (siliceous fluids) and are related to probable events of alkaline magmatism, penecontemporaneous to the sedimentation of the Caiuá Group (FERNANDES *et al.*, 1993, 2012). These silicifications are responsible for the maintenance of testimonial hills, which stand out in the landscape due to resistance to denudation processes.

[1] **Duricrust**: generic term designated for the hardened layer or horizon (iron, aluminium, calcium etc) cemented by supergene enrichment processes (Widdowson, 2007).

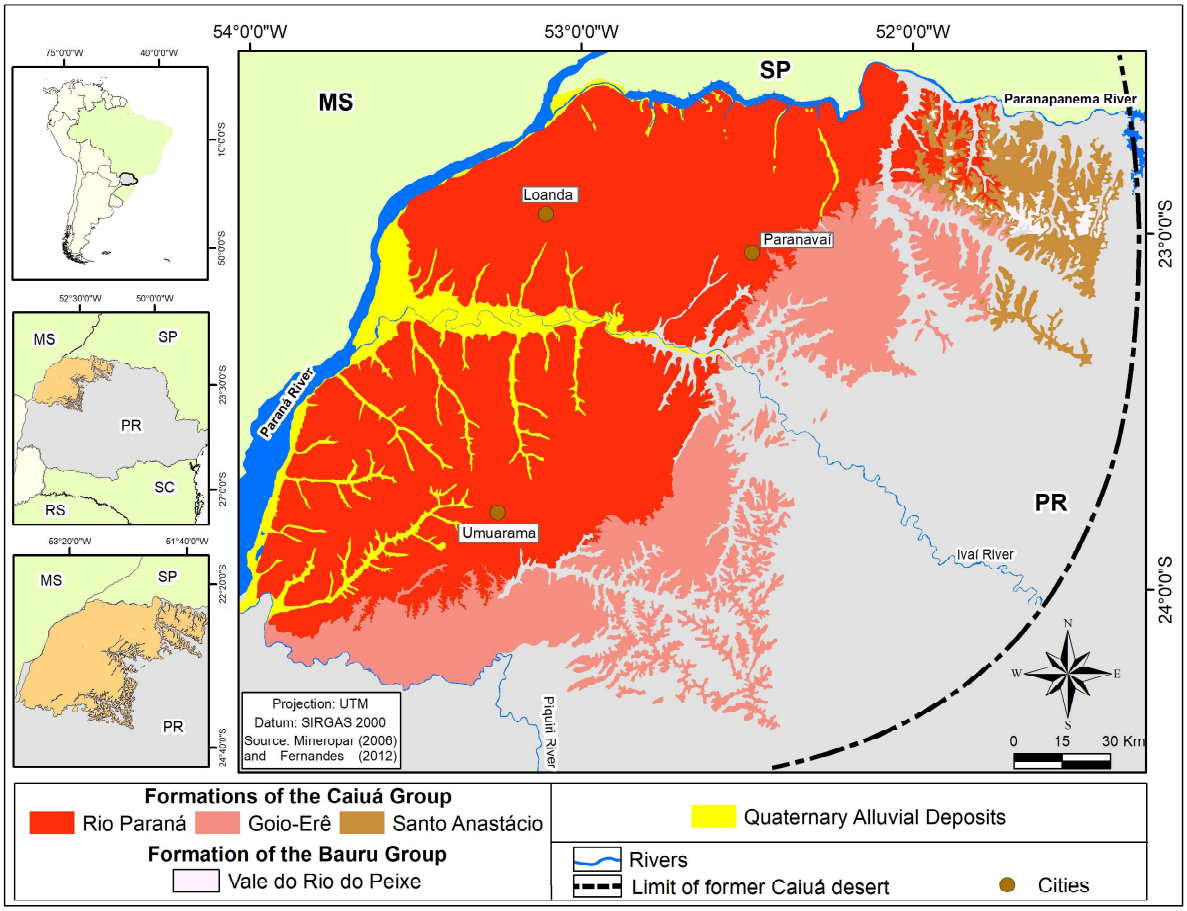

Figure 1 - Location of the Northwest of Paraná and geology of the Caiuá Group. Source: Mineropar (2006), Fernandes et al. (2012).

After the sedimentation process of the formations of the Caiuá Group (Tunorian-Maastrichtian), it was observed the development of planation surfaces, related to climate oscillations (alternation between dry and humid climate) along the Cenozoic (BIGARELLA *et al.*, 2003).

In the Northwest of Paraná, Justus (1985) engaged a study of the planation surfaces by the polycyclic evolution model of the relief proposed by Bigarella *et al.*, (1965), and systematically mapped the planed levels of the region via the radar images of the project RADAMBRASIL, associated with field analysis. In his work, he identified two planation surfaces called Interplanaltic Surface I and II, corresponding to the Pd1 of the stipulated age of the Quaternary.

Under these surfaces it was verified the occurrence of ferruginous duricrust of pedogenic origin (JUSTUS, 1985), which were mobilized along slopes and are, nowadays, in the form of stone lines. According to the author (cited above), duricrust stone lines are products resulting from planation process and support morphological features of small elevations, such as hillocks and knocks, that differ from the low-relief landscape, characteristic of the region.

Materials and methods

The study of profiles with the presence of ferruginous duricrust previously identified by Fumiya *et al.* (2016, 2017) consisted of a morphostratigraphic analysis based on the association between landforms, constitution and lithological organization (HUGHES, 2010). This analysis sought to recognize elements that indicate the preservation of materials resulting from the sculpting processes of the area modeling, such as: layers of stone line, colluviums, erosive discontinuity, and buried or decapitated horizons.

In order to classify the size of the materials described in the profiles, the following criteria were adopted in Table 1.

Table 1: Criteria for classification, according to size.

Diameter	Nomenclature
>200mm	- Boulder
200-20mm	- Cobble
20-2mm	- Gravel

Source: Santos et al. (2015).

The mineral characterization was performed by X-ray diffraction (XRD), and the samples were analyzed by the powder method (natural sample) in an X-ray diffractometer (model X'Pert Pro MPD, PW 3040/60 PANalytical). The following instrumental standards were used: scan of 5º-75º 2θ, 40 kV, 30 mA; step 0.02 ° in time / step of 20s; fixed slit ½ and anti-spreading 5º; 10mm mask and spinning sample movement, with 1 rps.

For the micromorphological analysis, undisturbed samples were collected, in a 13cm x 7cm paper box, and the preparation of the thin sections followed the procedures described in Castro (2002). Analysis of the thin slides was performed with the aid of a Leica polarized optical light microscopy, petrographic type.

Results and discussion

Previous studies performed by Fumiya *et al.* (2016, 2017), on the identification by morphometric index of relief features (knocks, hillocks and hills) supported by materials more resistant to denudation in the Northwest of Paraná, allowed the selection of 14 profiles to be studied (Figure 2, below), from which 11 profiles, with the presence of ferruginous duricrust, were selected for analysis.

A research was carried out in the field to find out the type of material responsible for the maintenance of geomorphological features in the landscape. Three types of materials were found: sandstones with carbonaceous cement (Figure 2 - F01); sandstones with silica cement (Figure 2 - F03, F05-08); and duricrust with ferruginous cement (Figure 2 - F02, F04, F09-14).

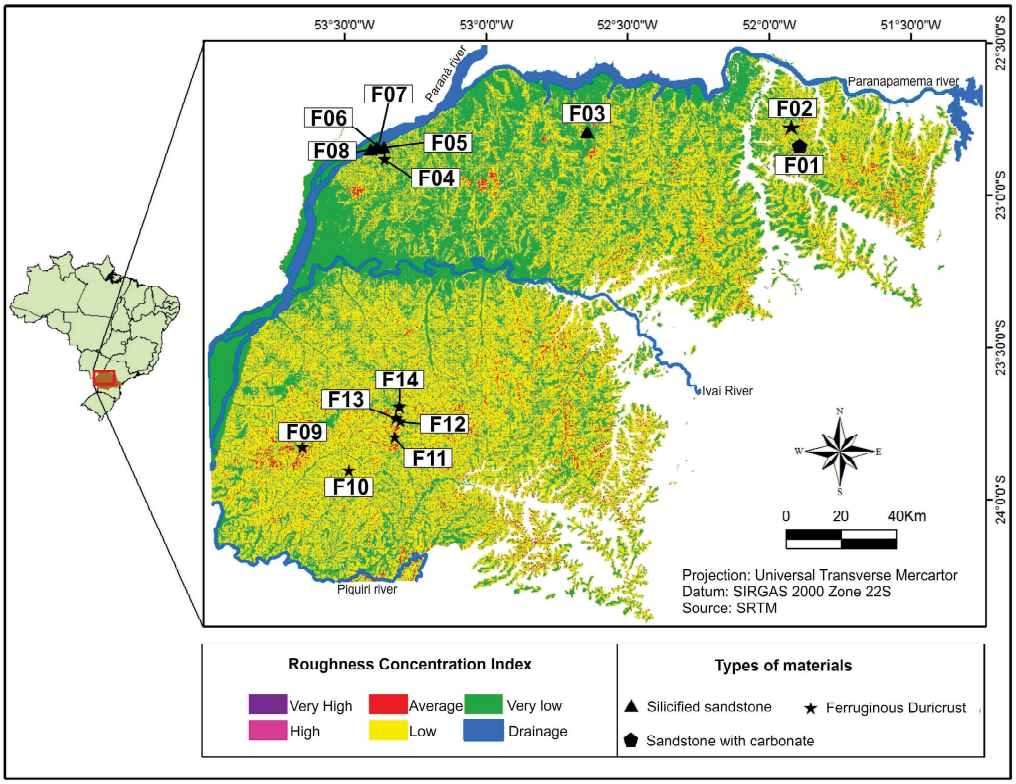

Figure 2 - Framing of the study area and Roughness Concentration Index values in the localization of local morphological features, in the area of occurrence of the Caiuá Group, in the Northwest of Paraná. Adaptation: Fumiya et al. (2016).

Sequentially, the types of cements in different types of rocks and ferruginous duricrust present in the geomorphological features are shown in Figure 3, showing that they have different origins: the silica cements (Figure 3 - A2), of hydrothermal origin (FERNANDES *et al.*, 1993); the carbonaceous cements (Figure 3 - B2), from an arid environment (FERNANDES and COIMBRA, 1994); and the ferruginous duricrust (Figure 3 - C2), of pedogenic origin (JUSTUS, 1985).

These characteristics were confirmed by micromorphological analysis in which it was found that the silicate cement involves the detrital grains of quartz in texture syntax (Figure 3 - A3); the carbonate cement, in poikilotopic texture (Figure 3 - B3); and the ferruginous cement impregnates the matrix bottom (Figure 3 - C3).

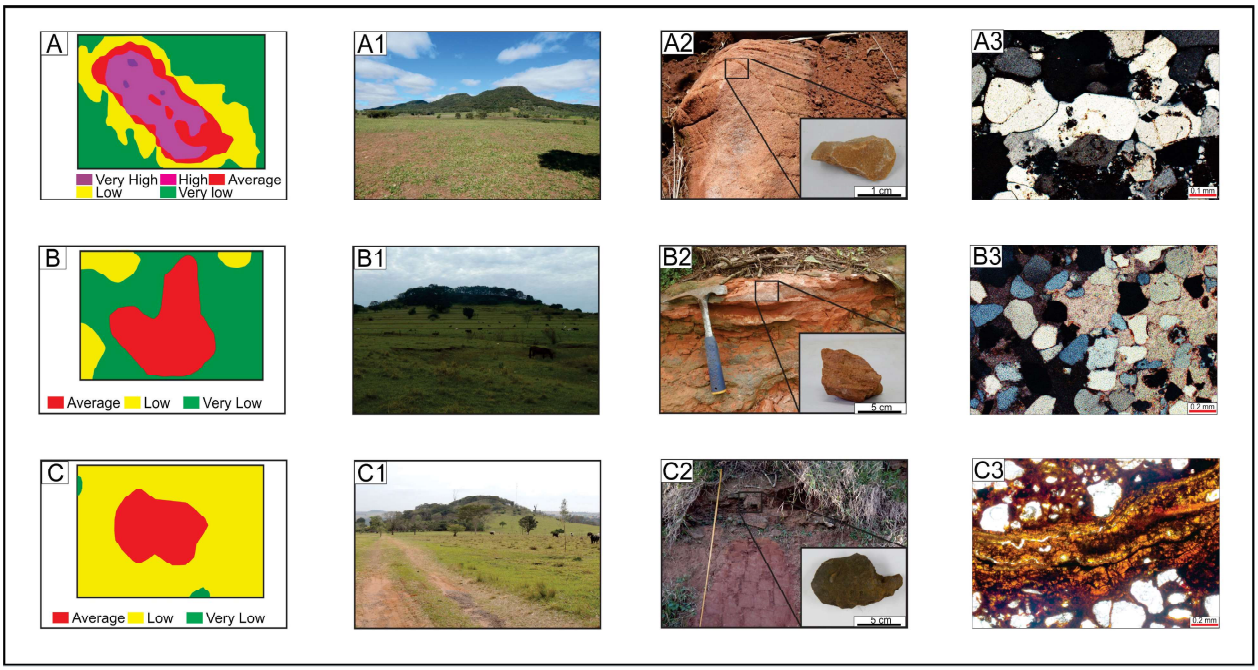

Figure 3 - Roughness Concentration Index (RCC) and relief features. A) Mortar ICR. A1) Photograph of the hill. A2) Silicified sandstone. A3) Photomicrography of silicified sandstone with syntax texture (XPL). B) Mortar ICR. B1) Photograph of a hillock. B2) Photograph of carbonate sandstone. B3) Photomicrography of carbonate sandstone with poikilotopic texture (XPL). C) Mortar ICR. C1) Photograph of a hillock. C2) Photograph of duricrust. C3) Photomicrograph of duricrust, impregnation of the matrix background by iron and fi ller fi lling by iron / manganese (PL). PL – transmitted light; XPL – polarized light

From the field study, we opted for the analysis of 11 features of relief sustained by ferruginous duricrust or with an abundance of it. As shown in Figure 2, these forms are concentrated in two regions: near the Paraná River (Figure 2 - F04-08) and in the interfluve between the Ivaí and Piquiri river basins (Figure 2 - F09-14). From this recognition, a description was made of the materials present in these landforms, in cuts and profiles.

In the morphological analysis of the ferruginous duricrust, it was verified that among them there are differences in size, depending on the type of sandstone that they developed, being divided in gravels, cobble and boulder, that can occur in the shape of layers (direction of transported material), accompanying the morphology of the features or as sparse materials on the slope.

In this way, the description of the profiles was presented in two sets of features: features near the Paraná River (Figure 2 - F04-08) and features located in the dividers between the Piquiri and Ivaí river basins (Figure 2 - F09-14).

Near the Paraná River, profiles were described in three hillocks (Figure 2 - F05-07) and one knocks (Figure 2 - F08).

These profiles are sculpted, as shown in Figure 4, in silicified sandstones (Figure 4 - A1). In these features, ferruginous duricrust gravels with a size of 1 to 5 cm (Figure 4-A2) can be observed, sparse on the surface of the feature, and forming stone line on the slopes of the landforms. It was also possible to observe fragments and boulder of silicified sandstone, charcoal fragments

and rounded quartz gravels (Figure 4 - A3), being the silicified sandstone the responsible factor for the conservation of this feature in the landscape (FERNANDES *et al.*, 1993; FUMIYA *et al.*, 2016).

Due to the proximity of the hillocks and the knock to the Paraná river, it is possible that the rounded quartz gravel (Figure 4-A3) has been carried and deposited in the landforms by the Paraná river. Subsequently the gravels were probably incorporated to the weathered material by processes of mobilization, along the slopes of the features, composing the stone line present and spread on the surface.

Near the Paraná river, another morphological feature is classified as knock (according to Figure 2 - F04), but this one developed under sandstones, without silica or carbonates cements; with metric-size ferruginous duricrust boulders (Figure 4 - B1-B2), in the shape of stone line (Figure 4 - B3), accompanying the morphology of the feature. These ferruginous materials are determinant for its preservation in the landscape.

Unlike silicified sandstone features, this is farther from the Paraná River (Figure 2 - F04) and may not have been influenced by the passage of the river channel in the past, explaining the absence of rounded quartz gravel.

The mineral composition (XRD) of the ferruginous duricrust in the analyzed features is formed by goethite and quartz (Figure 4 - C); the micromorphology evidences the presence of nodules and cement of goethite and angular quartz to subangular (Figure 4 - D).

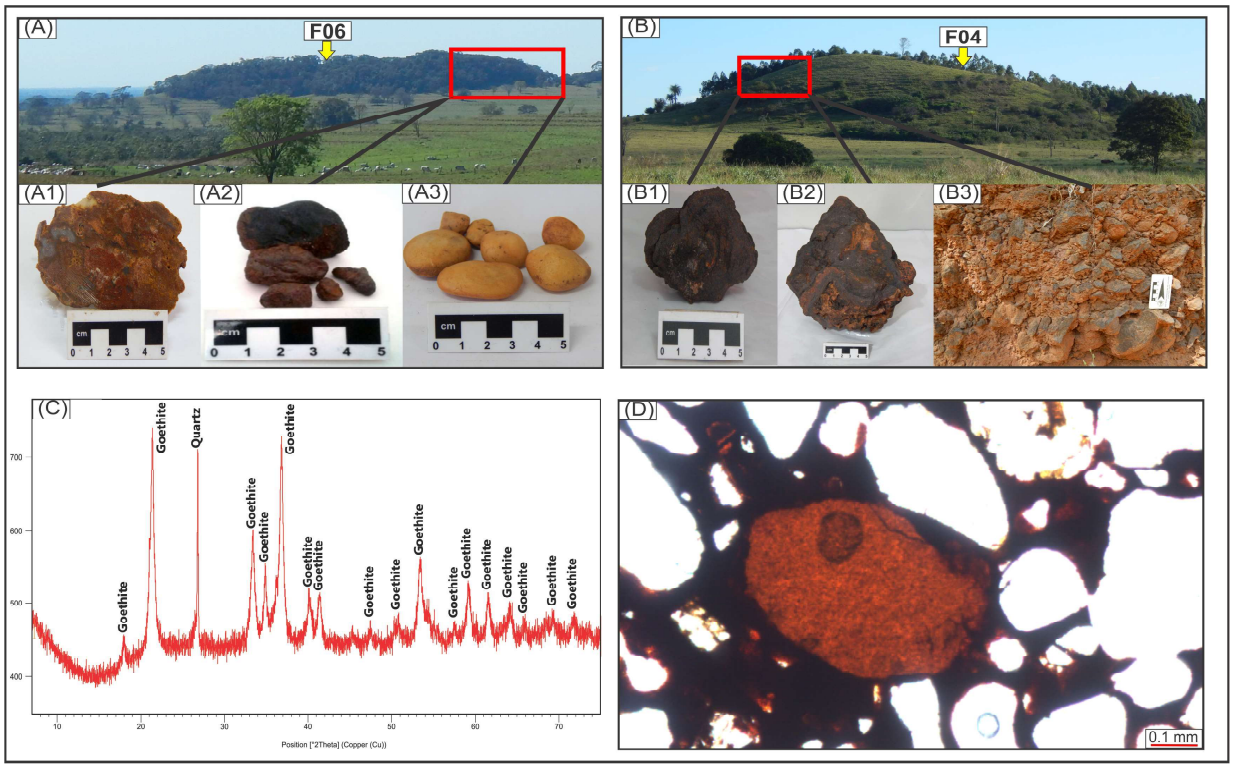

Figure 4 - Landform and materials that support them. A) Hillocks maintained by silicified sandstone, near the Paraná River. A1) Silicified sandstone (sawn). A2) Duricrust cobble. A3) Rolled quartz cobble. B) knock maintained by ferruginous duricrust. B1-B2) Angular and subangled duricrust. B3) Stone line with disorderly orientation. C) duricrust XRD, indicating the presence of quartz and goethite (cement). D) Photomicrograph of duricrust, showing cement, ferruginous nodules and angular crystals to quartz sub-rounded.

In the interfluve between the basins of the Ivaí and Piquiri rivers, six relief features take place, being five hillocks and one knock (Figure 2 - F08-14), that developed on sandstones, without silica or carbonate cements. Under these landforms ferruginous duricrust occur in the form of boulder to gravel.

Duricrust present in hillocks and knocks (Figure 2-F08-13) are in the form of stone lines, as illustrated in Figure 5. The morphology follows the features of Figure 5-A, with a thickness varying from 40 to 85 cm. They are composed of cobble, pebble and heterometric duricrust gravel, from angular to sub-angular shape (Figure 5 -

A2), which are up to 70 cm in size. The organization of the ferruginous materials is disordered (Figure 5 - A3), without cementing agents between the fragments.

In the profiles the following sequence was observed: colluviums, layer of ferruginous duricrust (line of stone) and horizons of decapitated and buried alterations.

The colluviums may or may not contain millimetric ferruginous fragments. The layers of duricrust lie in apparent discordance on the saprolite (altered rock) and appear to mobilize the materials (disordered organization), characterizing these profiles as allochthonous.

The saprolite, located just below the layers of the ferruginous materials in the analyzed profiles, presents an apparent erosive discordance. This suggest they might be part of paleohorizonts/saprolites, which were probably partially scoured during events of erosion / deposition of layers of ferruginized materials and colluviums.

The mineral composition (XRD) of duricrust in the analyzed landforms are goethite and quartz (Figure 5 - C); the micromorphology also evidences the presence of cement and coating / filling of goethite and angular quartz to subangular (Figure 5 - D).

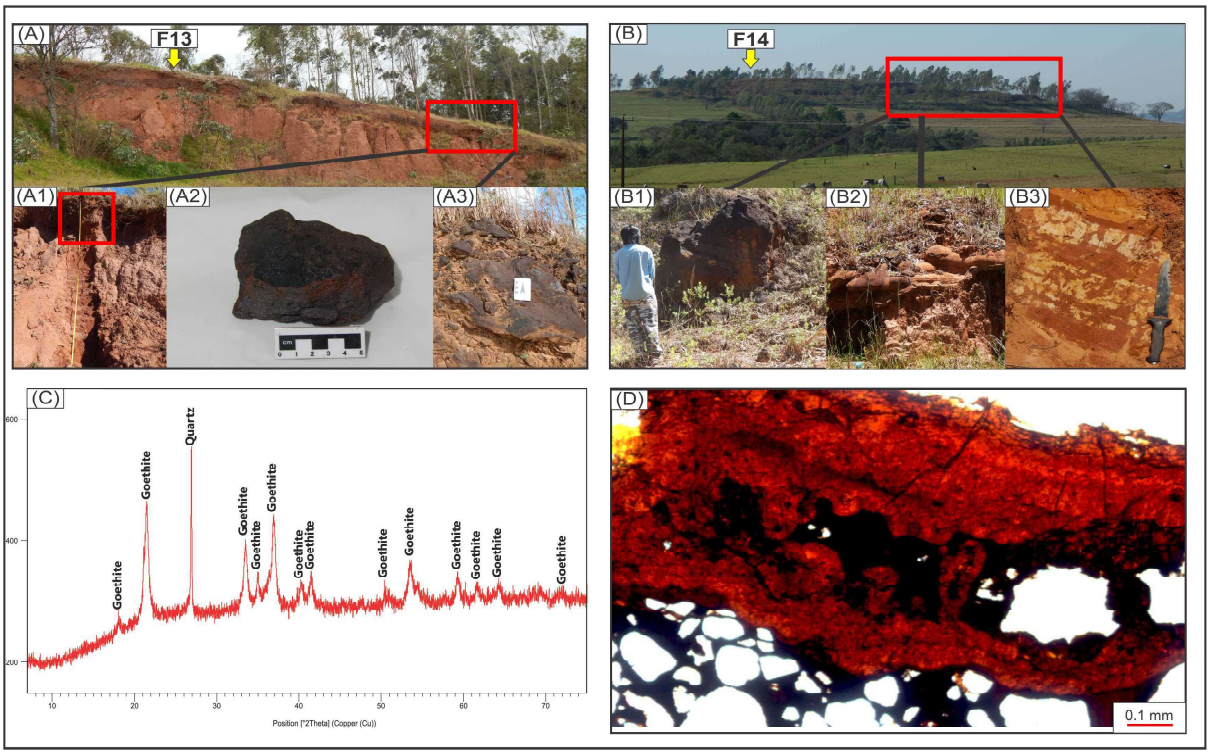

Figure 5 - Landforms and their ferruginous duricrust support. A) Hillock maintained by duricrust (Interfluve Piquiri-Ivaí). A1) Profile with duricrust. A2) Fragment of duricrust. A3) Duricrust stone line. B) knock maintained by duricrust. B1-B2) Horizon of ferruginous duricrust, thickness of 2m. B2) Continuous ferric horizon. B3) Horizon mottled following the stratification of the rock. C) Duricrust XRD, indicating the presence of quartz and goethite (cement). D) Photomicrograph of duricrust, evidence of cement, ferruginous coating / fill and angular to sub-rounded quartz crystals.

A situation opposite to the other landform that occur in the interfluve between the Ivaí and Piquiri river basins, where duricrust appears to have a native origin, is the hillock called F14 (Figure 2 - F14). Duricrust in this feature presents a continuous ferruginous horizon (Figure 5 - B1 - B2), showing no mobilization or evidence of erosive discontinuity, as well as showing a mottled horizon (Figure 5 - B3) below ferruginous duricrust. The association between these facts may indicate that the material of this feature is in situ situation, in contrast with the organization of the other profiles analyzed.

Observations in the P14 profile also allowed us to verify that duricrust developed irregularly, by "levels", obeying the stratification of the rock, initially generating mottled horizons and, subsequently, placoid duricrust, both "inclined" (Figure 6 - A-A1). The formation of the

placoid duricrust results from the cementation of the matrix floor by iron-rich solutions, resulting in pore closure (cementation) and permeability reduction. This result allows the retention and accumulation of these solutions for a longer time (period of ferrugination), allowing greater iron precipitation and duricrust thickening.

Thus, it is understood that the development of duricrust in tops of relief features (knocks and hillocks), in the Northwest of Paraná, occurs by preferential zones of accumulation for iron, and its initial development is lithodependent. In cases of intense ferruginations, "welding" may occur between different levels of duricrust and compose a single horizon (Figure 6 - B-B1).

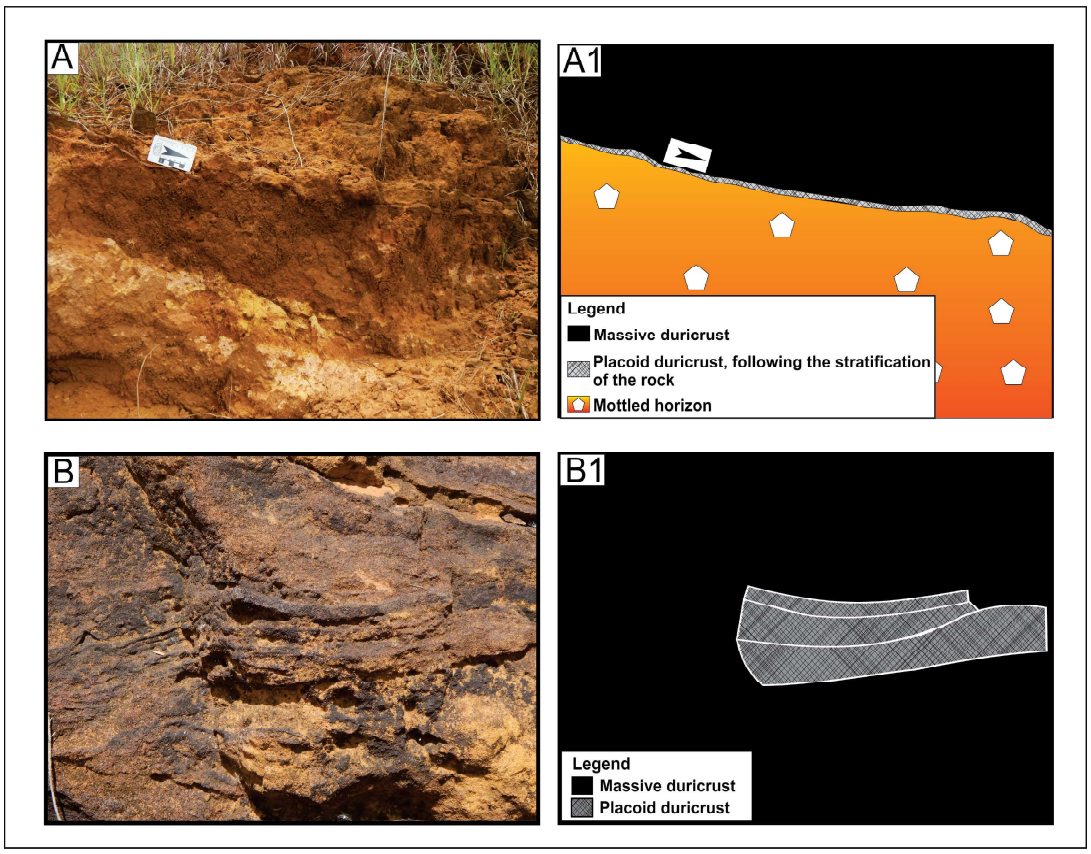

Figure 6 - Duricrust horizon of feature F14. A) Photograph of duricrust with preservation of placoid duricrust. A1) Illustration of A. B) Photograph of "soldier" placoid duricrust, preserved in ferruginized boulder. (B1) Illustration of B.

From the morphological, mineralogical (XRD) and micromorphological analysis of the materials found in the relief features with ferruginous duricrust, it was possible to observe that most of the profiles present mobilization.

In this sense, it was verified that there are two types of profiles - the allochthonous and autochthonous (Figure 7). Allochthonous profiles present disordered orientation of the layers of ferruginous duricrust (stone line), erosive discontinuity and decapitation of alteration horizons (Figure 7- P04-P13); the autochthonous one presents in situ profiles, with horizons genetically related to each other, being in the best state of preservation between the profiles analyzed (Figure 7 -P14).

Based on the results of this work, we propose a schematic outline of the evolution of the profiles with duricrust, from its genesis to the present arrangement, in hillocks and knocks (Figure 8). In this hypothetical model, the first phase of the development of the profiles with duricrust would occur due to the weathering of the sandstone (Figure 8 - A-B); the second phase would be the solubilization and concentration of ferrous iron (Fe^{2+}), and the formation of profiles with duricrust (Figure 8 - C-D); the third phase would occur by erosion and decapitation of the profiles (Figure 8 - E); and the fourth phase would be due to the complete dismantling of the profile with duricrust and the generation of stone lines (Figure 8 - F).

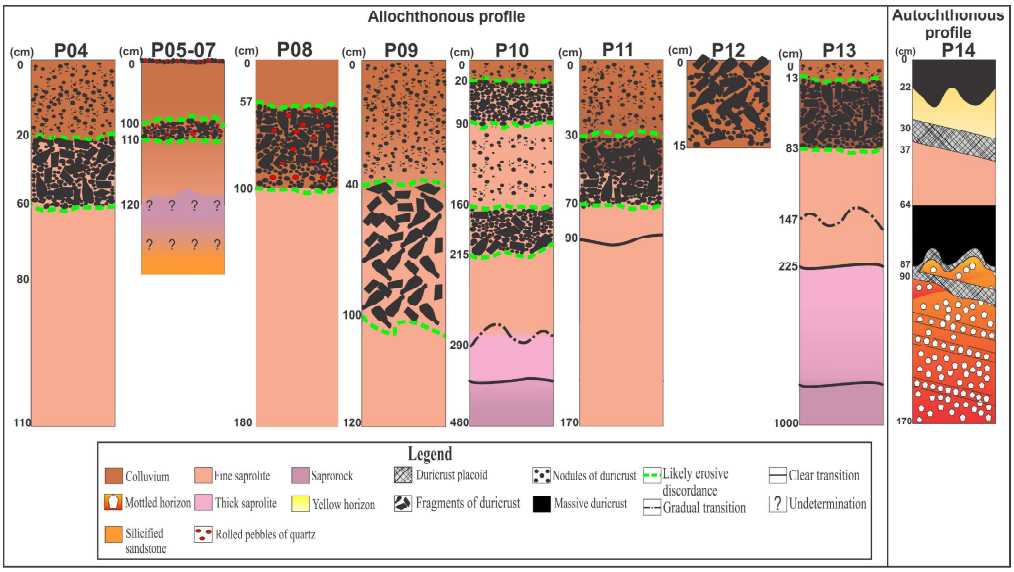

Figure 7 - Illustrations of some analyzed profiles, in different relief features. The nomenclature of the profiles follows the geomorphological features corresponding to those already denominated in Figure 2.

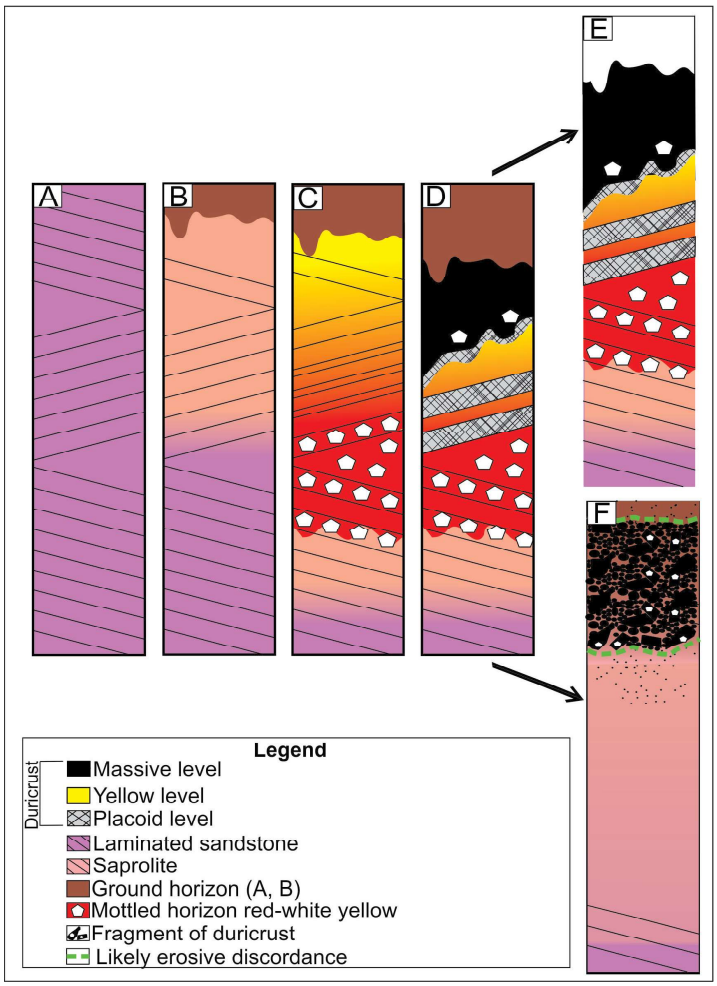

Figure 8 - Representation of the probable evolution of the profiles with duricrust and its current organization: allochthonous (mobilized) and autochthonous (in situ). A) Sandstone Caiuá without change. B) Alteration of sandstone and formation of regolith. C) Advancement of pedogenesis and development of pedological horizons. D) Mobilization and accumulation of iron, culminating in the formation of ferruginous duricrust. E) Remains partially eroded of duricrusts. F) Mobilization and deposition of the duricrusts in disordered orientation, resulting in the current arrangement of the ferruginous materials of most of the analyzed profiles.

Conclusion

The morphological studies of the materials present in the profiles with ferruginous duricrusts (colluviums, fragments of ferruginous duricrust, buried horizons) suggest evidence of past processes of decapitation of the profiles by erosion and mobilization of the duricrusts. The use of XRD and micromorphology techniques helped to determine the mineral composition of duricrusts (goethite and quartz) and sandstone with silica and carbonate cements.

From the analyzes made in the profiles, in relation to the meaning of the geomorphological dynamics in the Northwest of Paraná, it is only possible to suggest that, between the colluvial layers, stone lines (ferruginous duricrusts) and underlying horizons (saprolite), there are apparent erosive discordance. These probable erosive discordance may have been caused by events of large magnitudes (relief planation episodes?), in which the materials resulting from these processes (colluviums, fragments of ferruginous duricrust) remained as vestiges in the present landscape. Such degradational sedimentary features, identified in the profiles on knocks and hillocks, may be associated with generalized colluviation events in the Northwest of Paraná during the Quaternary, as indicated by the dating data developed by Optically Stimulated Luminescence (SALLUN *et al.*, 2007, 2010, 2011).

When registering possible occurrences of past degradation processes, ferruginous duricrusts, in prominent landforms in the Northwest of Paraná, may be key elements for the understanding of the relationship of geomorphological processes in the landscape transformations and the validity of paleoclimatic conditions contrasted with current ones, given that they contribute (ferruginous duricrusts), in part, to the sculpting of the present relief (support of knocks and hillocks). This hypothesis can be confirmed by geochronological studies of $^{40}Ar/^{39}Ar$, (U-Th)/He and Optically Stimulated Luminescence.

Acknowledgments

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