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Geomorfhological dynamics of colluvial deposits in the Borborema Plateau (Northeast Brazil) through the use of scanning electron microscopy on the 200-250 µm fraction

Dinâmica geomorfológica de depósitos coluviais do Planalto da Borborema (Nordeste do Brasil) através do emprego de microscopia eletrônica de varredura em fração de 200-250 µm

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Resumo: No Planalto da Borborema, Nordeste do Brasil, a definição dos tipos de processos superfíciais envolvidos na deposição de sedimentos coluviais e aluvio-coluviais permanece elusiva. A maior parte das interpretações se dão com base nas relações de campo e macrofábrica das seções estratigráficas. O presente estudo propõe uma avaliação das superfícies dos grãos de areia de quartzo e microclina, na fração 200-250µm, proveniente da matriz de cascalheiras datadas desde o último máximo glacial até o período histórico, por meio do emprego da análise micromorfológica dos grãos, assistida por microscópio eletrônico de varredura ambiental, no intuito de avaliar os processos subaéreos aos quais estiveram submetidos. As texturas superficiais encontradas nos grãos de areia foram agrupadas visualmente e quantificadas com base na metodologia adotada para depósitos quaternários com trajetórias erosivo/deposicionais conhecidas. A história indicada pelas texturas de superfície aponta para a presença de controles climáticos (mecânicos e intempéricos), além do tempo de soterramento, sobre a fisionomia dos grãos, com maior incidência de feições mecânicas nos grãos provenientes de deposição recente e das áreas topograficamente mais baixas da base das encostas do Planalto sob climas semiáridos.

Palavras-chave: Micromorfologia; Depósitos de Encosta; Ambiente Semiárido;

Abstract: In the Borborema Highlands, Northeast Brazil, the definition of the types of surface processes involved in the deposition of colluvial and alluvial-colluvial sediments remains elusive. Most interpretations rely on field-based and macrofabric observation along stratigraphic sections. The present study proposes an evaluation of the surfaces of quartz and microcline sand grains in the 200-250µm fraction, originating from gravel matrices dating from the last glacial maximum to the historical period, through the use of micromorphological analysis, assisted by an environmental scanning electron microscope, to evaluate the subaerial processes to which they were subjected. The surface textures found in the sand grains were visually grouped and quantified based on the methodology adopted for Quaternary deposits with known erosion/depositional trajectories. The history indicated by the surface textures points to the presence of climatic controls (mechanical and weathering), in addition to burial time, on the aspect of the grains, with a greater incidence of mechanical features in those originating from recent deposition and topographically lower areas in the surroundings of Highland's escarpments under semi-arid climates.

Keywords: Micromorphology; Hillslope Deposits; Semi-arid Environment;

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1. Introduction

The geomorphic characteristics and hillslope deposits of the Borborema Highlands are attributed to the occurrence of torrential surface flows controlled by changes in the energy input of the climate system throughout the late Pleistocene and Holocene (Corrêa, 2001; Corrêa & Monteiro, 2020; Listo et al., 2023). However, the definition of surface process types remains elusive and interpreted based on field evidence and macrofabric relationships of stratigraphic sections.

Given this scenario, we propose evaluating quartz and microcline sand grains from gravel deposit matrices, lithostratigraphically recognized as derived from debris or mud flows, using micromorphological analysis assisted by environmental electron scanning (EES). This technique allows micrographs of untreated samples to be obtained without surface metallization. Several authors have evaluated the textural characteristics of quartz grains that evolved from various depositional environments (Vos et al., 2014; Armstrong-Altrin et al., 2022; Hossain et al., 2024), as well as of heavy minerals and garnet (Velbel et al., 2007; Bónová et al., 2024).

The surface textures found in the sand grains were visually grouped and quantified based on the methodology adopted for Quaternary deposits with known sedimentary histories, including grains of eluvial, colluvial, and alluvial origin (Culver et al., 1983; Goudie & Bull, 1984; Bull et al., 1987).

2. Methodology

The study area corresponds to the western and southern escarpment of the Borborema Highlands, structured on the Serra da Baixa Verde massif, in the north-central part of the state of Pernambuco, 400 km west of the city of Recife. It consists of a topographically prominent Neoproterozoic syenitic batholith that cuts through less resistant Neoproterozoic and Mesoproterozoic metamorphic complexes (Corrêa & Monteiro, 2020). The area is located between the coordinates of 7º 41'S" / 7º 54'S" and 38º 00' W / 38º 11' W, comprising a total surface area of approximately 400 km2. The Serra da Baixa Verde massif forms the regional divide between the states of Pernambuco and Paraíba, separating the hydrographic basins of the Piancó River to the north and the Pajeú River to the south. The study focused on topographical hollows with colluvial filling in drainage catchments on the summit surface above 1,000 m and colluvial ramps at the massif's footslope in altitudes between 500 and 600 m (Figure 1).

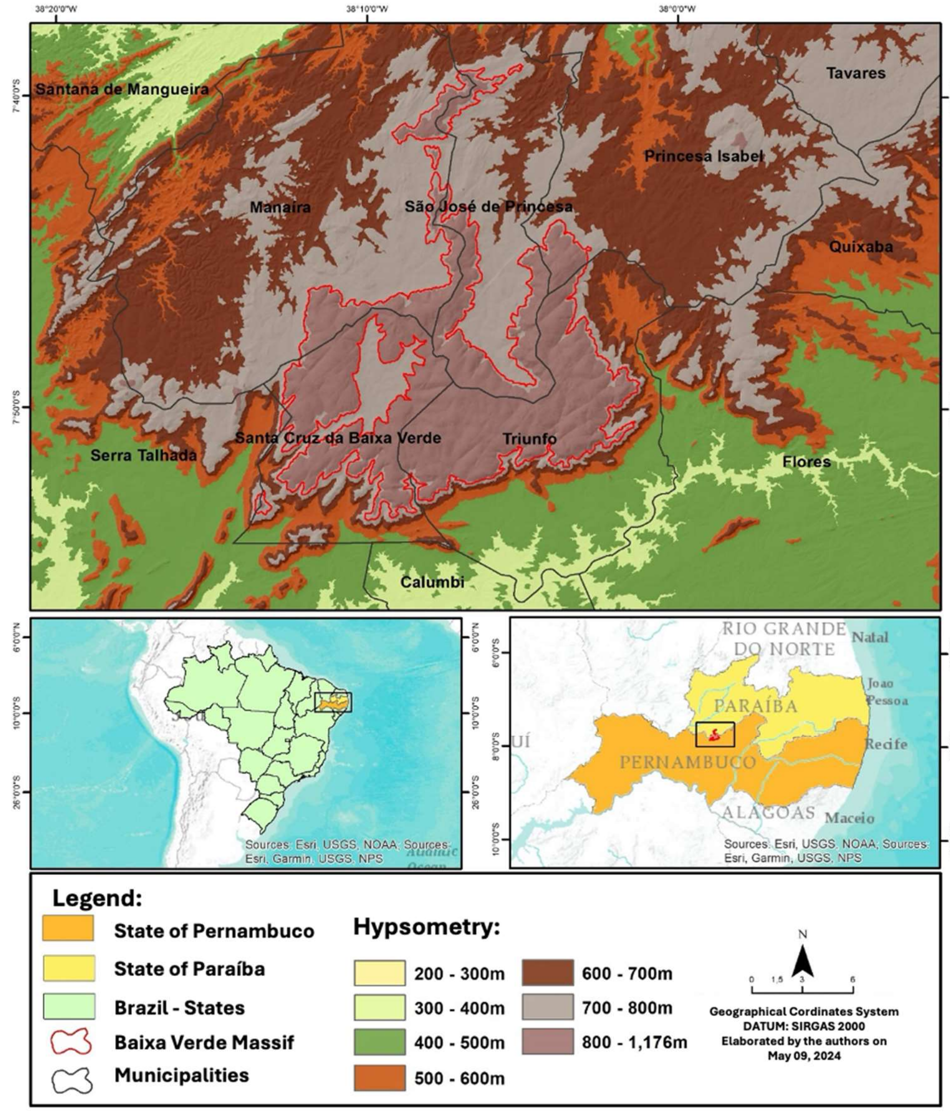


Figure 1 – Hypsometric map of the western escarpment of the Borborema Highlands (State of Pernambuco), with the Baixa Verde Massif and its surroundings. Mapa Hipsométrico da escarpa ocidental do Planalto da Borborema (PE). Source: Authors (2024).

The occurrence of topographic hollows in unchanneled catchments and other forms of colluvial deposition was used as a guideline for choosing the sampling areas. The establishment of the morphostratigraphy of the area, associated with the absolute dating of the sediments by Optically Stimulated Luminescence (OSL) in previous studies (Corrêa, 2001; Corrêa & Monteiro, 2020), allowed the genesis of the deposits to be elucidated through the correlation between the depositional structures, sediment macrofabrics, and the associated morphogenetic processes, acting within a specific temporal scale.

A mappable morphostratigraphic unit can be defined as a rock body – and, by extension, incohesive surface covers – identified primarily by its surface shape (Lowe & Walker, 2015). After selecting the sampling areas, morphostratigraphic maps were prepared to indicate the relationship between the relief forms and the surface geology (Hughes, 2010; Böse, 2014; Catuneanu and Zecchin). To this end, it was decided that the maps would offer a comprehensive view of the collection areas accompanied by stratigraphic sections illustrating the sequences of surface covers that structure the landscapes (Corrêa, 2001).

The sampling procedures for micromorphological analysis by Scanning Electron Microscopy (SEM) of grains in the 200 - 250 µm fraction were guided by the stratigraphic levels dated by LOE (Corrêa, 2001; Corrêa & Monteiro, 2020). The sediments were collected at the same levels as the vertical sections to refine the analyses regarding the history of transport and sedimentation associated with the deposition of colluvium and its possible environmental implications, current and past.

Thirteen samples were collected from four sampling areas, two of which were located at the summit of the massif between altitudes of 850 and 1,100 m, in a subhumid environment with 1,300 mm of annual precipitation, and two on the southern escarpment, between 550 and 600 m, in the semi-arid domain with annual totals of less than 600 mm (Corrêa et al., 2019) (Figure 2).

At the Federal University of Pernambuco, Recife, the samples were subjected to micromorphological analysis by scanning electron microscopy. The device used was the Electroscan 2020 model, which allows the analysis of non-metalized samples and, therefore, favors the study of the surface features of quartz or microcline grains without the need for any prior treatment that could mask or alter the features acquired by the type of transport or weathering suffered in the hillside environment.

The methodology applied was that of Goudie and Bull (1984), and the fundamental goal was the diagnosis of transport and chemical weathering features superimposed on the grains' original surfaces. The samples were separated into 10g portions and treated with a deflocculating agent (calcium hexametaphosphate) to clean the clay particles aggregated to the surface. The sand grains in the fraction between 200 and 250 µm were randomly selected and mounted in stubs on an inert resin adhesive base.

The choice of this particular granulometric fraction is due to the premise investigated by Krinsley and Doornkamp (1973), that this fraction represents the breaking point between the predominance of transport by suspension (grains < 200 µm) and by traction (grains > 400 µm). The former would, therefore, imply a predominance of features inherited from chemical weathering, while the latter would display surface features greatly influenced by abrasion. However, it is still necessary to consider the morphological characteristics of each grain, which are inherited from mineralogy, crystallography, and primary lithological provenance (Mahaney, 2002). As Trewin (1995) posits, the study of the surface features of quartz in the sand fraction in the 200-250µm fraction is guided by the belief that conclusions about the depositional environments and types of transport can be drawn from this mineral's surface features. The abundance of microcline, a potassium feldspar known for its resistance to weathering, in the study area made it a unique addition to the analysis.

One hundred grains per sample were analyzed, and an attempt was made to give a detailed qualitative character to the study, producing several images at various magnification scales for each grain. The results provide an overview of the weathering morphologies and mechanical wear imposed by the environments of the summit hillslopes and surroundings of the Serra da Baixa Verde massif on the surfaces of quartz and microcline sand grains in the 200-250µm fraction, bearing in mind that these were the two minerals in the area capable of retaining the marks of the alteration processes targeted by this study on their surfaces.

Thirty-two categories of surface features were selected from a combination of those proposed by Goudie and Bull (1984) and Trewin (1995). These were grouped into characteristics of mechanical, morphological, and chemical origins and numbered from 1 to 32 (Table 1). This numbering was used to construct summary tables of the occurrence of types of surface features for each of the 13 samples studied. The samples were identified by the prefix SBV, indicating "sediment from the Serra da Baixa Verde massif," followed by the numbering of the sampling point on the vertical sections (e.g., SBV11; SBV12; SBV21).

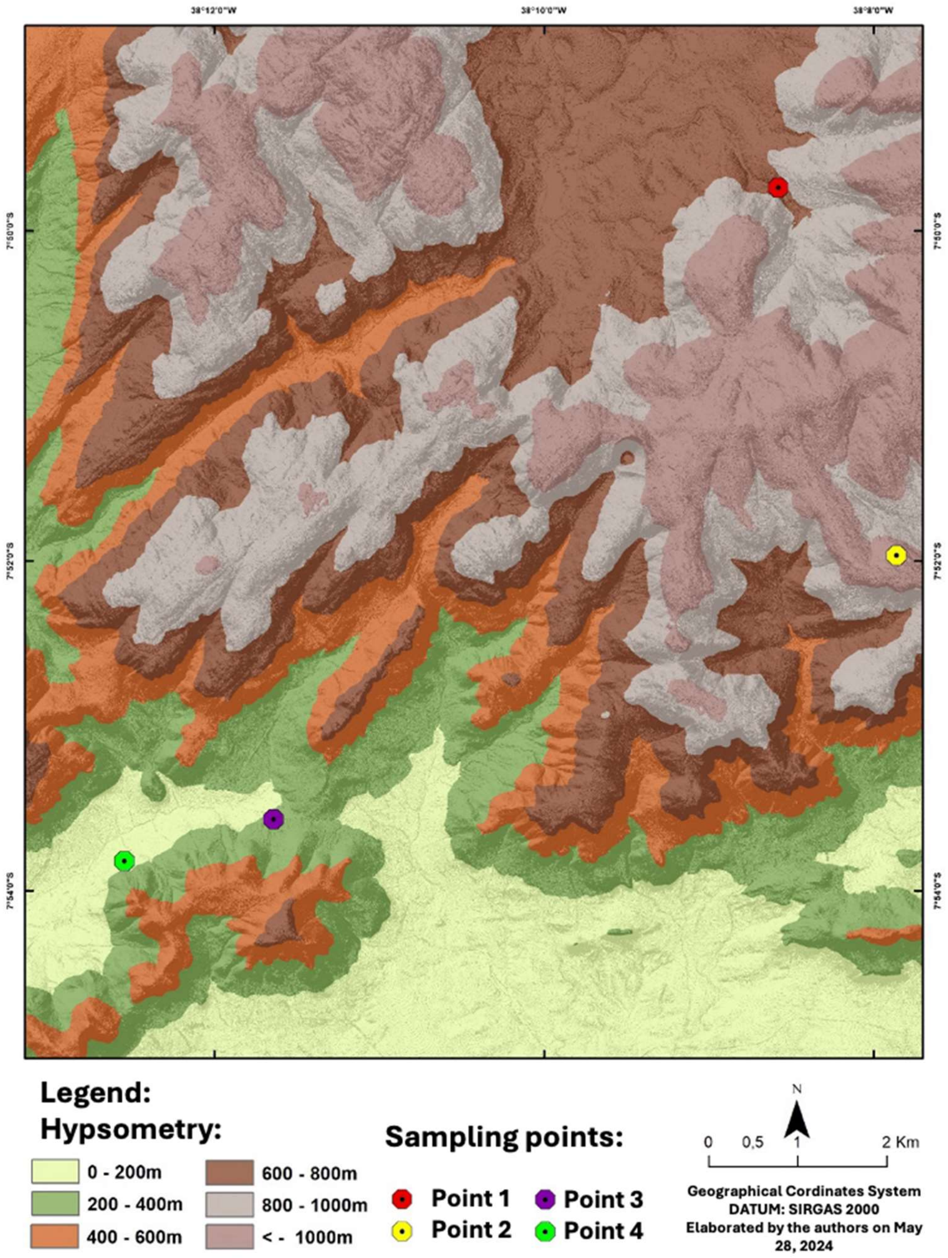


Figure 2 – Hypsometric map of the Southern escarpment and Summit surface of the Serra da Baixa Verde Massif with the distribution of the sampling points for SEM analysis.
Source: Authors (2024).

Table 1 – Types of surface features analysed in quartz and microcline grains in the study area from their grouping in mechanical, morphological and Chemical features.

TYPES OF SURFACE FEATURES		
MECHANICAL	**MORPHOLOGICAL**	**CHEMICAL**
1. Cracks 2. Edges abrasion 3. Fractured blocks (< 10 μ) 4. Fractured blocks (>10 μ) 5. Concoidal fractures (< 10 μ) 6. Concoidal fractures (>10 μ) 7. Straight steps 8. Arcuate steps 9. Parallel striations 10. Imbrincated indentations 11. Fractured plates 12. Meandering ridges 13. Straight scratches 14. Curved scratches 15. V-shaped mechanical cavities 16. Discoidal concavities	17. Rounded 18. Sub-rounded 19. Sub-angular 20. Angular 21. Low relief 22. Medium relief 23. High relief	24. Oriented solution cavities 25. Anastomosis 26. Matte surface 27. Solution cavities 28. Solution fractures 29. Scaling 30. Carapace 31. Amorphous cavities 32. Euhedral silica

Source: Authors (2024).

The results were grouped in tables according to the percentages of occurrence of the surface features analyzed. The evaluation criteria are visual and, therefore, subject to a degree of subjectivity inherent to the technique.

The detailed geomorphological mapping of the sampling areas aimed to establish the geomorphic units in a GIS environment using the QGIS 3.3.4 software, based on the Digital Terrain Model (DTM) of the Pernambuco Tridimensional Database (PE3D) and the Orthophoto at a scale of 1:5,000, in which shaded reliefs were generated with insolation azimuths of 315º and 65º elevation to highlight the features of ridges and escarpments, separating them from the flat depositional features of the valley floor. The classification of the forms followed the proposal of Corrêa (2001) and Corrêa and Monteiro (2020): Rocky and eluvial summits and hillslopes (CER and CE), colluvial hillslopes (EC), colluvial-alluvial ramps (RCA); undifferentiated terraces (TI), alluvial fan terrace (TLA) and alluvial plain (PA).

The interpretation of the images and DTM, combined with the crucial role of fieldwork, allowed for the in loco identification of the depositional features and the validation of the units mapped in the office. The fieldwork was instrumental in separating hillslopes from the pediment ramps by steepness and extension, with the latter being restricted to the semi-arid surroundings of the massif with slopes lower than 7º and continuous extensions greater than 100 meters. The slopes were then subdivided by the presence or absence of colluvial cover.

In the field, this distinction occurs due to well-marked topographic knickpoints between the accumulation ramps and the steep sectors upstream structured in rock or in situ eluvium. This morphological evidence was added to the sediments containing structures characteristic of hillslope deposits (e.g., alternation between gravel and muddy deposits, stone lines, imbrication of larger clasts towards the foot of the slope). The same criterion was adopted for the summit surfaces adjacent to the rocky-eluvial sectors of the hillslopes, which were also differentiated by presenting continuous eluvial cover, which led to the identification of the "eluvial summit" unit.

Finally, the fluvial domain's morphostratigraphic units were separated according to morphology, forming materials, and contemporaneity of the forms. This process involved distinguishing active alluvial plains with current accumulation, adjacent to the channels, from the highest sectors beyond the banks forming terrace levels. These terrace levels, which could not be individualized by altimetric criteria in the areas where they occur, were also identified.

The topographic continuity of the terraces with the lower hillslopes sometimes occurs without loss of lateral continuity of the first form, which rises as a colluvial-alluvial ramp filling old erosional hollows through the interdigitation of slope sedimentation with the laminar flows of the alluvial plain during floods. At isolated points of the merging between the alluvial plains and the hillslopes, old alluvial fans were reshaped and incorporated into the top of the terraces, of which a lobed morphology with the apex facing the slope remains in the landscape (Figure 3).

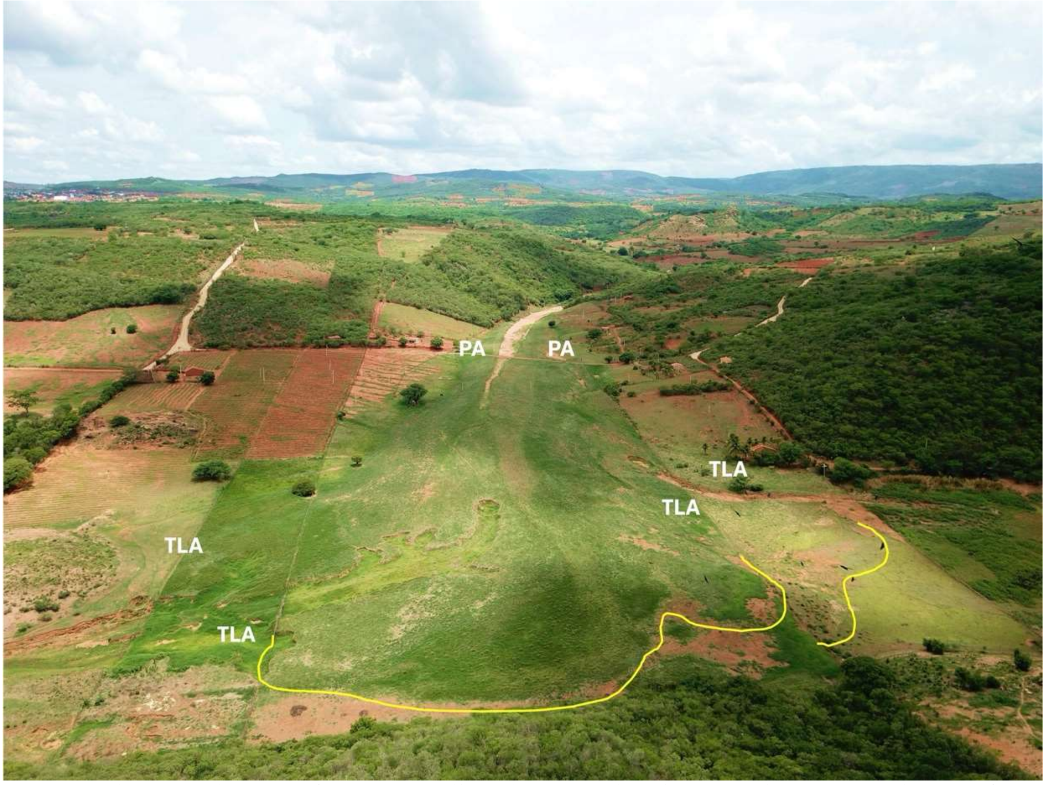


Figure 3 – Accumulation and erosion forms in an alluvial plain within the Serra da Baixa Verde Massif. PA (Alluvial plain), TLA (Terrace in reshaped alluvial fan), Yellow line (lobate morphology of fans' fronts)
Source: Authors (2024).

3. Results and discussion

An assessment of surface features by category type was carried out by the total percentage of occurrence of grains from each of the 13 samples analyzed. Results were organized in table form (Table 1). In parentheses is the percentage of grains with the dominant occurrence of each feature type, equivalent to more than 75% of the features identified on the surface. Thus, for example, for sample SBV11, 46% of the analyzed grains exhibited mechanical wear features, and in 38% of these, mechanical features were dominant. The results for each sample are shown in Tables 2 to 5. Each sample comprises 100 grains of sand in the 200-250 µm fraction containing quartz or microcline.

The data representations express the average percentage of occurrence of each diagnostic property per grain, represented in the table by the symbols corresponding to the features of abundant occurrence (value 4), common (value 3), sparse (value 2), and rare (value 1). From these values, the average relative to the frequency of the surface features was calculated for the 100 grains of each sample. Based on the work of Trewin (1995), an interpretative legend was created for the percentage occurrence of diagnostic features on the surfaces of the grains as follows: > 75% (abundant); 25–75% (common); 5–25% (sparse); and <5% (rare).

Table 2 – Percentage of occurrence of mechanical, morphological, and chemical features per sample (100 grains), and percentage of grains with occurrence of dominant surface features (>75%) per category. The green color indicates samples from the subhumid environment (summits and upper hillslopes), and the gray color indicates the semi-arid environment (lower hillslopes).

Sample	***Total % of mechanical features categories***	***Total % of morphological features categories***	***Total % of Chemical features categories***
SBV11	*46 (38)*	*40 (12)*	*35 (16)*
SBV12	*47 (36)*	*28 (50)*	*33 (43)*
SBV21 (regolito)	*32 (28)*	*28 (100)*	*34 (36)*
SBV22	*39 (31)*	*33 (83)*	*57 (55)*
SBV23	*47 (33)*	*28 (30)*	*45 (29)*
SBV41	*68 (26)*	*28 (25)*	*58 (52)*
SBV42	*64 (24)*	*28 (60)*	*60 (42)*
SBV51	*73 (28)*	*28 (57)*	*57 (53)*
SBV52	*62 (56)*	*31 (47)*	*65 (39)*
SBV53	*76 (41)*	*28 (71)*	*63 (20)*
SBV61	*69 (27)*	*28 (75)*	*65 (49)*
SBV62	*70 (28)*	*28 (75)*	*52 (39)*
SBV63	*70 (70)*	*28 (83)*	*52 (28)*

Source: the authors (2024).

3.1 Sampling area 1

The first sampling area is located on a colluvial hillslope north of the urban center of Santa Cruz da Baixa Verde, in Engenho Boa Esperança. The colluvial hillslope is at the base of a circular elevation with a summit of 1,014 meters. The sampling point is located at coordinates 7º48'42" S and 38º09'12" W, at an altitude of 840 meters, in a gully in the middle-lower sector of the colluvial hillslope with convex morphology (Figure 3A and Figure 3C).

From the base to the top, the profile described (Figure 3B) is approximately 2.05 meters high, comprising 50 cm of basal conglomerate and 155 cm of fine red colluvium. The contact between the syenitic basement and the basal conglomerate was not observed in the studied profile. However, the erosive contact between the hillslope sediments and the underlying bedrock outcrops at other points along the gully bottom in the vicinity of the studied transect.

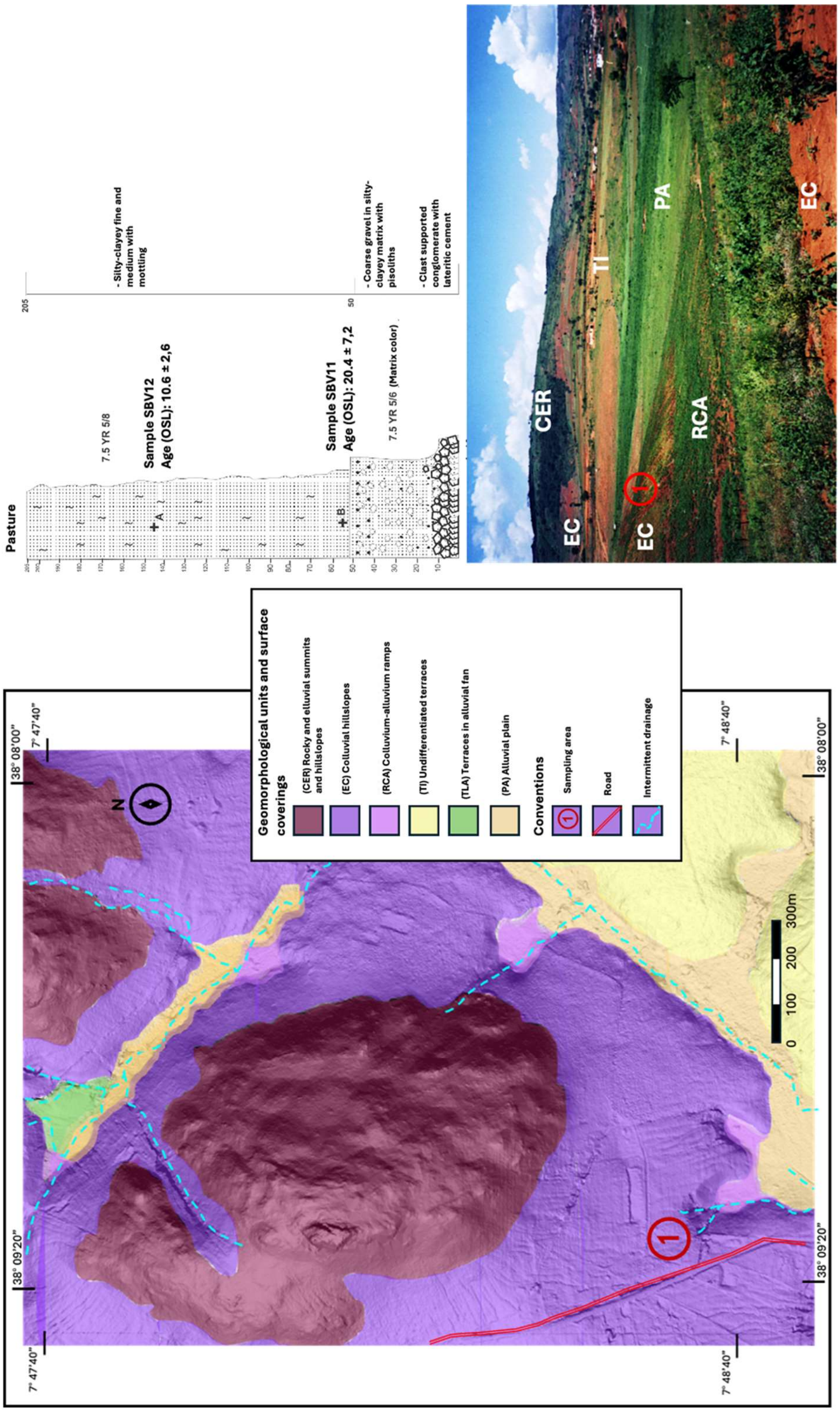


Figure 3 – Geomorphological and stratigraphical units of sampling area 1.
Source: Authors (2024).

Two samples were collected and dated using the OSL method in the fine colluvium layer, 55 and 145 cm from the base of the profile, resulting in mean ages of 20.4 Ka ± 7.2 and 10.6 Ka ± 2.6, respectively (Corrêa & Monteiro, 2020). The samples subjected to analysis of surface features of the sand grains by SEM were collected at the same stratigraphic level as the dating (Table 2). To illustrate the identified physiognomies, grains representative of the sampled stratigraphic levels were chosen (Figure 3B). In area 1, grains SBV11b and SBV12a were chosen to represent the surface features predominant at each level. The surface of grain SBV11b exhibits edge abrasion with a new phase of solution cavity formation. At the same time, SBV12a corresponds to a high-relief quartz grain with smoothed edges – possibly due to transport – and solution cavities (Figure 4).

Table 3 – Synthesis of the surface features identified in 100 grains for each sampling level (SBV11 and SBV12) of sampling area 1.

	Mechanical																**Morphological**							**Chemical**								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**
SBV11	⧈	■	■	■	⧈	⧈	▣	⧈	□	□	□	□	⧈	⧈	⧈	□	□	▣	▣	□	□	▣	□	□	□	▣	▣	⧈	□	□	▣	□
SBV12	⧈	▣	⧈	⧈	▣	⧈	⧈	⧈	⧈	⧈	□	□	□	⧈	□	▣	□	⧈	▣	□	⧈	▣	□	□	⧈	⧈	▣	⧈	▣	□	▣	□

□ **< 5% - rare** ⧈ **5 a 25 % - sparse** ▣ **25 a 75 % - common** ■ **> 75% - abundant**

Source: Authors (2024).

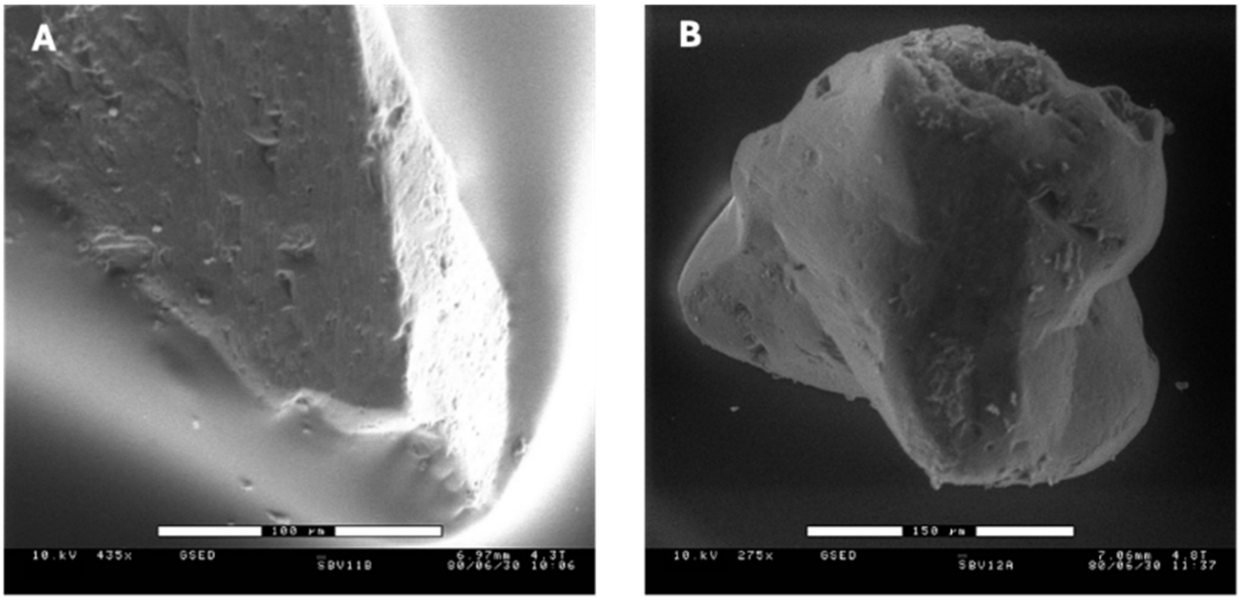


Figure 4 – Photomicrographs of surface features of grains from sampling area 1.. A (SBV11b) – 425x, B (SBV12a) – 275x.
Source: Authors (2024).

3.2 Sampling area 2

The second sampling area is located at Sítio São José dos Pilotos, in the municipality of Triunfo, at coordinates 7º49'45" S and 38º08'38" W, at an altitude of 890 meters, in a hollow in the lower middle section of a convex hillslope (Figure 5A). The erosion incision is part of a system of radial gullies that occupies a hollow's middle and lower slopes with a generally concave morphology (Figure 5C). The colluvial hillslope extends from the middle slope to the confluence with a first-order channel. It exhibits a gently convex morphology with a lobate front corresponding to the distal sector of a mudflow. The colluvial material thickens toward the axis of the hollow. The hollow is a zero-order unchanneled catchment.

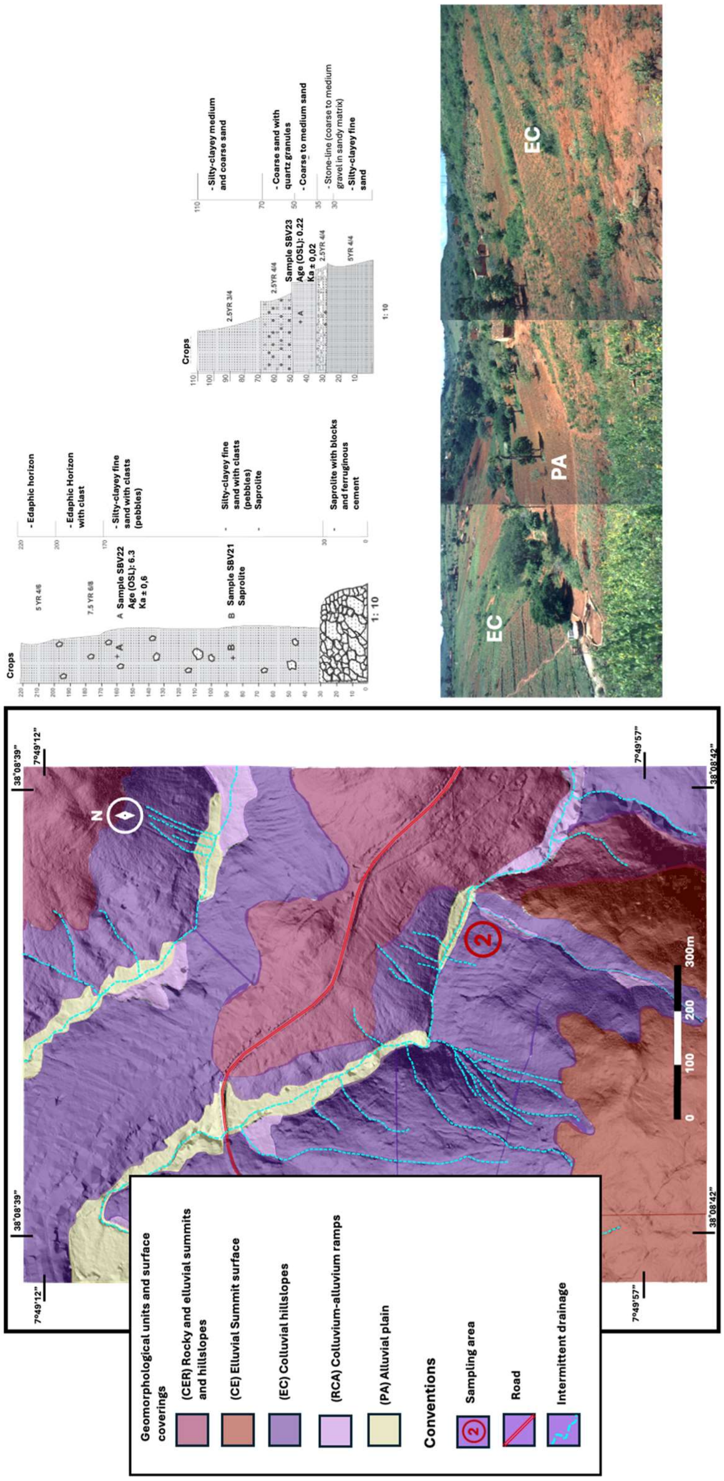


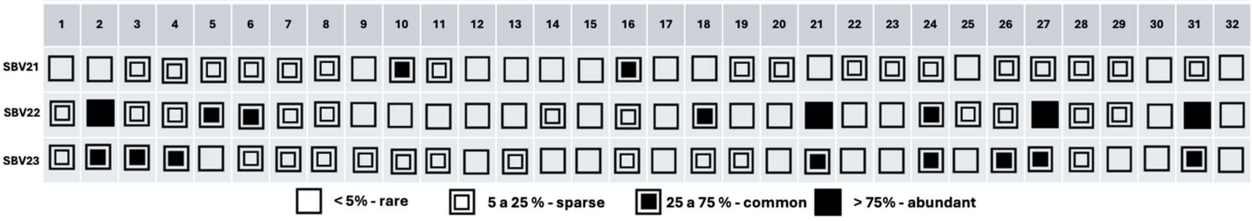
Figure 5 – Geomorphological and stratigraphical units of sampling area 2.
Source: Authors (2024).

The colluvial cover consists of three distinct stratigraphic units. The first unit is a basal conglomeratic unit with lateritic cement and a thinner colluvium with a silty matrix containing larger clasts, both occurring in the middle slope section. The total thickness from the base to the top is 2.2 m (refer to Figure 5B). The basal unit (SBV21) corresponds to the in situ regolith developed on the peralkaline syenite of the Serra da Baixa Verde. The thinner colluvium (SBV22) that covers the basal unit has an OSL age of 6.3 Ka ± 0.6 (Corrêa & Monteiro, 2020).

On the lower slope, there is a third unit (SBV23) with a slightly channeled structure, which intercalates gravel and coarse sand layers with layers of finer sand with higher clay content. The lobate morphology of this unit suggests the occurrence of mudflows, reworked from uphill materials. The sampled profile has a thickness of 1.1 m. The stratigraphic level dated by OSL resulted in an age of 0.23 Ka ± 0.02, a significant finding that provides crucial insights into the geomorphological history of the area. The material was sampled for SEM analysis and identification of the surface morphology of the grains (Table 3, Figure 6).

The samples corresponding to the dated levels were analyzed by SEM to describe the surface features of the grains. Grains SBV21q and SBV21i, originating from the underlying regolith of the fine-grained Holocene colluvium, present sharp and serrated edges and concoidal fractures. In turn, grains SBV22h and SBV23g, originating from the fine-grained Holocene colluvium of the mid-slope and the coarsely stratified, recent colluvium of the lower slope, present rounded morphology with fractured blocks and concoidal fractures with smoothed edges and polished faces. All these physiognomies indicate transport in subaqueous conditions (Goudie & Bull, 1984), such as mudflows (Figure 6).

Table 4 – Synthesis of the surface features identified in 100 grains for each sampling level (SBV21, SBV22 and SBV23) of sampling area 2.



	Mechanical																Morphological							Chemical								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
SBV21	□	□	⧈	⧈	⧈	⧈	⧈	⧈	□	▣	⧈	□	□	□	□	▣	□	□	⧈	⧈	□	⧈	⧈	⧈	□	⧈	⧈	⧈	⧈	□	⧈	□
SBV22	⧈	■	⧈	⧈	▣	▣	⧈	⧈	□	□	□	□	□	⧈	□	⧈	□	▣	□	□	■	□	□	▣	⧈	⧈	■	⧈	⧈	□	■	□
SBV23	⧈	▣	▣	▣	□	⧈	⧈	⧈	⧈	⧈	⧈	□	⧈	□	□	⧈	□	⧈	⧈	□	▣	□	□	▣	□	▣	▣	⧈	□	□	▣	□

□ < 5% - rare ⧈ 5 a 25 % - sparse ▣ 25 a 75 % - common ■ > 75% - abundant

Source: Authors (2024).

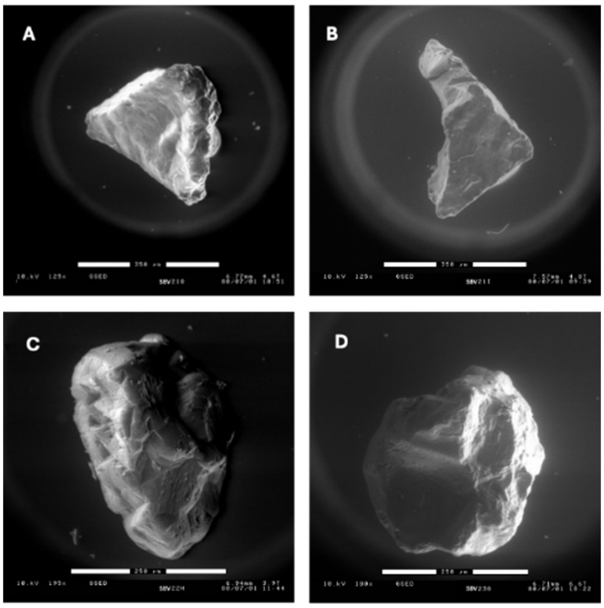


Figure 6 – Photomicrographs of surface features of grains from sampling area 2. A (SBV21q) – 125x, B (SBV21i) – 255x, C (SBV22h) – 195x and D (SBV23g) – 180x.
Source: The authors (2024).

3.3 Sampling area 3

The third sampling area is located on a colluvial ramp near the southern escarpment of the Serra da Baixa Verde massif at 7º53’35” S and 38º11’39” W at an altitude of 570 meters (Figure 7A). The colluvial ramp cut by gullies occurs near the village of Jatiúca, between the municipalities of Santa Cruz da Baixa Verde and Serra Talhada. Six points were sampled in this area, which presented the most diverse stratigraphy among the colluvial hillslopes within the massif.

The middle and lower slopes in the sampling area are covered by overlapping sequences of colluvium ramps, with an average gradient between 10º and 11º at the surface. The stratigraphy comprises a basal conglomerate and at least two upper sequences of finer colluvium. The finer units are separated by gravel beds and discontinuous stone-lines (Figure 7B).

Samples for various analyses were collected at two points, one at the base and the other at the middle of the slope. The first sampled point corresponds to the top of a basal conglomeratic layer along the margins of a trench excavated by a stream parallel to the base of the colluvium ramps. The material collected is a gravel matrix supported on the upper level of the basal conglomeratic unit. The lower level of this unit is a clast-supported conglomerate, exhibiting imbrication of the larger clasts towards the slope base. The gravel layers showed a constant upward fining and ages corresponding to the mid-Holocene, ranging from 7.1 Ka ± 2.5 to 7.2 Ka ± 0.3 (Corrêa & Monteiro, 2020) (Figure 7B).

At the second collection point, samples were taken at 60, 105, and 160 cm from the surface, along a mid-slope exposure, where a drainage line longitudinally sections the colluvial deposit. The first sampled level corresponds to the middle of the upper colluvial unit, a fine reddish colluvium; the second dated level refers to the top of a gravel bed, at the same level as the charcoal fragments, and the third level refers to the top of the lower fine colluvium located below the gravel bed. In this profile, ages ranged from the lower Holocene (8.9 Ka ± 0.5 and 8.5 Ka ± 2.6) to the middle Holocene (4.7 Ka ± 0.3), providing a comprehensive chronological framework.

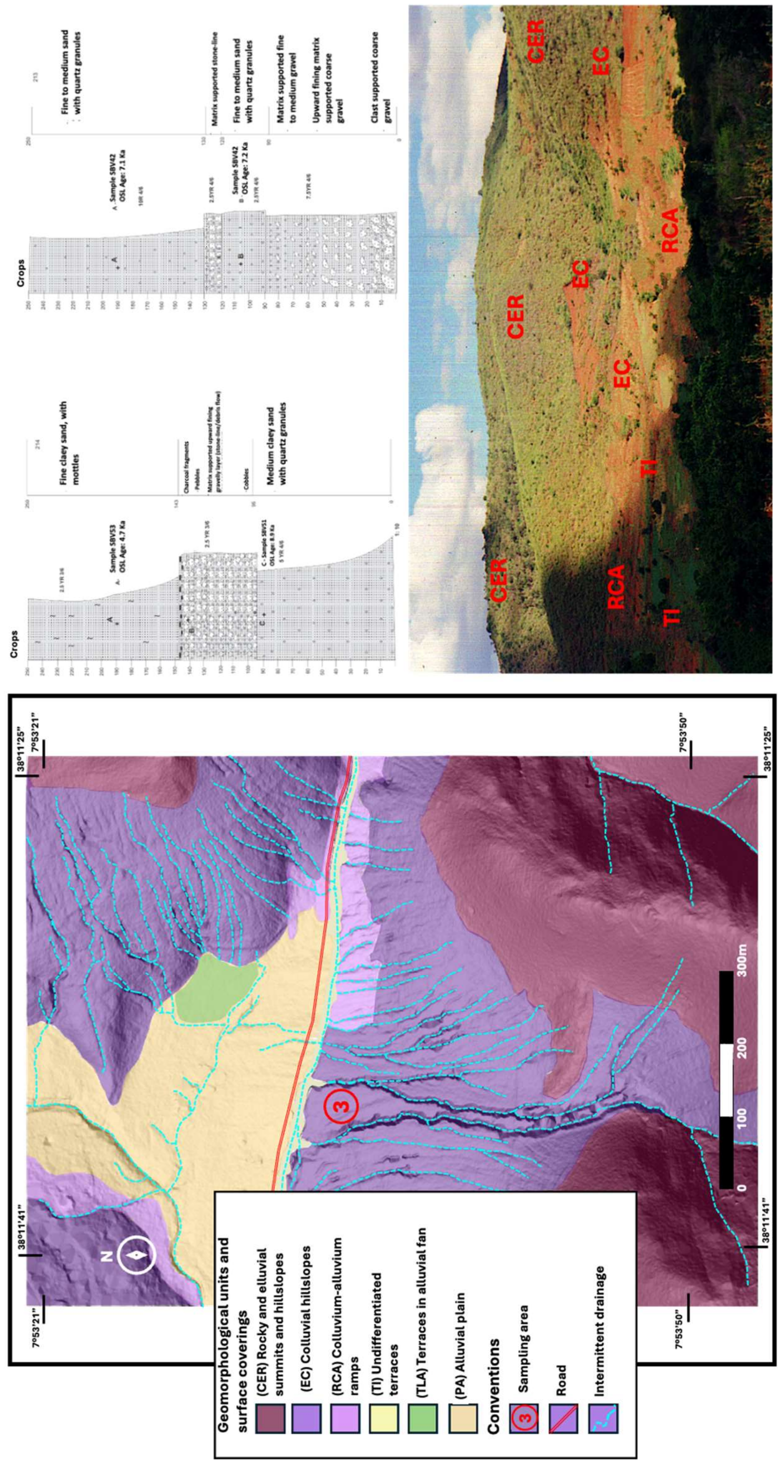


Figure 7 – Geomorphological and stratigraphical units of sampling area 3.
Source: Authors (2024).

The surfaces of the grains of sample SBV41, corresponding to a debris flow, present well-developed mechanical and chemical dissolution features (Table 4). Grains SBV41E and SBV41F present rounded, low-relief morphologies without edges, scales, and superficial cavities of geochemical dissolution (etching and pitting). The detail of the upper edge of grain SBV41F presents evidence of mechanical abrasion associated with the debris flow (Figures 8A and 8B).

When observed at two magnification intensities (190 and 650x), the microcline grain SBV41H presents a sub-rounded morphology with stepped fractures superimposed on chemical dissolution in scales (top of debris flow). The stepped fractures subordinate to the mineral's cleavage can be observed in detail, superimposed on the surface with marks of intense chemical dissolution (Figures 8C and 8D).

Table 5 – Synthesis of the surface features identified in 100 grains for each sampling level (SBV41, SBV42, SBV51, SBV52 and SBV53) of sampling area 3.

	Mechanical																Morphological							Chemical								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
SBV41	⧈	▣	⧈	⧈	⧈	▣	▣	▣	▣	▣	▣	⧈	⧈	⧈	□	⧈	□	□	⧈	⧈	⧈	⧈	□	▣	⧈	▣	▣	▣	▣	□	▣	□
SBV42	⧈	▣	⧈	⧈	▣	▣	⧈	⧈	⧈	⧈	⧈	⧈	⧈	⧈	□	⧈	□	⧈	⧈	⧈	⧈	⧈	□	▣	⧈	▣	▣	⧈	⧈	□	▣	□
SBV51	⧈	■	▣	▣	▣	▣	⧈	⧈	⧈	▣	⧈	⧈	⧈	⧈	□	▣	□	⧈	⧈	□	⧈	⧈	□	▣	⧈	▣	■	⧈	⧈	□	■	□
SBV52	▣	▣	▣	▣	▣	▣	▣	▣	⧈	▣	□	□	▣	□	□	▣	□	▣	⧈	⧈	▣	□	□	▣	⧈	▣	▣	⧈	⧈	□	⧈	□
SBV53	▣	▣	▣	▣	■	■	▣	■	⧈	▣	⧈	⧈	⧈	□	□	▣	□	□	▣	□	▣	□	⧈	⧈	▣	▣	▣	⧈	▣	□	⧈	□

□ < 5% - rare ⧈ 5 a 25 % - sparse ▣ 25 a 75 % - common ■ > 75% - abundant

Source: Authors (2024).

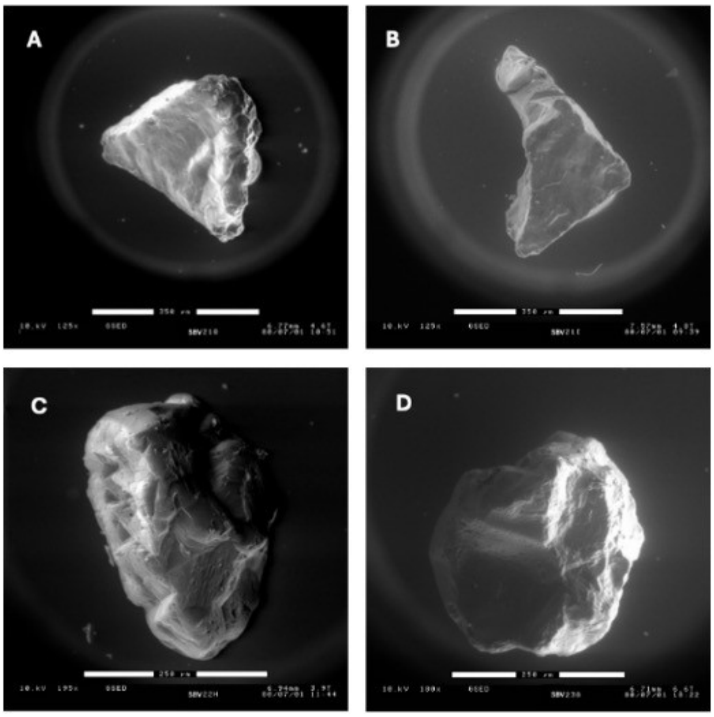


Figure 8 – Photomicrographs of surface features of grains from sampling area 3. A (SBV41E) – 150x, B (SBV41F) – 550x, C (SBV41N) – 190x and D (SBV41N) – 650x.
Source: Authors (2024).

In sample SBV42, collected at the top of a debris flow, grain SBV42 C presents a subrounded morphology with arcuate fractures on the edge (Figure 9A). At 490x magnification, it is possible to observe details of the discoid concavities and smoothed concoidal fractures on its surface. These features attest to the mechanical wear to which the grain was subjected during transport by debris flow and in the hillslope environment (De Haas et al., 2020) (Figure 9B).

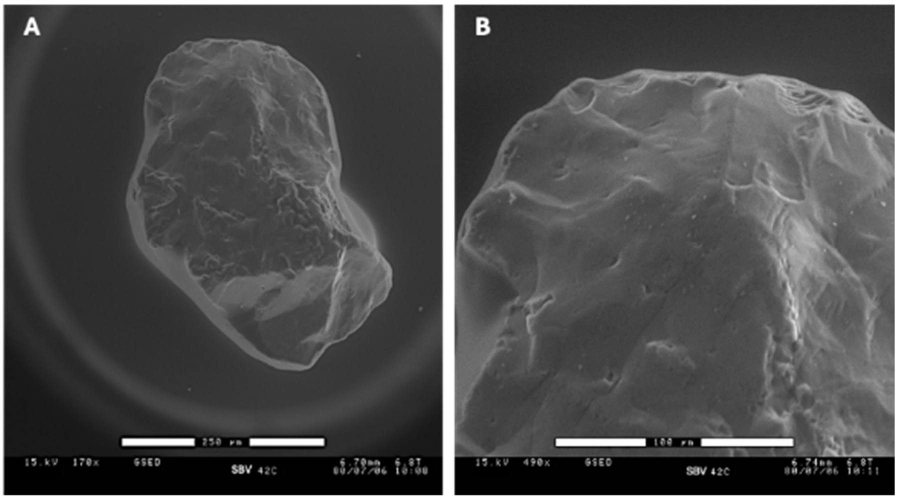


Figure 9 – Photomicrographs of surface features of grains from sampling area 3. A (SBV42C) – 170x, B (SBV42C) – 490x.
Source: Authors (2024).

At the other sampling point in sampling area 03, halfway up the hillslope, on a colluvium ramp, sample SBV51, represented by grain SBV51J, corresponds to a mudflow deposit. The grain has a rounded morphology, multiple discoid concavities, and polished faces and edges. The detail of the upper face with minor chemical wear on the surfaces corroborates the idea of the occurrence of a short period of weathering prior to transportation (Figures 10A and 10B).

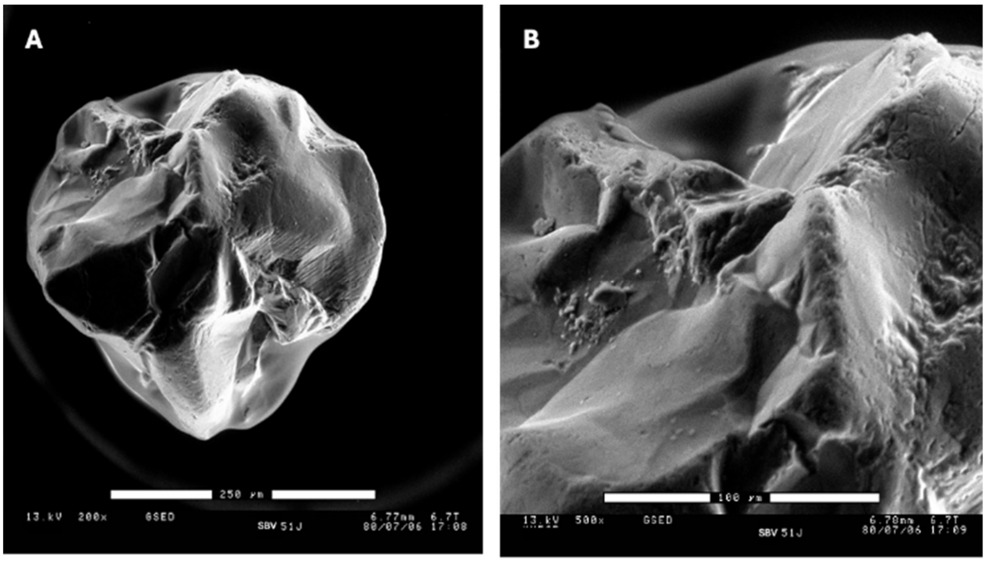


Figure 10 – Photomicrographs of surface features of grains from sampling area 3. A (SBV51J) – 200x, B (SBV51J) – 500x.
Source: Authors (2024).

The top of the Lower Holocene debris flow represented by sample SBV52 and the mud flow corresponding to sample SBV53 presented similar characteristics on the grain surface, as evidenced by samples SBV52F and SBV53I. In the case of SBV52F (Figures 11A and 11B), the grain shows evidence of rounding of the faces due to chemical weathering, with the formation of scales and dissolution cavities, which are superimposed by concoidal fractures truncating the edges that contain evidence of a previous phase of more intense chemical dissolution.

On the other hand, grain SBV53I presents high relief and edges smoothed by chemical weathering. The presence of several fractures truncating the strongly altered surface could potentially indicate the persistence of more humid conditions since the Lower Holocene. At a detailed (500x magnification) level, the textural difference between a relatively fresh fractured zone and the surface extensively flaked by dissolution can be observed (Figures 11C and 11D).

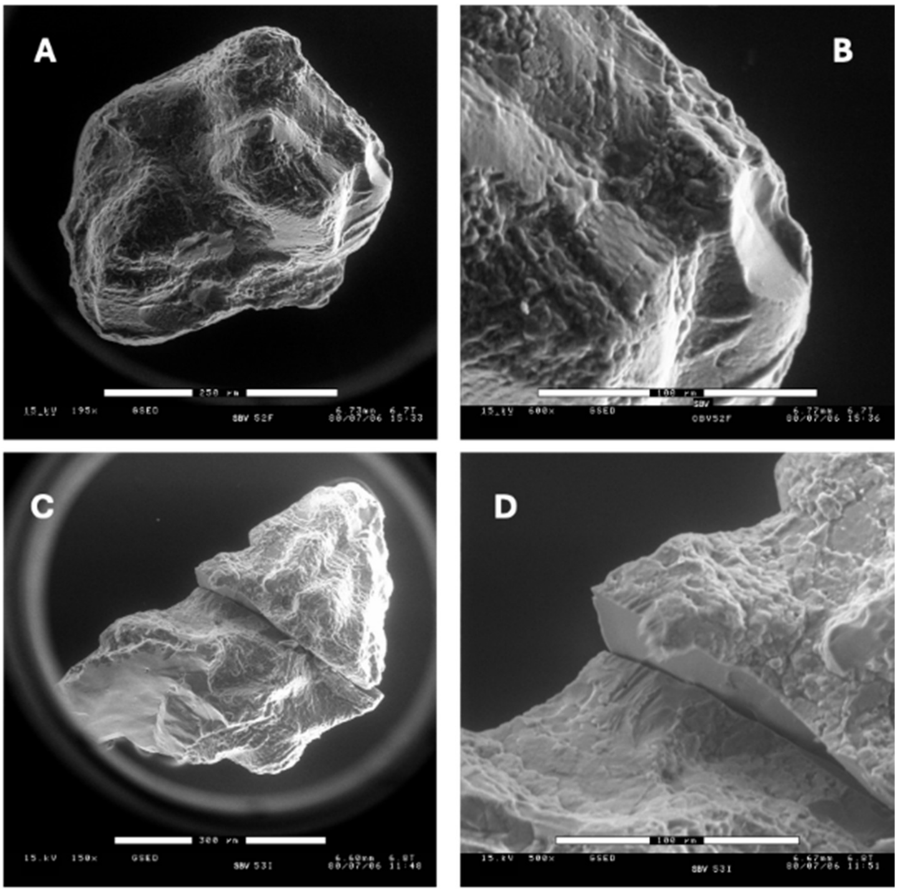


Figure 11 – Photomicrographs of surface features of grains from sampling area 3. A (SBV52F) – 195x, B (SBV52F) – 600x, C (SBV53I) – 150x, D (SBV53I) – 500x.
Source: Authors (2024).

3.4 Sampling area 4

The fourth sampling area consists of a colluvium ramp with a 9.5º inclination, delimited upstream by a topographic knick with a rocky slope with a steepness > 25º and downstream by a pediment feature with detrital cover (Figure 12C). Pediment ramps were characterized by their steepness < 7º and length greater than 100 meters, and they may be structured in the bedrock, with or without eluvium residuum, or present colluvial detrital cover, generally associated with the action of laminar flow (sheet-flow) (Pelletier, 2010). The sampling area is located at 07º53’50” S and 38º12’33” W at an altitude of 570 m, on a topographic spur associated with the southern escarpment of the Serra da Baixa Verde massif, in the municipality of Serra Talhada (Figure 12A).

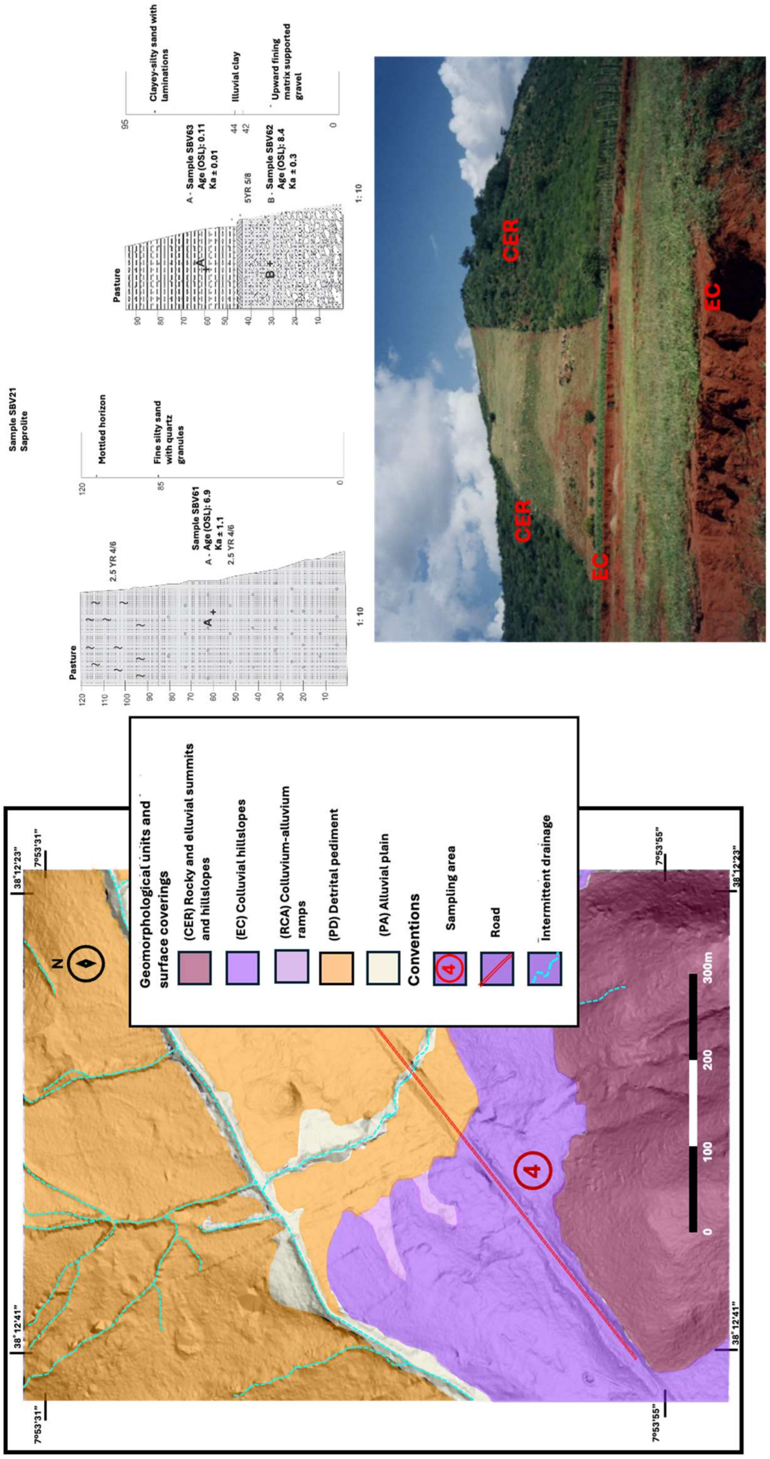


Figure 12 – Geomorphological and stratigraphical units of sampling area 4.
Source: Authors (2024).

The colluvium ramp displays several exposures of the deposit in the form of benches, which allowed the observation of three distinct stratigraphic units: a thin, reddish, massive colluvium, a basal conglomerate, which fills paleo-depressions and stream channels, and a third, finely stratified unit located in the middle slope above the basal conglomerate, but without direct contact with the fine reddish colluvium (Figure 12B). The top of the conglomeratic layer presents levels cemented by lateritic concretions.

The samples for SEM analysis were collected from the same levels subjected to OSL dating (Table 5 and Figure 13). The massive reddish colluvium, with an OSL age of 6.9 ka ± 1.1 (Corrêa & Monteiro, 2020), gives way to a laminated, sub-contemporary (ca. 110 years) colluvium downslope, which confirms that the processes that operated on the hillslope changed over time, from gravitational flows to unchanneled laminar flows.

Table 5 – Synthesis of the surface features identified in 100 grains for each sampling level (SBV61, SBV62 and SBV63) of sampling area 3.

	Mechanical																Morphological							Chemical								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
SBV61	⧈	■	▣	▣	▣	▣	▣	▣	⧈	▣	⧈	⧈	⧈	□	⧈	▣	⧈	⧈	⧈	□	■	□	□	▣	▣	▣	■	▣	▣	□	▣	□
SBV62	▣	■	▣	▣	▣	▣	⧈	⧈	⧈	⧈	□	▣	▣	□	⧈	▣	□	⧈	⧈	□	▣	⧈	□	▣	⧈	▣	▣	▣	▣	□	▣	□
SBV63	⧈	▣	▣	▣	▣	▣	▣	▣	⧈	⧈	⧈	□	⧈	⧈	▣	▣	□	⧈	□	⧈	■	□	□	⧈	⧈	⧈	▣	▣	⧈	□	▣	□

□ **< 5% - rare** ⧈ **5 a 25 % - sparse** ▣ **25 a 75 % - common** ■ **> 75% - abundant**

Source: Authors (2024).

The basal conglomerate, with an OSL age of 8.4 Ka ± 0.3 (Corrêa & Monteiro, 2020), showed upward fining, ranging from a clast-supported gravel deposit on the pebble fraction at the base to layers of irregularly laminated quartz pebbles at the top of the sequence. The deposit fills paleo-depressions and possibly an old channel in the center of the hillslope, thus constituting a discrete local relief inversion where a convex slope segment has replaced a concave hollow due to aggradation.

The grain SBV61G, originating from the middle Holocene reddish fine colluvium, has a rounded morphology due to chemical weathering. At 340x magnification, several solution cavities were observed (Figure 13). It is postulated that the greater presence of solution features in the grains of this deposit derives from the low gradient of the lower slope sector, forming a sub-horizontal plane with free drainage.

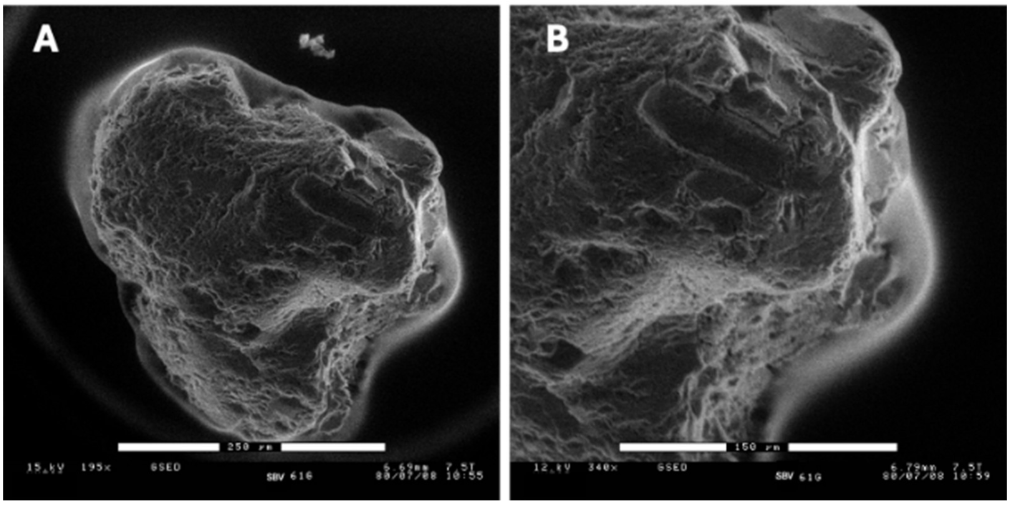


Figure 13 – Photomicrographs of surface features of grains from sampling area 4. A (SBV61G) – 195x, B (SBV61G) - 340x.
Source: Authors (2024).

The sediments of sample SBV62, the top of the conglomerate that fills the paleo-depressions on the colluvial slope, present conspicuous features of mechanical wear. Grain SBV62F, for example, exhibits subangular morphology with several concoidal fractures. At 500x magnification, it is possible to observe a detail of the upper edge with several fractures and concavities of mechanical origin and edges with truncated edges (Figure 14).

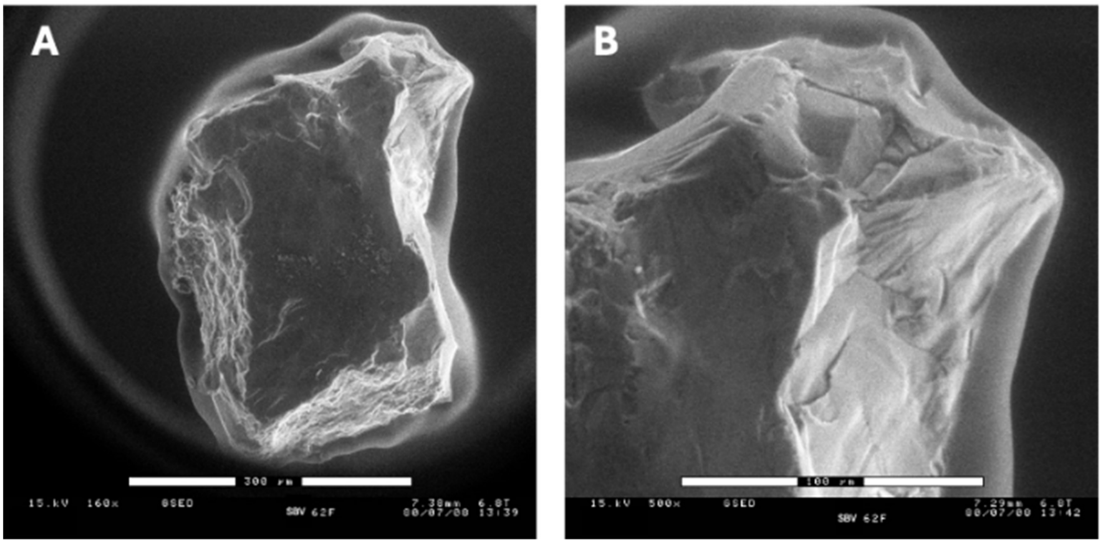


Figure 14 – Photomicrographs of surface features of grains from sampling area 4. A (SBV62F) –160x, B (SBV62F) - 500x.
Source: Authors (2024).

The SBV 63G grain from the sub-contemporary laminated colluvium presents an angular morphology with high relief and blocky fractures in steps, in addition to a truncated concoidal fracture. The detail of the upper face with 345x magnification reveals overlapping of the features of mechanical origin (concoidal and blocky fracture) on the surface with marks of chemical dissolution (Figure 15).

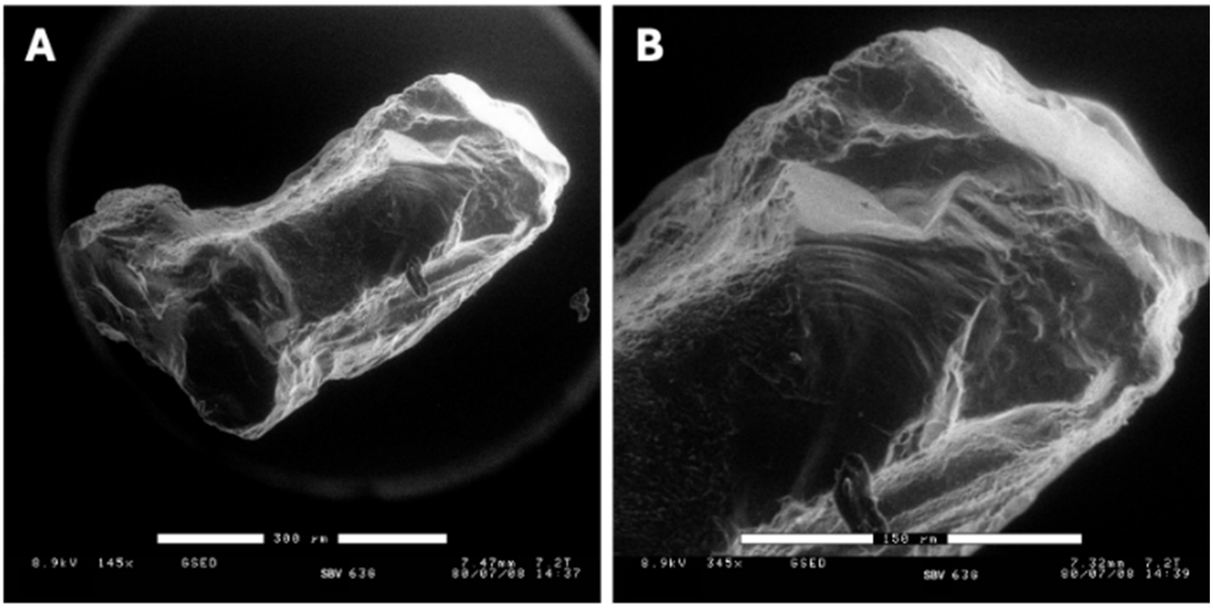


Figure 15 – Photomicrographs of surface features of grains from sampling area 4. A (SBV63G) – 145x, B (SBV63G) - 345x.
Source: Authors (2024).

The samples exhibited similar micromorphological patterns, with a predominance of mechanical features, notable or discrete, superimposed on chemical features, which suggests the occurrence of erosive reworking phases truncating evidence of chemical weathering. However, mechanical features are more numerous in the most recent samples, and in those from the semiarid sector of the massif, while in the subhumid climate domain, both chemical and mechanical features occur in smaller numbers. The climate contributed to the better preservation of the features, especially the mechanical ones, of the semiarid samples. The morphological features occur in an almost constant proportion, which indicates a repetitive pattern, possibly related to the type of weathering suffered by the grains and their common lithological origin. Goudie and Bull (1984) identified edge abrasion as the primary evidence for short-distance transport from the source area, typical of hillslope deposits, with a predominance of hyperconcentrated flows with large amounts of sand. This abrasion is closely related to the roughness of the transport environment, i.e., the occurrence of rough deposits and phenoclasts mixed with the transported material.

In practically all samples analyzed, evidence of mechanical edge abrasion was found, often superimposed on rounding by chemical solution or generating break planes that truncate the ends of the edges. The grains from the regolith sample – SBV21 – presented the lowest percentage of mechanical features occurrence among all samples. Generally, the ends of the grains in this sample do not exhibit well-marked edges, with no sign of mechanical wear. On the other hand, the morphological features are notably angular, possibly inherited from the primary structures of the parent rock. However, chemical weathering has left characteristic solution forms on grains' surfaces.

4. Final Considerations

Analysis of quartz and microcline grains in the 200-250µm fraction shows that their surfaces lack textures that solely attest to mechanical wear. The surface textures indicate a complex weathering history from the source rock, transport, reworking, and new superimposed weathering phases.

The surfaces of grains weathered in a non-uniform manner point to chemical weathering of the source rock, the syenite of the Serra da Baixa Verde massif. This fact is also supported by the weathering of other minerals in the sandy fraction, such as microcline, and the occurrence of in situ eluvial mantles with the formation of supergene minerals, especially montmorillonite, kaolinite, and Fe and Al oxide-hydroxides (Corrêa, 2001).

The close correspondence between the frequencies of the surface texture coincides with that indicated for transport by hyper-concentrated and laminar flows, pointing to a colluvial and alluvial component in the depositional history of the grains. The recurrence of abrasion features in the colluvial grains and the macro-fabric of the stratigraphic sections suggest a colluvial origin for the deposits, such as alluvial components in the lower sectors of the ramps, as in the case of sampling area 04 on a detrital pediment.

The history indicated by the surface textures also points to the presence of climatic controls (mechanical and weathering), in addition to the burial time, on the physiognomy of the grains, with a greater incidence of mechanical features in the grains from recent deposition and in the lower areas of the surroundings of the massif under semi-arid climates. Finally, this evaluation of the geomorphic characteristics recovered from the electron microscopy of the sand grains points to the prevalence of climatic conditions ranging from semi-arid to subhumid in the surroundings and summit of the massif, respectively, at least since the last glacial maximum, although under the influence of events of greater torrentiality capable of generating debris flows.

References

Bull, P. A., Goudie, A. S., Williams, D. P., Watson, A. Colluvium: A scanning electron microscope analysis of a neglected sediment type. In: Marshall, J. R. (ed.) *Clastic Particles: Scanning Electron Microscopy and Shape*. Analysis of Sedimentary and Volcanic Clasts". New York: Van Nostrand Reinhold. 1987. p. 16-35.

Corrêa, A. C. B. *Dinâmica geomorfológica dos compartimentos elevados do Planalto da Borborema, Nordeste do Brasil*. 2001. 386 f. Tese (Doutorado em Geografia) – Programa de Pós-Graduação em Geografia, Universidade Estadual Paulista, Rio Claro, SP, 2001.

Corrêa, A.C.B., Monteiro, K.A. Geomorphological dynamics of the elevated geosystems of the Borborema Highlands, Northeast of Brazil, from optically stimulated luminescence dating of hillslope sediments. *William Morris Davis - Revista de Geomorfologia*. 1(1): 162-185, 2020.

De Haas, N.S., De Lange, S.I., Pudasaini, S.P. Similarities and contrasts between the subaerial and subaqueous deposits of subaerially triggered debris flows: An analogue experimental study. *Journal of Sedimentary Research.* 90 (9): 1128–1138, 2020.

Culver, S. J., Bull, P. A., Campbell, S., Shakesby, R. A., Whalley, W. B. Environmental discrimination based on quartz grain surface textures: A statistical investigation. *Sedimentology*. 30: 129–136, 1983.

Goudie, A. S., Bull, P. A. Slope process change and colluvium deposition in Swaziland: An SEM analysis. *Earth Surface Processes and Landforms*. 9: 289–299, 1984.

Krinsley, D. H., Doornkamp, J. C. *Atlas of quartz sand surface textures*. Cambridge: Cambridge University Press, 2011.

Listo, D. G. S., Balder, R.F.T.M., Corrêa, A.C.B., Ramos, D.A.M.C., Calegari, M. R. Weathering pits as a geochronometer of environmental changes in the State of Pernambuco, Northeastern Brazil. *Quaternary International*. 649: 58-71, 2023.

Lowe, J.J., Walker, M.C.J. *Reconstructing Quaternary environments*. New York: John Wiley & Sons. 1984

Pelletier, J. D. How do pediments form? A numerical modeling investigation with comparison to pediments in southern Arizona, USA. *GSA Bulletin.* 122 (11-12): 1815–1829, 2010.

Trewin, N. H. Use of the scanning electron microscope in sedimentology. In: Tucker, M. *Techniques in Sedimentology*. London: Blackwell, 1995, p. 229 -273.