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Facies genesis and dominant hydrological process in Quaternary deposits of colluvial in the semi-arid of Alagoas – a microsedimentological approach

Gênese de fácies e processo hidrológico dominante em depósitos quaternários coluviais no semiárido de Alagoas: uma abordagem microsedimentológica

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Abstract: colluvial deposits from the distal, medial, and proximal sectors of colluvial hillslopes in the semi-arid region of Alagoas were studied, with a focus on sandy mud sediments. Although frequently classified in the field as massive, these sediments are hypothesized to correspond to successions of thin, laminated layers formed by overland flow. The aim of the study was to clarify the genesis of the facies and the dominant hydrological processes, particularly for sandy mud. Three representative stratigraphic profiles from each sector were analyzed through field descriptions and grain size analysis, complemented by microsedimentology for sandy mud sediments. The results indicate that all sectors display similar facies successions: laminated sandy mud, massive muddy gravel, and massive silty gravel, with the first predominating. Microsedimentology revealed that the apparent homogeneity observed in the field is superficial, exposing laminations formed by shallow high-density flows originating from overland flow. The galaxy microstructure proved to be a marker of internal turbulence within the flows. High-density overland flow was the predominant hydrological process over the last 15,000 years.

Keywords: Colluvium; Microstruture; Overland flow.

Resumo: Foram estudados colúvios dos setores distal, mediano e proximal de encostas coluviais no semiárido de Alagoas, com ênfase em sedimentos lama arenosa. Embora em campo seja frequentemente classificada como maciça, levantou-se a hipótese de que esses sedimentos correspondem a sucessões de camadas delgadas com fábrica laminada, formadas por escoamento superficial. O objetivo do estudo foi esclarecer a gênese das fácies e os processos hidrológicos dominantes, especialmente para a lama arenosa. Três perfis estratigráficos representativos de cada setor foram analisados por meio de descrições de campo e granulometria, complementado pela microsedimentologia para sedimentos lama arenosa. Os resultados indicam que todos os setores apresentam sucessões semelhantes de fácies: lama arenosa laminada, lama cascalhenta maciça e cascalho lamoso maciço, com predomínio da primeira. A microsedimentologia evidenciou que a aparente homogeneidade observada em campo é superficial, revelando laminações formadas por fluxos de alta-densidade-rasos originados do escoamento superficial. A microestrutura galáxia mostrou-se um marcador da turbulência interna dos fluxos. O escoamento superficial de alta-densidade foi o processo hidrológico predominante nos últimos 15.000 anos.

Palavras-chave: Colúvio; Microestrutura; Escoamento superficial.

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1. Introdution

Colluvial deposits are common on hillslopes developed over crystalline and crystallophyllian massifs, as well as along the escarpments of sedimentary plateaus in the semiarid environment of northeastern Brazil (CLAUDINO-SALES; FALCÃO SOBRINHO, 2024). (CLAUDINO-SALES; FALCÃO SOBRINHO, 2024). In this region, previous studies have identified sandy mud sediments interbedded with both matrix-supported and clast-supported conglomerates, all displaying massive fabric (CORRÊA, 2001; CORRÊA; LIRA; TAVARES 2020; LIMA et al., 2017; FONSÊCA; GOIS et al., 2021; LIMA et al., 2023). In contrast, laminated sandy mud has rarely been reported, probably due to the difficulty of identifying this fabric directly in the field.

On the other hand, optically stimulated luminescence (OSL) ages obtained from the base and top of massive sandy mud facies reveal age differences that may reach several tens of thousands of years. This suggests that the textural homogeneity and massive fabric of colluvial deposits may be only apparent, given the inherent limitations of direct field observation. Thus, these deposits may actually consist of successions of thin laminated beds. Such an interpretation challenges the traditional view that associates the massive fabric observed in the field with mass-movement events, raising questions about the dominant hydrological process responsible for their formation.

Based on this premise, we hypothesized that these deposits may, in fact, correspond to successions of thin layers with laminated fabric generated by overland-flow processes. To test this hypothesis, colluvial deposits from the distal, middle, and proximal sectors of colluvial hillslopes in the semiarid region of Alagoas were investigated, primarily through the description of thin sections from a sedimentological perspective, herein referred to as microsedimentology (analysis using a petrographic microscope) (MENZES; VAN DER MEER, 2018; PAISANI; MANICA, 2025). This approach also allowed the dynamic behavior of the depositional agents to be interpreted. In summary, the aim of this study was to investigate facies genesis and the hydrological processes responsible for Quaternary colluvial-hillslope deposits in the semiarid region of Alagoas, with particular emphasis on sandy mud layers.

2. Methods

2.1 Geographic setting of the study area

The study area is located in the western portion of the state of Alagoas, northeastern Brazil (Figure 1), where the Água Branca and Mata Grande massifs are situated. These massifs are geomorphological features that stand out within the semiarid landscape due to their topographic amplitude, which favors relatively mild temperatures (mean of 22 °C) and higher annual rainfall (>800 mm) compared to the surrounding areas (approximately 550 mm). The convex summits of these massifs act as source areas for sediments delivered to the colluvial hillslopes. The massifs are surrounded by pediments, both developed predominantly on crystalline and crystallophyllian rocks of the Borborema Province (CPRM, 2021), covered by Caatinga vegetation and dissected mainly by an intermittent drainage network.

2.2 Procedures

Outcrops of colluvial deposits containing sandy mud-bearing sedimentary successions on colluvial hillslopes were previously identified during macrogeomorphological mapping of the Água Branca and Mata Grande massifs in the semiarid region of Alagoas (SILVA et al., no prelo). Among the surveyed outcrops, three were selected based on their potential for detailed stratigraphic-profile description: Baixa do Galo (distal sector), Preguiçoso (middle sector), and Batuque (proximal sector), named after the local communities where they occur (Figure 1). The Preguiçoso outcrop was initially described by Silva, Corrêa; Lima (2021) and is reanalyzed here using a microsedimentological approach.

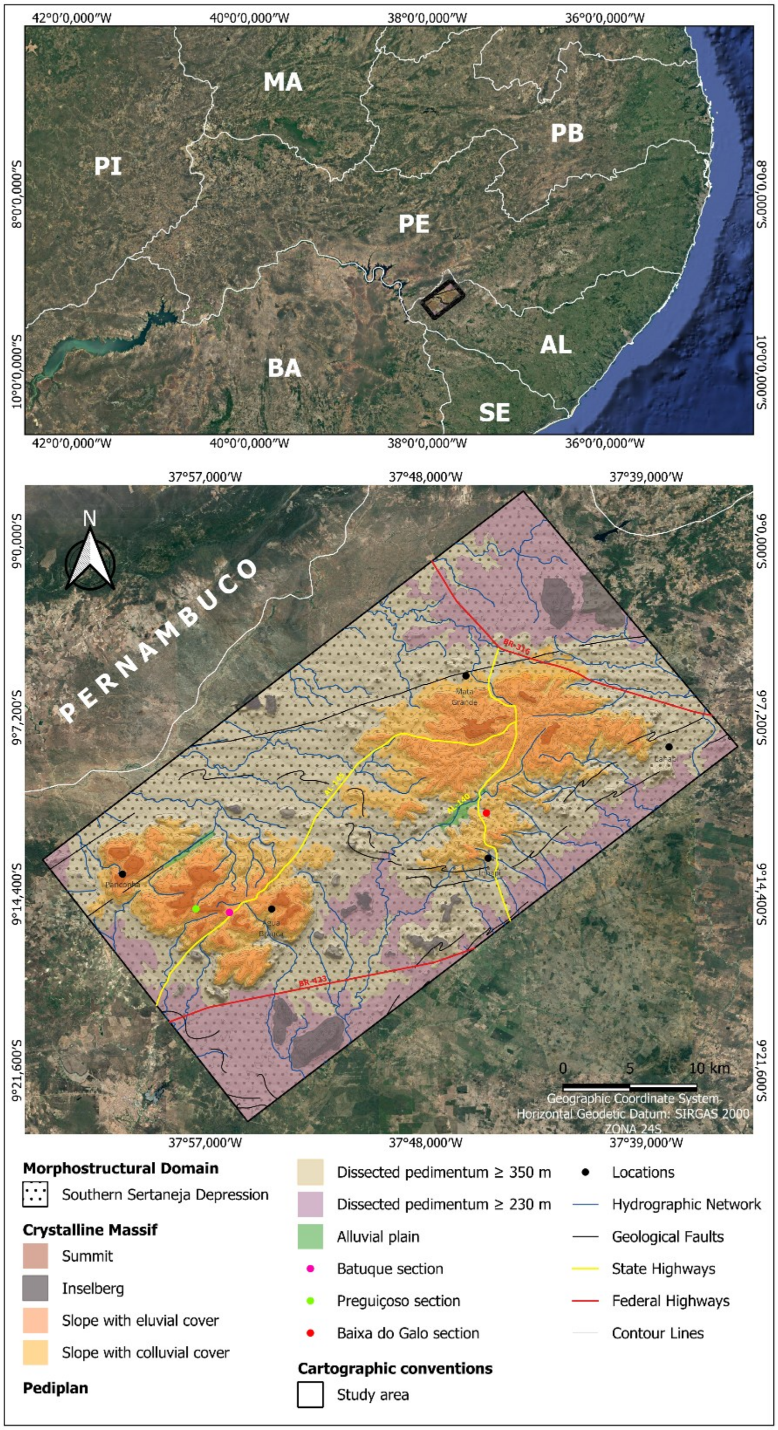

Figure 1 – Location of the colluvial deposits from the Distal (Baixa do Galo), Middle (Preguiçoso), and Proximal (Batuque) hillslope sectors in relation to the geomorphological units of the Água Branca and Mata Grande massifs, semiarid region of Alagoas State, northeastern Brazil.
Source: Silva (2025).

Bed differentiation was based on lithological criteria, supported by field descriptions (thickness, upper boundary, texture, color, and fabric/internal organization), grain-size trends (grain-size diagrams), and microsedimentological analysis. For sandy mud beds, the fabric observed in the field was verified through microsedimentological analysis, while grain-size trends were used to refine bed boundaries and identify discontinuities within sandy mud lithologies. These trends were established from the grain-size proportions of the matrix (clay, sand, granule, and pebble fractions according to the Wentworth scale; WENTWORTH, 1922). The grain-size diagrams were constructed from a total of 83 samples collected at 10 cm depth intervals and analyzed in the laboratory using pipette and sieve methods following wet separation. The integration of these descriptive criteria enabled the identification of facies, whose codes were simplified according to lithology and sedimentary structure, adapting the criteria and nomenclature proposed by Ghibaudo (1992) for subaqueous sediment-gravity-flow deposits. In addition, a total of seven OSL ages obtained by Silva; Côrrea; Lima (2021) and Silva (2025) were compiled in order to establish the temporal framework of the stratigraphic successions.

The fabric of the sandy mud beds was analyzed through a microsedimentological approach applied to a total of 22 thin sections. Regarding the descriptions, it should be noted that there is currently no universally accepted nomenclature or specific descriptive criteria for the microsedimentological analysis of hillslope deposits (Paisani; Manica, 2025). Therefore, the microsedimentological descriptions presented here were based on the identification of lamination and their external organization (upper boundary following CAMPBELL, 1967) and internal organization (matrix type, composition of the fine and coarse fractions, and microstructure of both fractions), as well as syn- and post-depositional modifications (pores, water-induced pedofeatures, and degree of pedality).

To compare the occurrence of coarse-fraction microstructures and to identify the microsedimentological signature of the hydrological sedimentation process, a morphometric analysis of the coarse-fraction microstructures was carried out. The occurrence of coarse-fraction microstructures was quantified using the Microstructure Concentration Index (Mci) proposed by Paisani and Manica (2025). The %Mi parameter was estimated by visual inspection of thin-section images using the comparison chart of FitzPatrick (1980), whereas the Ai and Ats parameters were calculated from digital images using the Macro Curve Meter tool in CorelDRAW 2020. For each occurrence of a galaxy-type microstructure (Appendix 1), the following parameters were obtained: mean diameter ($d_{galaxy\text{-}mean}$), maximum diameter ($d_{galaxy\text{-}maximum}$), as well as the ranges of the Microstructure Concentration Index ($\Delta_{galaxy\text{-}Mci}$), mean diameter ($\Delta d_{galaxy\text{-}mean}$), and maximum diameter ($\Delta d_{galaxy\text{-}maximum}$). The $d_{galaxy\text{-}mean}$ and $d_{galaxy\text{-}maximum}$ parameters were derived from area measurements. Finally, the morphometric indices and parameters (Mci, $d_{galaxy\text{-}mean}$, $d_{galaxy\text{-}maximum}$, $\Delta_{galaxy\text{-}Mci}$, $\Delta d_{médio\text{-}galáxia}$ e $\Delta d_{galaxy\text{-}mean}$) were compared through statistical correlation analysis using the t-test.

3. Results

3.1 Stratigraphy

The analyzed stratigraphic profiles range from 200 cm (Proximal Sector) to 390 cm (Distal Sector) in thickness and comprise sandy mud, gravelly mud, and muddy gravel lithologies (Figures 2a, 3a, and 4a). All lithologies exhibit a massive fabric in field observations; however, microsedimentological analysis revealed that the sandy mud is laminated, displaying horizontal lamination (Section 3.2). The deposits are characterized by an oxidic matrix whose color value and chroma vary according to the contents of hematite, goethite, and organic matter (5YR 3/3, 4/2, 5/2, 5/8, 6/2, 6/4; 7.5YR 4/3, 4/6, 5/8, 6/8) (Figure 5).

The number of beds is remarkably similar among the stratigraphic profiles, with 12 beds in the Distal Sector and 11 beds in both the Middle and Proximal sectors. Bed thicknesses range from 10 to 50 cm (Figures 2a, 3a, and 4a). Of these, 7 to 10 correspond to sandy mud beds, whereas 1 to 2 are gravelly mud and muddy gravel beds in each stratigraphic profile, with thicknesses also ranging from 10 to 50 cm. Gradational upper boundaries dominate the stacking pattern of sandy mud beds in the Distal and Proximal sectors, whereas erosional boundaries prevail in the Middle Sector. Regarding chronology, OSL ages obtained from the three outcrops range from 560 ± 40 to 15,070 ± 1,100 yr BP (Figures 2a, 3a, and 4a).

The beds recognized in the analyzed hillslope sectors were grouped into three facies: laminated sandy mud (horizontal lamination; SMd), massive gravelly mud (GMm), and massive muddy gravel (MGm) (Figure 5). In the Middle Sector, a succession of SMd and MGm facies is observed during the period between >10,200 and >3,400 yr BP (Beds I–VI), followed by a succession of GMm and SMd facies from 3,400 yr BP to the present (Beds VII–XI) (Figures 2a, 3a, and 4a). In the Proximal Sector, similar trends are observed, although with fewer facies intercalations. The first succession spans the period between >15,070 and >3,525 yr BP (Beds I–VI), whereas the second extends from 3,525 yr BP to the present (Beds VII–XI). In the Distal Sector, the facies succession is restricted to a single occurrence of GMm and SMd facies from

5,000 yr BP to the present. Regarding the proportional thickness of the facies relative to the total deposit thickness, SMd is the dominant facies in all analyzed sectors (Figure 6).

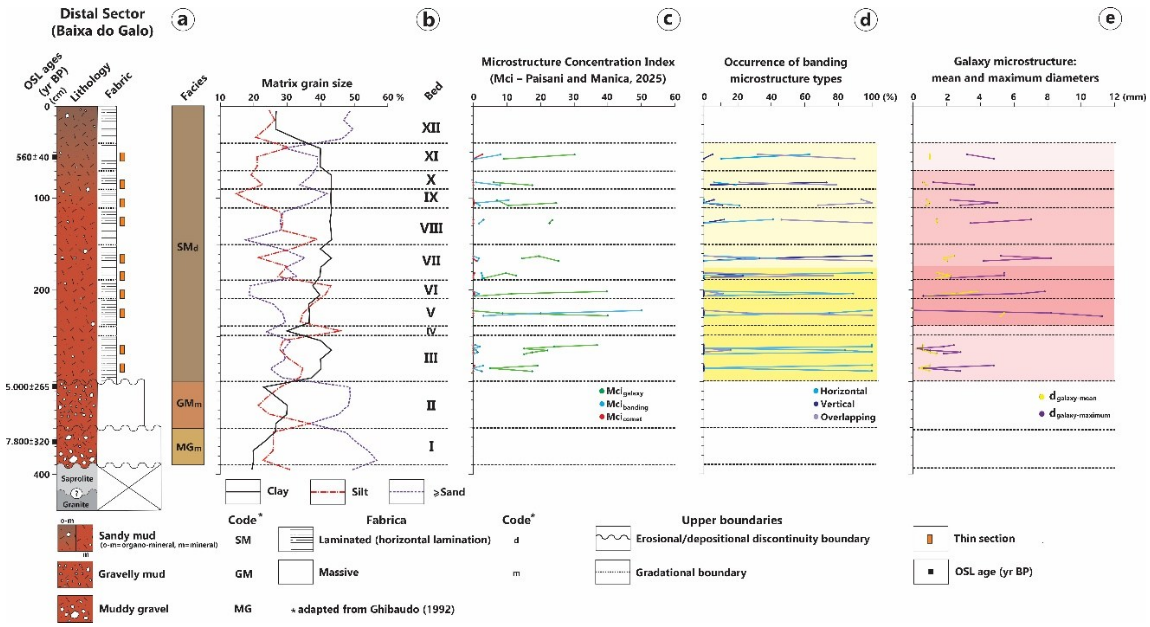

Figure 2 – Baixa do Galo columnar section showing OSL ages, lithology, fabric, sedimentary facies, and the location of thin sections and micromorphometric parameters.
Source: Silva (2025).

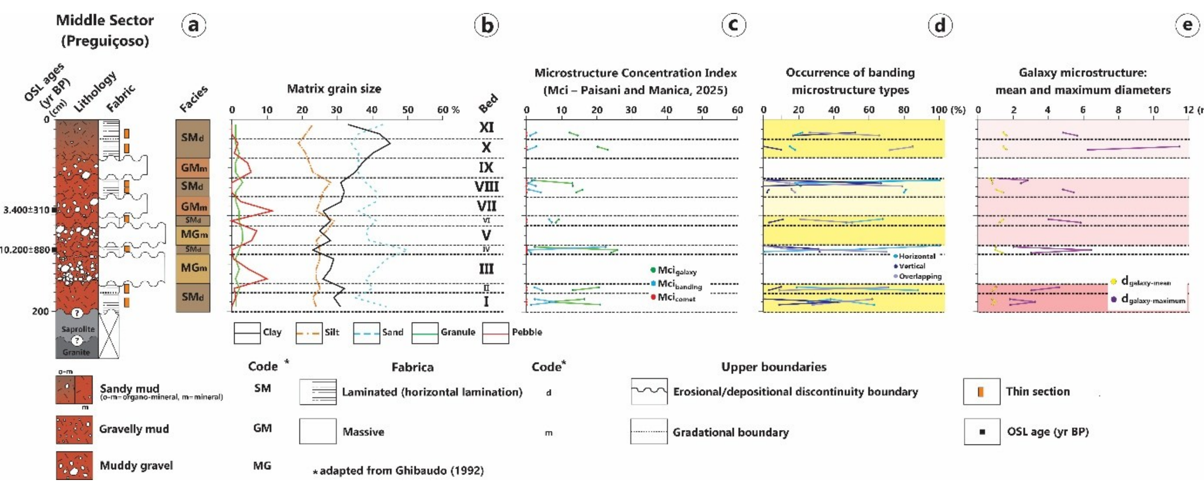

Figure 3 – Preguiçoso columnar section showing OSL ages, lithology, fabric, sedimentary facies, and the location of thin sections and micromorphometric parameters.
Source: Silva (2025) and OSL ages obtained by Silva et al (2021).

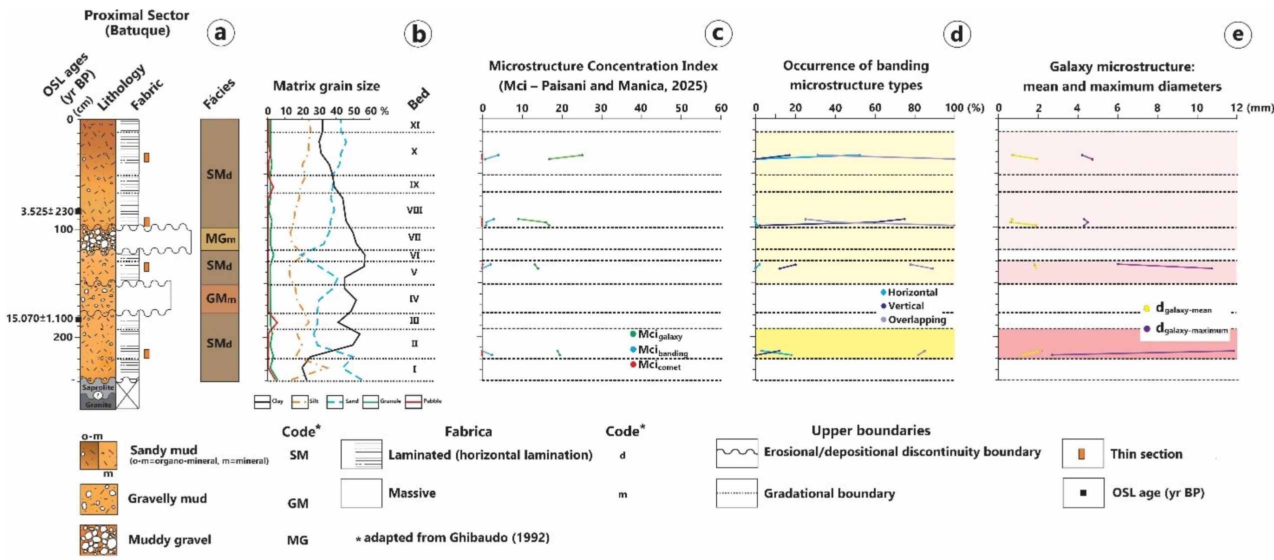

Figure 4 – Batuque columnar section showing OSL ages, lithology, fabric, sedimentary facies, and the location of thin sections and micromorphometric parameters.
Source: Silva (2025).

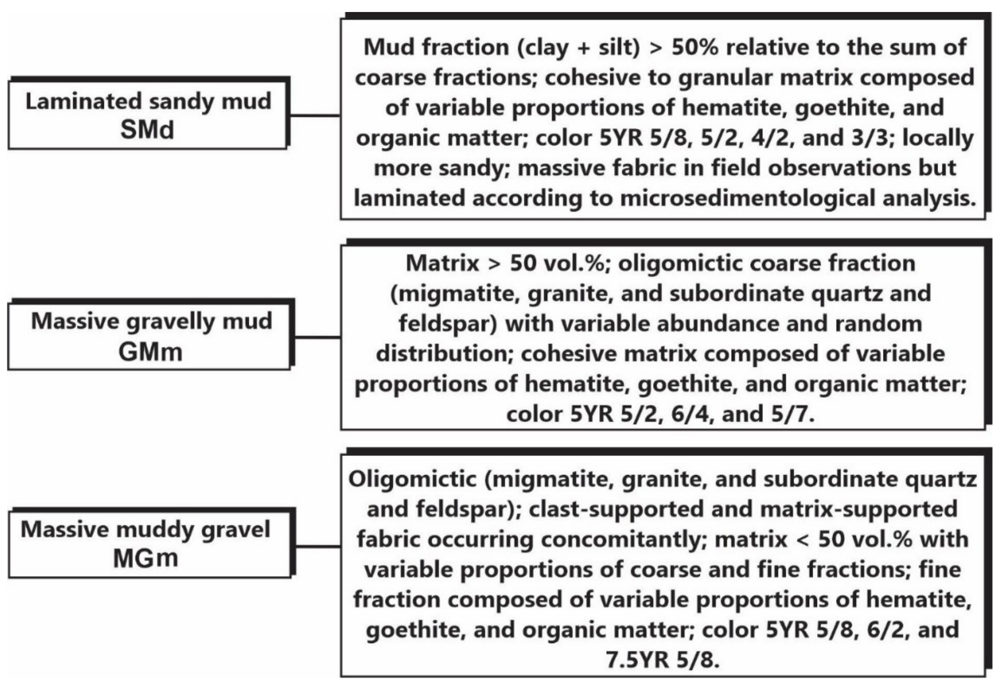

Figure 5 – Facies descriptions.
Source: Authors (2025).

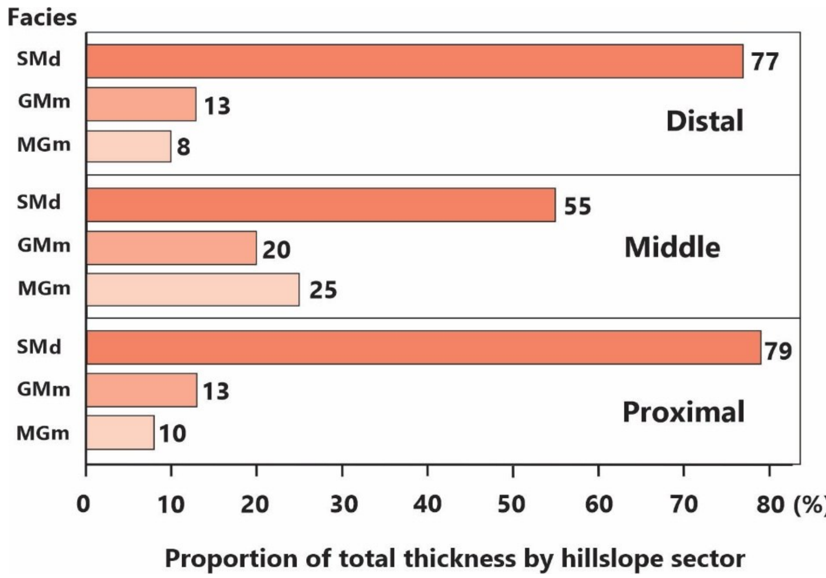

Figure 6 – Proportional contribution of each facies to the total deposit thickness in the Distal, Middle, and Proximal sectors.
Source: Silva (2025).

3.2 Microsedimentology

3.2.1 Qualitative description

The sandy mud facies identified in the Distal, Middle, and Proximal sectors exhibits similar properties, although with heterogeneous occurrence. The main similarity lies in its laminated fabric (horizontal lamination), with laminae averaging 13 mm in thickness (Figure 7). Upper boundaries are predominantly wavy-parallel-continuous in the Distal Sector and wavy-nonparallel-continuous in the Proximal and Middle sectors, respectively. The matrix is predominantly dense > granular and locally granular > dense, consisting of a mixture of primary minerals and papule-, nodule-, and soil aggregate-type pedosediments (PAISANI et al., 2023a) (Appendix 1). The laminae can be differentiated by the distribution of coarse-fraction microstructures, including galaxy-type (primary minerals > pedosediments), banding (horizontal, vertical, and imbricated), comet, grain stacking, and random microstructures (PAISANI et al., 2023a) (Appendix 1). Random microstructures are common, comet microstructures are rare, grain stacking occurs locally, and galaxy microstructures are dominant (Figure 7). The fine-fraction microstructure (Appendix 1) is homogeneous and composed of speckled and undifferentiated distributions, with locally porostriated and granostriated patterns. Post-depositional pedofeatures are weakly developed and include pore types (cracks, cavities, and biogenic channels) and water-induced features (depletion or impregnation of iron oxyhydroxides in the matrix, pores, and coarse-fraction grains). In areas where the matrix is granular, intergranular porosity is dominant, as expected.

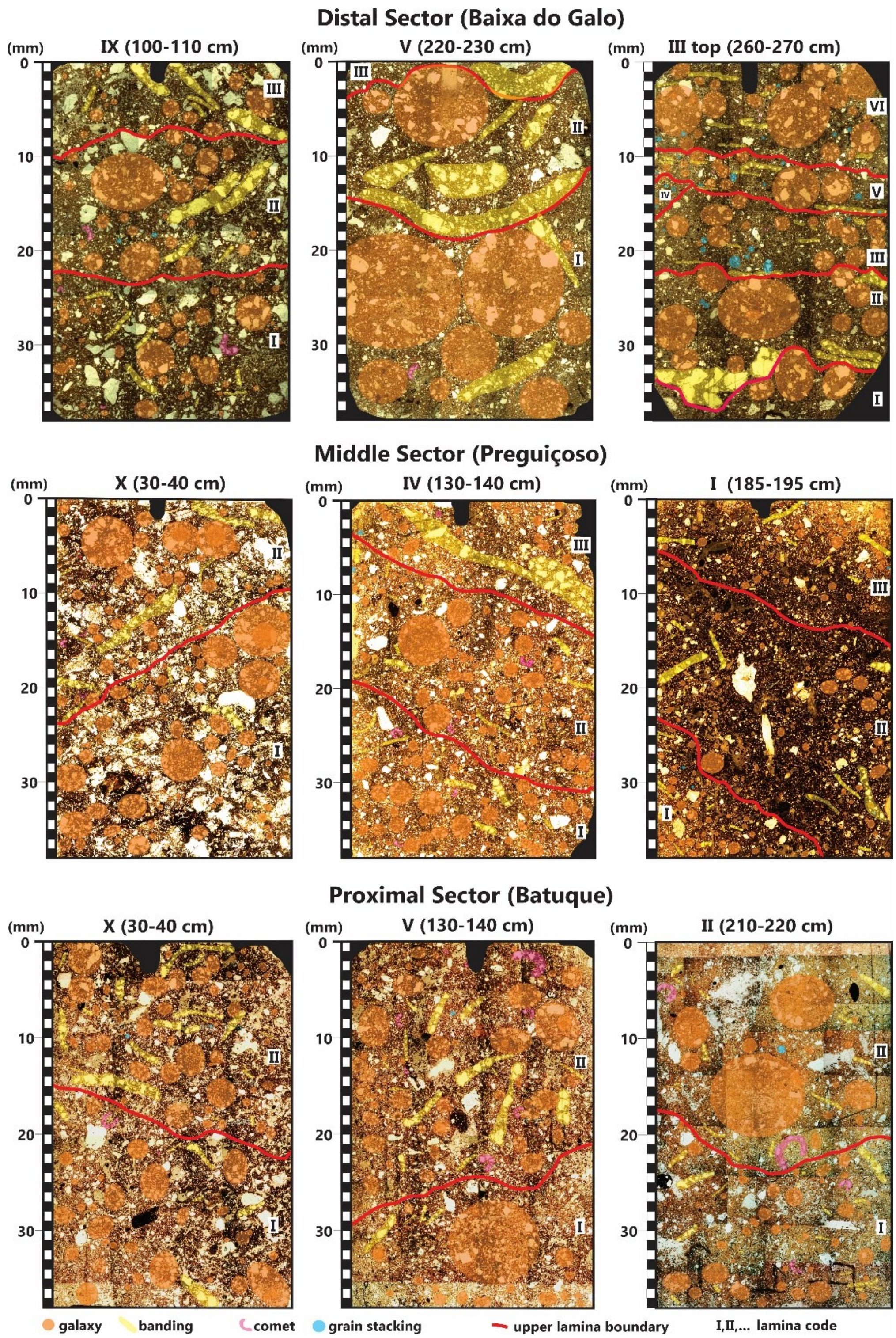

Figure 7 – Microestruture of the SMd facies.
Source: Silva (2025).

3.2.2 Quantitative description

3.2.2.1 Mci, $d_{galaxy\text{-}mean}$, and $d_{galaxy\text{-}maximum}$

The quantification of sedimentological microstructures associated with the coarse fraction is an important key for interpreting the sedimentation processes of colluvial deposits. The Microstructure Concentration Index (Mci), proposed by Paisani and Manica (2025), was applied to assess the degree of occurrence of the sedimentary microstructures that are most recurrent in the stratigraphic record and have the greatest process-related significance. In this context, galaxy microstructures (Mci_{galaxy}), banding microstructures ($Mci_{banding}$) and comet microstructures (Mci_{comet}) are particularly noteworthy. Their values range from 0.1 to 50 in the Distal Sector, with lower ranges in the Middle and Proximal sectors (0.1–26). The highest relative values correspond to Mci_{galaxy} in all three stratigraphic profiles, except for Bed V in the Distal Sector, where $Mci_{banding}$ predominates (Figures 2c, 3c, and 4c).

Horizontal banding predominates in Beds III–VII of the Distal Sector and Beds I–VIII of the Middle Sector. In the remaining beds, imbricated banding is more common and is the dominant banding type in the Proximal Sector (Figures 2d, 3d, and 4d). The mean diameter of galaxy microstructures ($d_{galaxy\text{-}mean}$) ranges from 0.2 to 5.4 mm, 0.6 to 1.6 mm, and 0.6 to 2.1 mm in the Distal, Middle, and Proximal sectors, respectively (Figures 2e, 3e, and 4e). The maximum diameter ($d_{galaxy\text{-}maximum}$) ranges from 0 to 11.2 mm, 1.4 to 11.2 mm, and 2.7 to 11.8 mm in the respective sectors. In general, galaxy microstructures exhibit internal variation in $d_{galaxy\text{-}maximum}$ within individual beds, while displaying distinct trends of increasing maximum diameter with depth across the three analyzed stratigraphic profiles.

3.2.2.2 Statistical correlations among Mci_{galaxy}, $d_{galaxy\text{-}mean}$, and $d_{galaxy\text{-}maximum}$

The statistical correlation among the microsedimentological indices Mci_{galaxy}, $d_{galaxy\text{-}mean}$, and $d_{galaxy\text{-}maximum}$ for the beds of the Distal, Middle, and Proximal sector stratigraphic profiles is important for evaluating the degree of dependency among these variables and the relative influence of sedimentation processes along the different hillslope sectors. Comparison between Mci_{galaxy} and $Mci_{banding}$ for all thin sections from the three stratigraphic profiles reveals no statistical correlation ($R^2 = 0.04$, $r = -0.19$, p-value < 0.001) (Figure 8a). In contrast, the amplitude of Mci_{galaxy} (ΔMci_{galaxy} = difference between maximum and minimum Mci_{galaxy} values) shows a progressive increase from the Proximal Sector (Batuque) to the Distal Sector (Baixa do Galo) (ΔMci_{galaxy}-Proximal = 16, ΔMci_{galaxy}-Middle = 24, and ΔMci_{galaxy}-Distal = 40). The amplitude of dgalaxy-maximum follows the same increasing trend from the Proximal Sector (Batuque) to the Distal Sector (Baixa do Galo) ($\Delta d_{galaxy\text{-}maximum}$-Proximal = 9.1, $\Delta d_{galaxy\text{-}maximum}$-Middle = 9.8, and $\Delta d_{galaxy\text{-}maximum}$-Distal = 11). Comparison between these parameters reveals a strong statistical correlation ($R^2 = 0.99$, $r = 0.99$, p-value > 0.05) (Figure 8e). Only the amplitude of $d_{galaxy\text{-}mean}$ does not follow this progressive trend, being lowest in the Middle Sector beds ($\Delta d_{galaxy\text{-}mean}$-Middle = 1, $\Delta d_{galaxy\text{-}mean}$-Proximal = 1.5, and $\Delta d_{galaxy\text{-}mean}$-Distal = 5.2). Nevertheless, the highest value is recorded in the Distal Sector (Baixa do Galo), and a significant statistical correlation is observed when comparing ΔMci_{galaxy} and $\Delta d_{galaxy\text{-}mean}$ (Figure 8f). Overall, beds from the Distal Sector (Baixa do Galo) exhibit the highest values of ΔMci_{galaxy}, $\Delta d_{galaxy\text{-}maximum}$, and $\Delta d_{galaxy\text{-}mean}$. Finally, a significant positive correlation exists between $d_{galaxy\text{-}maximum}$ and $d_{galaxy\text{-}mean}$ for galaxy microstructures considering all beds from the three sectors ($R^2 = 0.60$, $r = 0.76$, p-value < 0.001) (Figure 8b). In contrast, comparisons between Mci_{galaxy} and $d_{galaxy\text{-}maximum}$, as well as between Mci_{galaxy} and $d_{galaxy\text{-}mean}$, reveal no significant correlation, either between Mci_{galaxy} and $d_{galaxy\text{-}mean}$ ($R^2 = 0.22$, $r = 0.47$, p-value > 0.05) or between Mci_{galaxy} and $d_{galaxy\text{-}maximum}$ ($R^2 = 0.19$, $r = 0.44$, p-value < 0.01) (Figures 8c and 8d).

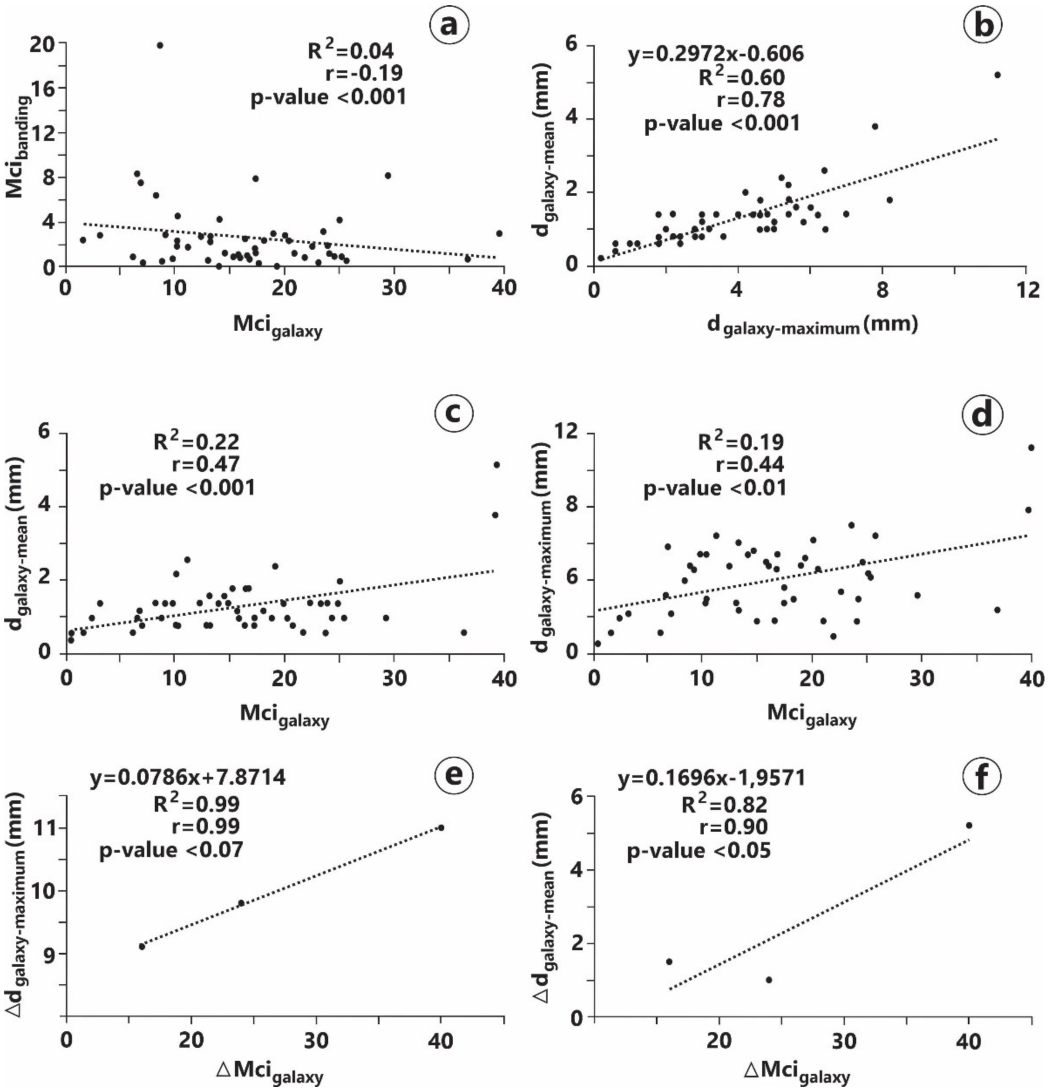

Figure 8 – Statistical correlations between Mci_{galaxy} and $Mci_{banding}$ (a), $d_{galaxy-maximum}$ and $d_{galaxy-mean}$ (b), Mci_{galaxy} and $d_{galaxy-mean}$ (c), Mci_{galaxy} and $d_{galaxy-maximum}$ (d), ΔMci_{galaxy} and $\Delta d_{galaxy-maximum}$ (e), and ΔMci_{galaxy} and $\Delta d_{galaxy-mean}$ (f).
Source: Silva (2025).

4. Discussion

4.1 Facies genesis

4.1.1 Laminated sandy mud

The sandy mud facies consists of beds displaying horizontal lamination and an average thickness of 20 cm, whose internal organization was identified through microsedimentological analysis. The textural homogeneity and massive fabric observed in the field are therefore only apparent, reflecting the inherent limitations of field-scale observations. Laminated sandy mud predominates in the stratigraphic records of all three hillslope sectors, occurring in 7 to 10 beds and reaching its highest recurrence in the Distal Sector (Baixa do Galo) (Figs. 2–4). Microsedimentological analysis of the laminae revealed similar properties, although with heterogeneous occurrence. These similarities include the average lamina thickness (13 mm), the predominance of wavy-parallel-continuous upper boundaries in the Distal Sector and wavy-nonparallel-continuous upper boundaries in the Proximal and Middle sectors, the dominance of dense > granular matrix, locally granular > dense, and the mixture of primary minerals and pedosediments. Particularly noteworthy is the dominance of galaxy microstructures (primary minerals > pedosediments) within the coarse fraction, followed by horizontal > imbricated > vertical banding, whereas comet microstructures are rare. These properties are accompanied by the homogeneity of the fine-fraction microstructure, composed of speckled and undifferentiated distributions and, locally, porostriated and granostriated patterns, as well as weak post-depositional transformation indicated by the absence of pedality.

The sedimentation process responsible for this facies was similar across the Proximal (Batuque), Middle (Preguiçoso), and Distal (Baixa do Galo) sectors of the colluvial hillslopes. It was characterized by high-density flows that were predominantly cohesive (dense matrix) and occasionally non-cohesive (granular matrix), with thicknesses compatible with the formation of individual laminae (PAISANI et al., 2023a). Assuming that the average thickness of the original flows can be inferred from the mean thickness of the laminae (13 mm), flow depths are estimated to have reached approximately 90.8 ± 26 mm (Appendix 2), indicating the occurrence of shallow high-density flows (PAISANI et al., 2023a,b).Based on these observations, the shallow high-density flows responsible for the laminated sandy mud facies originated from overland flow (hydrological process) carrying high sediment concentrations from the source area. This interpretation is supported by the fact that the Proximal Sector (Batuque) already exhibits microsedimentological characteristics similar to those observed in the other sectors, although differences in microstructure concentration are evident.

Galaxy and banding microstructures (horizontal, vertical, and imbricated), particularly galaxy microstructures, constitute essential properties for understanding the dynamics of shallow high-density flows generated by overland flow. Galaxy microstructures are predominant, whereas banding is less frequent and comet microstructures are rare, as indicated by the Microstructure Concentration Index (Mci). Although galaxy, comet, and banding microstructures may occur concomitantly, only galaxy and comet microstructures presumably share similar formation mechanisms. Comet microstructures exhibit a circular morphology analogous to that of galaxy microstructures, but with incomplete arching of sand grains, reflecting the limited availability of coarse particles required to complete the circular morphology. Thus, it is assumed that galaxy and comet microstructures are generated by the same mechanism, namely turbulence (PAISANI et al., 2023a,b), whereas banding results from an independent mechanism. This independence is corroborated by the absence of a statistical correlation between Mci_{galaxy} and $Mci_{banding}$, indicating that these sedimentary microstructures originate from distinct formation mechanisms.

The occurrence of galaxy microstructures indicates significant internal deformation within shallow high-density flows, controlled by turbulence, a mechanism already recognized in clayey-sandy and sandy-clayey sediment-laden flows (SUMNER; TALLING; AMY, 2009). Turbulence has also been identified as the process governing the formation of galaxy microstructures in transitional to high-density flows with both dense and granular matrices (PAISANI et al., 2023a,b). In cohesive flows, turbulence acts by disrupting the continuous structural framework formed by the aggregation of colloidal particles, thereby reducing the yield strength and viscosity of the flow (SUMNER; TALLING; AMY, 2009). Accordingly, galaxy microstructures constitute a key indicator of turbulence-driven deformation in shallow high-density flows.

Different degrees of turbulence among laminae within stratigraphic beds can be inferred from the relative values of the maximum diameter of galaxy microstructures ($d_{galaxy\text{-}maximum}$). Similarly, variations in turbulence among laminae can be assessed by comparing the amplitude of galaxy microstructure occurrence (ΔMci_{galaxy}) with the amplitudes of their maximum and mean diameters ($\Delta d_{galaxy\text{-}maximum}$ and $\Delta d_{galaxy\text{-}mean}$). Values of $d_{galaxy\text{-}maximum}$ vary with depth, indicating cyclic trends of increasing ($> d_{galaxy\text{-}maximum}$) or decreasing ($< d_{galaxy\text{-}maximum}$) turbulence, as suggested by the trend shifts observed in the Distal Sector (Baixa do Galo). When comparing the amplitude of galaxy microstructure occurrence (ΔMci_{galaxy}) among laminae from different hillslope sectors, turbulence increases from the Proximal Sector ($< \Delta Mci_{galaxy}$) to the Distal Sector ($> \Delta Mci_{galaxy}$), as expected. This trend is reinforced by the positive correlations between ΔMci_{galaxy}–$\Delta d_{galaxy\text{-}maximum}$ and ΔMci_{galaxy}–$\Delta d_{galaxy\text{-}mean}$, both of which increase progressively from the Proximal Sector (Batuque) to the Distal Sector (Baixa do Galo). Thus, the morphometric properties of galaxy microstructures function as a sedimentological signature of both the degree of turbulence in shallow high-density flows and the hillslope sector in which the colluvial deposit was formed. Additionally, $d_{galaxy\text{-}mean}$ can be estimated from $d_{galaxy\text{-}maximum}$ due to the highly significant positive correlation between these parameters. In contrast, the diameters of galaxy microstructures appear to be independent of the degree of occurrence of these features, as indicated by the absence of statistical correlations between Mci_{galaxy} and $d_{galaxy\text{-}maximum}$ and between Mci_{galaxy} and $d_{galaxy\text{-}mean}$.

Banding microstructures, although less frequent, occur in horizontal, imbricated, and vertical arrangements and are commonly associated with galaxy and comet microstructures. The mechanisms responsible for the formation of these banding structures in shallow high-density flows (whether characterized by dense or granular matrices) remain unclear.

4.1.2 Massive gravelly mud and massive muddy gravel

The thickness of the massive gravelly mud facies ranges from 20 to 50 cm, with an average of 28 cm, whereas the massive muddy gravel facies ranges from 20 to 30 cm in thickness, with an average of 23 cm. The latter generally exhibits a random distribution of pebbles and has commonly been described in Quaternary geomorphological studies from the semiarid region of northeastern Brazil as a gravel bed, regionally known as *cascalheira* (CORRÊA, 2001; FONSECA et al., 2020; LIMA et al., 2023). An exception is Bed V of the Middle Sector (Fig. 3), where the massive muddy gravel facies displays a typical stone-line arrangement. At first glance, this gravel-rich horizon could be interpreted as a paleostone pavement, as proposed in the classical literature (BIGARELLA et al., 1965). However, the upward increase in pebble concentration, expressed by inverse grading in the grain-size diagram, is indicative of a cohesive high-density flow, commonly referred to as a cohesive debris flow (LOWE, 1979). Inverse grading is expected in weakly diluted cohesive debris flows, in which larger gravel clasts may be transported upward within the matrix by flotation associated with matrix-strength forces (POSTMA; NEMEC; KLEINSPEHN, 1988). Overall, the massive gravelly mud facies is interpreted here as the product of cohesive debris flows (cohesive high-density flows), although under more diluted conditions, allowing pebbles to assume a random distribution within the matrix.

The genesis of the massive muddy gravel facies remains uncertain. It may have originated from non-cohesive debris flows, in which grain support is controlled primarily by dispersive pressure mechanisms (MIDDLETON; HAMPTON, 1973), or from the reworking of pre-existing cohesive debris-flow deposits (PAISANI et al., 2023a). In the latter case, the removal of matrix material from a pre-existing cohesive debris-flow deposit by overland flow promotes the resedimentation of pebbles, resulting in a relative enrichment of the deposit in coarse particles (NEMEC; KAZANCI, 1999).

In summary, the massive gravelly mud facies is interpreted as the product of cohesive debris flows (cohesive high-density flows), whereas the massive muddy gravel facies may have been generated either by non-cohesive debris flows (non-cohesive high-density flows) or by the reworking of pre-existing cohesive debris-flow deposits.

4.2 Dominant hydrological process in sediment accumulation on colluvial hillslopes

The depositional dynamics observed in the Distal (Baixa do Galo), Middle (Preguiçoso), and Proximal (Batuque) sectors reveal a remarkable similarity in facies assemblages, consisting of laminated sandy mud (horizontal lamination), massive gravelly mud, and massive muddy gravel. Among these, laminated sandy mud is particularly prominent, exhibiting the greatest proportional thicknesses and the highest number of beds in all analyzed stratigraphic profiles. In contrast, massive gravelly mud and massive muddy gravel are thinner and less frequent, indicating a secondary role in colluvial deposition.

By contrast, debris flows (cohesive and/or non-cohesive) are typically associated with high-magnitude hydrological events and occur with lower relative frequency than overland flow (THOMAS, 1994), yet they did not produce thick deposits on the hillslopes of the study area. On the studied hillslopes, overland flow exhibiting the dynamic behavior of high-density flows recurred throughout the last 15,000 yr BP and accumulated approximately 300 cm of sediment in the Distal Sector, demonstrating a high relative capacity for sediment transport and deposition.

The preservation of the laminated sandy mud facies appears to depend not only on favorable accommodation conditions but also on the dynamic behavior of overland flow carrying high sediment concentrations (high-density flow). This finding contrasts with the traditional interpretation of overland flow as a low-density fluid flow (low sediment concentration), commonly regarded as having a limited contribution to hillslope sedimentation (PAISANI et al., 2023a,b). Based on the evidence presented, it is clear that, regardless of the colluvial-hillslope sector, overland flow exhibiting the dynamic behavior of high-density flows was the dominant hydrological process responsible for the formation of colluvial deposits in the study area throughout the last 15,000 yr BP.

5. Conclusions

The colluvial deposits from the Proximal, Middle, and Distal sectors of the hillslopes developed on the studied crystalline massifs exhibit similar facies successions, consisting of laminated sandy mud (horizontal lamination), massive gravelly mud, and massive muddy gravel. Despite this similarity, differences in thickness and recurrence indicate that laminated sandy mud is the dominant facies in all sectors, whereas massive gravelly mud and massive muddy gravel play a secondary role in colluvial sedimentation.

Microsedimentological analysis of the sandy mud sediments was crucial in demonstrating that the homogeneous appearance observed in the field is, in fact, only apparent, as previously inferred. Furthermore, this analysis revealed that: (a) the laminae were produced by shallow high-density flows generated by overland flow carrying high sediment concentrations from the source area, ruling out the progressive transformation of mass movements into mud flows commonly expected in hillslope environments; and (b) galaxy microstructures constitute a useful sedimentological marker for identifying both the internal turbulence of the flows and the position of the deposit along the hillslope, particularly in dissected landscapes or in areas characterized by reworked ramp morphology.

Regardless of hillslope sector, overland flow exhibiting the dynamic behavior of high-density flows was the dominant hydrological process responsible for the formation of colluvial deposits in the study area throughout the last 15,000 yr BP. Microsedimentology, as a scale extension of conventional sedimentology, proved to be a highly effective tool for identifying the flows responsible for the formation of end-member deposits on colluvial hillslopes and for elucidating the mechanisms associated with their depositional dynamics.

Appendix 1 – Microsedimentological Glossary

Dense matrix: results from the complete disintegration of the original pedological structure due to liquefaction of the pedological micromass (PAISANI et al., 2023a).

Granular matrix: composed of a coarse fraction dominated by soil-aggregate pedosediments (PAISANI et al., 2023a).

Pedosediments: relict soil features that retain relative structural stability and were not completely disintegrated during liquefaction of the pedological micromass (PAISANI et al., 2023a).

Galaxy microstructure: also referred to as turbate, rotate, rotation, or microcircle; defined as a circular or elliptical arrangement of the coarse fraction (minerals or pedosediments), with or without a core stone (PAISANI et al., 2023a,b; PAISANI; MANICA, 2025).

Comet microstructure: arcuate arrangement of the coarse fraction (PAISANI et al., 2023a).

Banding microstructure: alignment of coarse-fraction grains within a muddy matrix, where the coarse fraction occurs in modest proportions relative to the matrix.

Grain-stacking microstructure: arrangement in which the coarse fraction occurs in modest proportions relative to the muddy matrix and grains display point, concavo-convex, and/or longitudinal contacts.

Random microstructure: absence of preferential alignment among coarse-fraction grains.

Fine-fraction microstructure: preferential orientation of the fine fraction expressed by birefringence patterns of the b-fabric.

Appendix 2 – Estimation of the Mean Flow Depth of the High-Density Flows Responsible for the Formation of the Laminated Sandy Mud Facies

Premises

a) Laminae with wavy-parallel-continuous and wavy-nonparallel-continuous upper boundaries indicate limited erosional action by subsequent flows.
b) Laminae with wavy-nonparallel-discontinuous upper boundaries may reflect overriding of the flow body and tail caused by deceleration of the flow head, resulting in the formation of composite laminae.
c)Laminae with dense and granular matrices share a genesis associated with high-density flows.
d) Compaction in Quaternary colluvial deposits may be syndepositional or post-depositional. The former is identified by the presence of fluid-escape structures, whereas the latter is recognized by closed packing within granular-matrix laminae.
e) The thickness of the original flow (H_f) is a multiple of the preserved lamina thickness (H_L), initially disregarding the effect of compaction.
f) The mean depth of the original flow ($H_{f\text{-mean}}$) can be estimated from the mean thickness of individual or composite laminae ($H_{L\text{-mean}}$) through determination of a proportionality factor (k), according to Equation 1.
g) Assuming an average compaction effect of 10% for dense-matrix laminae and 20% for granular-matrix laminae, an average value of 15% is adopted.
h) Incorporating the compaction factor into the flow-depth estimation equation yields Equation 2, where C = 0.15 represents the mean compaction coefficient.

$$H_{f\text{-mean}} = k.H_{L\text{-mean}} \quad \text{(Eq.1)}$$

$$H_{f\text{-mean}} = (k.H_{L\text{-mean}}) / 1 - C \quad \text{(Eq.2)}$$

Empirical Basis

The estimation of the mean depth of high-density flows is based on the experimental results of Paisani et al. (2023b), which have broad applicability because they satisfy premises a, b, and f. The experiment includes cases of laminae generated by individual flows (R1), composite laminae (R2–R4), and mixed-genesis laminae (R5–R6, R7–R10) (Table 1). Statistical parameters derived from individual k values are presented in Table 2. The uncertainty associated with $H_{f\text{-mean}}$ was calculated using the standard error (SE) of k values.

Table 1 – Experimental data and parameters for estimating mean flow depth.

Experimental Run	Flow Volumetric Concentration (%)	H_f (mm)	$H_{L\text{-mean}}$ (mm)	k
R1	14,66	16	1,4	11,4
R2	16,37	5	2,4	2,1
R3	21,59	20	1,9	10,5
R4	16,11	20	3,3	6,1
R5-R6	19,19; 18,99	5	2,6	1,9
R7-R10	17,81; 18,02; 16,38; 25,36	10	2,8	3,6

Source: Paisani et al. (2023b).

Table 2 – Statistical parameters of individual k values.

Parameter	Value
n	6
k_{mean}	5,93
s	4,18
SE	1,70

n: number of observations
k_{mean}: arithmetic mean of k values.
s: sample standard deviation.
SE: standard error of the mean.
Source: Authos (2026).

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Declaration on the Use of Artificial Intelligence

The authors declare that a Generative Artificial Intelligence tool (ChatGPT, OpenAI) was used exclusively during the revision of the original manuscript with the sole purpose of improving textual fluency. No AI tool was employed in the conception of the study, data analysis, interpretation of results, or development of scientific arguments. All content was critically reviewed and validated by the authors, who assume full responsibility for the originality and accuracy of the final text, in accordance with Ordinance No. 2664/2026 of the National Council for Scientific and Technological Development (CNPq).

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