MAPPING GEOMORPHODYNAMICS IN HIGH-MAGNITUDE EVENTS: CONTRIBUTIONS TO THE PREVENTION OF LANDSLIDE-RELATED DISASTERS

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ABSTRACT

High-magnitude landslides are natural processes that shape steep slopes and valleys in southern and southeastern Brazil, while also being responsible for some of the most devastating natural disasters recorded in recent years. To improve disaster prevention strategies, this study aimed to analyze the geomorphodynamics of high-magnitude landslides in the Paraitinga Plateau (SP) associated with the extreme 2009/2010 event. The research adopted a detailed approach based on high-resolution geomorphological mapping, integrating multitemporal photointerpretation techniques, fieldwork, and analysis of erosional and depositional features. Results revealed that deeper landslides, linked to weathering mantle ruptures, were frequently associated with debris flows that reshaped valleys, forming depositional lobes in debris cones. Scouring from these flows was marked by plucking features in bedrock channels, contrasting with fluvial abrasion in downstream sections. Past deposits indicate historical recurrence of these processes, potentially intensified by anthropogenic changes like native vegetation removal. The study demonstrates that high-magnitude events, though rare, play a fundamental role in landscape as agents of slope and channel remodeling. Results highlight the importance of considering the integration of geomorphodynamic analyses into risk assessment, enhancing the understanding of mass movement dynamics and supporting forecasting in data-scarce regions, thereby contributing for more effective public policies for disaster prevention in humid tropical regions.

Keywords: Morphodynamic mapping; Slope-channel coupling processes; Tropical landscape evolution; Applied geomorphology to risks; Extreme morphogenetic processes; Multitemporal analysis of geomorphic processes.

RESUMO

MAPEAMENTO DA GEOMORFODINÂMICA EM EVENTOS DE ALTA MAGNITUDE: CONTRIBUIÇÕES PARA A PREVENÇÃO DE DESASTRES RELA-

CIONADOS A MOVIMENTOS DE MASSA. Movimentos de massa de alta magnitude são processos naturais que moldam encostas íngremes e vales no sul e sudeste do Brasil, sendo também responsáveis por alguns dos desastres naturais mais devastadores registrados nos últimos anos. Para aprimorar as estratégias de prevenção de desastres, este estudo teve como objetivo analisar a geomorfodinâmica de movimentos de massa de alta magnitude no Planalto de Paraitinga (SP), associados ao evento extremo de 2009/2010. A pesquisa adotou uma abordagem baseada em mapeamento geomorfológico de alta resolução, integrando técnicas de fotointerpretação multitemporal, trabalhos de campo e análise de feições erosivas e deposicionais. Os resultados revelaram que deslizamentos mais profundos, relacionados a rupturas no manto de intemperismo, foram frequentemente associados a fluxos de detritos que remodelaram os vales, formando lóbulos de deposição em cones de detritos. A incisão causada por esses fluxos foi marcada por feições de arrancamento em canais escavados na rocha, em contraste com a abrasão fluvial observada em trechos à jusante. Depósitos antigos indicam a recorrência histórica desses processos, potencialmente intensificada por alterações antrópicas, como a remoção da vegetação nativa. O estudo demonstra que, embora raros, os eventos de alta magnitude desempenham um papel fundamental na paisagem ao modificar encostas e canais. Os resultados destacam a importância de considerar a integração da análise geomorfodinâmica nas avaliações de risco, ampliando a compreensão da dinâmica dos movimentos de massa e apoiando a previsão de processos geomorfológicos em regiões com escassez de dados, contribuindo assim para políticas públicas mais eficazes de prevenção de desastres em ambientes tropicais úmidos.

Palavras-chave: Mapeamento morfodinâmico; Processos de interação vertente-canal; Evolução da paisagem tropical; Geomorfologia aplicada aos riscos; Processos morfogenéticos extremos; Análise multitemporal de processos geomórficos.

RESUMEN

CARTOGRAFÍA DE LA GEOMORFODINÁMICA EN EVENTOS DE ALTA MAGNITUD: CONTRIBUCIONES A LA PREVENCIÓN DE DESASTRES RELACIONADOS CON MOVIMIENTOS DE MASA. Los movimientos de masa de gran magnitud son procesos naturales que moldean laderas empinadas y valles en el sur y sudeste de Brasil, y también son responsables de algunos de los desastres naturales más devastadores registrados en los últimos años. Para mejorar las estrategias de prevención de desastres, este estudio tuvo como objetivo analizar la geomorfodinámica de movimientos de masa de gran magnitud en el Planalto de Paraitinga (SP), asociados al evento extremo de 2009/2010. La investigación adoptó un enfoque basado en el mapeo geomorfológico de alta resolución, integrando técnicas de fotointerpretación multitemporal, trabajos de campo y análisis de rasgos erosivos y deposicionales. Los resultados revelaron que los deslizamientos más profundos, relacionados con rupturas en el manto de meteorización, estuvieron frecuentemente asociados a flujos de detritos que remodelaron los valles, formando lóbulos de deposición en conos de detritos. La incisión causada por estos flujos estuvo marcada por rasgos de arranque en canales excavados en la roca, en contraste con la abrasión fluvial observada en los tramos aguas abajo. Depósitos antiguos indican la recurrencia histórica de estos procesos, potencialmente intensificada por alteraciones antrópicas, como la remoción de la vegetación nativa. El estudio demuestra que, aunque poco frecuentes, los eventos de gran magnitud desempeñan un papel fundamental en el paisaje al modificar laderas y canales. Los resultados destacan la importancia de considerar la integración del análisis geomorfodinámico en las evaluaciones de riesgo, ampliando la comprensión de la dinámica de los movimientos de masa y

apoyando la predicción de procesos geomorfológicos en regiones con escasez de datos, contribuyendo así a políticas públicas más eficaces de prevención de desastres en ambientes tropicales húmedos.

Palabras clave: Mapeo morfodinámico; Procesos de interacción ladera-canal; Evolución del paisaje tropical; Geomorfología aplicada a los riesgos; Procesos morfogenéticos extremos; Análisis multitemporal de procesos geomórficos.

1 INTRODUCTION

High-magnitude mass movements, triggered by extreme rainfall events and characterized by the occurrence of hundreds to thousands of landslides within a single episode, have been responsible for some of the most catastrophic natural disasters recorded in Brazil in recent years (Andrade et al., 2024; Avelar et al., 2013; Coelho et al., 2024; Dias et al., 2023; Egas et al., 2025; Lima et al., 2020; Stabile et al., 2024; Tomazzoli et al., 2009). Although relatively rare, these events have high destructive potential and can significantly reshape landscapes over short periods (Brunsden & Thornes, 1979; Clague & Stead, 2012; Church, 2010; Harvey, 2001; Selby, 1983).

Beyond their impacts on communities and infrastructure, high-magnitude landslides and debris flows events have been recognized as important agents in slope evolution, playing a decisive role in shaping steep slopes and associated valley bottoms (Benda & Dunne, 1987; Church, 2010; De Haas et al., 2022; De Ploey & Cruz, 1979; Gomes et al., 2022; Hack & Goodlett, 1960; Reneau & Dietrich, 1987; Selby, 1983; Stock & Dietrich, 2003, 2006; Tucker, 2015). Nevertheless, their low temporal frequency – with recurrence intervals that may span decades or even centuries – hinders both the preliminary identification of susceptible areas and the development of effective prevention strategies.

Event magnitude, as considered here, refers not only to the overall scale of geomorphic work – or the volume of mobilized material – resulting from a single triggering impulse such as an intense rainfall event, but may also encompass measures of landslide severity within the affected area, following the framework proposed by Crozier and Glade (1999). Spatial patterns of landsliding – including metrics such as density, average rates, or frequency per unit area – are often used in empirical studies to characterize events (Chang et al., 2008; Chen et al., 2012; Gallart, 1995; Guthrie et al., 2010; Marc et al., 2018; Reid, 1998), though these variables more directly reflect the severity and spatial manifestation of the processes than magnitude per se. Nevertheless, high-magnitude events frequently exhibit localized clusters or cores of especially high severity (Crozier, 2017), where landslide density and impacts are disproportionately concentrated. From a geomorphological systems perspective, however, high-magnitude events are best defined by their capacity to disrupt landscape connectivity and induce drastic morphological change, in line with the theory of landscape sensitivity (Brunsden & Thornes, 1979).

In this context, the recognition and geomorphological analysis of landforms and processes associated with high-magnitude events emerge as fundamental tools. The geomorphodynamic approach, in particular, offers valuable conceptual and methodological keys for understanding recent morphogenetic processes and their interactions with current relief.

For more frequent, lower-magnitude processes, geomorphodynamic studies typically focus on experimental research conducted in small areas over short observation periods (Cruz, 1985). However, capturing rare stochastic events through experimental studies may be impractical, making the mapping, measurement, and interpretation of recent – but completed – processes the only viable analytical approach.

To overcome this limitation, morphodynamically--focused geomorphological mapping enables the reconstruction of current landform activities and process rates (Coltrinari, 1984; Dramis et al., 2011). Thus, morphodynamic maps illustrate the typology and activity of geomorphological processes in an area, allowing the delineation of recent morphogenesis - including human activities - and helping predict future phenomena behavior (Brunsden, 1993; Dramis et al., 2011). This approach focuses on analyzing active morphogenesis (Verstappen, 1977), where geomorphological maps interpret recent landform evolution dynamics, revealing not just event causes and effects but also clues about recurrence, persistence, and potential reactivations.

The resulting cartographic products – so-called geomorphodynamic maps – can be used as strategic tools for disaster prevention, particularly addressing challenges posed by their inherent low frequency, such as the absence of long-term memory about past events and the low predictability related to lacking information about historical triggering conditions of high-magnitude events.

Building on these premises, using the 2009/2010 high-magnitude event in the Paraitinga Plateau (São Paulo State) as our study case, this research aimed to demonstrate the potential of geomorphodynamic mapping for understanding the relationships between geomorphology and the mass movements that occurred during that event. We highlight the main landscape modifications caused by landslides and debris flows triggered during the high-magnitude event and subsequent processes, while discussing the implications and potential of this approach for preventing mass movement-related disasters.

2 STUDY AREA

The Paraitinga Plateau (Figure 1), located in the eastern region of São Paulo State, belongs to the Atlantic Orogenic Belt Morphostructural Unit and the Atlantic Plateau Morphoscultural Unit (Ross & Moroz, 1997). It forms part of the Neoproterozoic Ribeira Belt, composed mainly of strongly
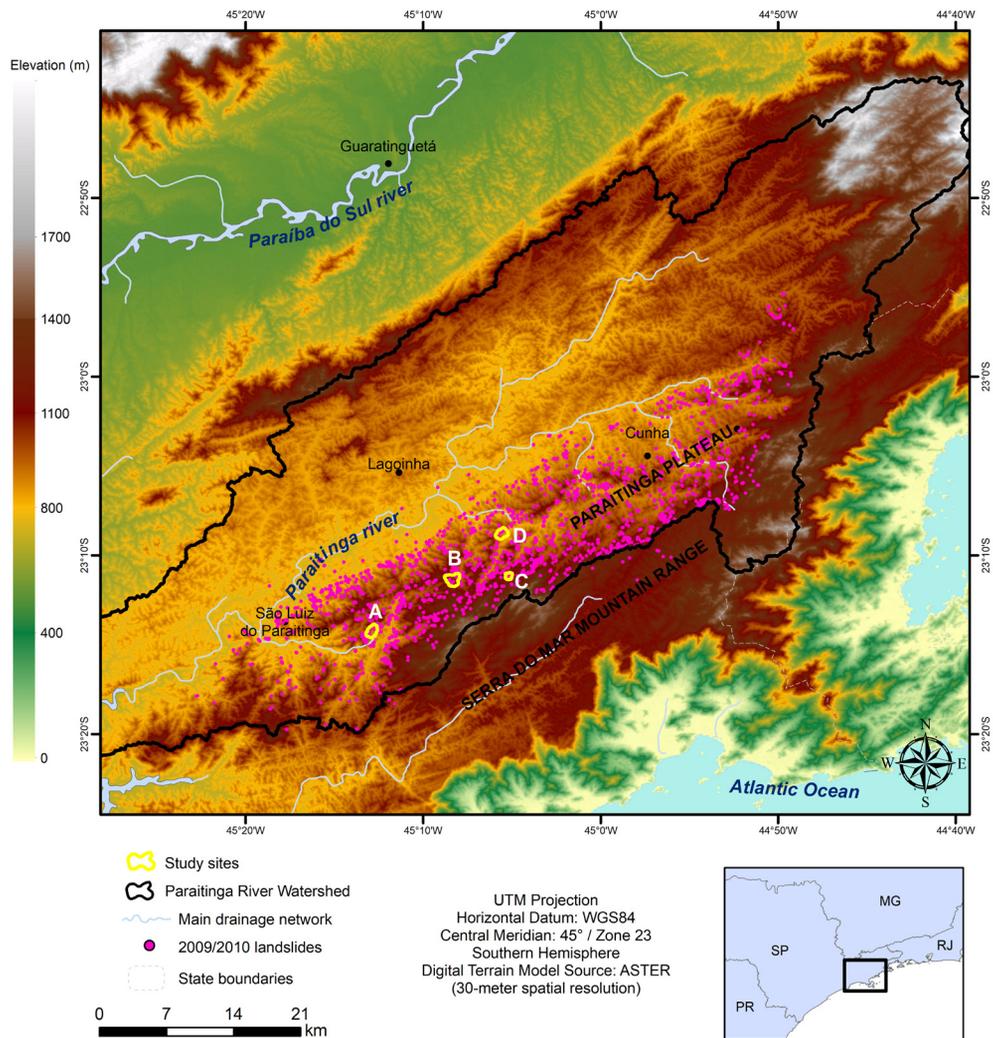

FIGURE 1 – Paraitinga Plateau and landslide scars triggered during the 2009/2010 event (Stabile & Colângelo, 2017). The study areas where geomorphodynamic mapping was conducted are highlighted in yellow: (A) Rincão, (B) Mato Dentro, (C) Tremembé, (D) Catioca.

deformed gneisses and syntectonic granites emplaced during the Brasiliano orogeny (Hasui et al., 1978, geological map at 1:200,000 scale; Fernandes, 1991, geological map at 1:200,000 scale). These granitoids, crystallized under ductile deformation conditions along NE–SW-oriented shear zones, giving rise to foliated and lineated structures that exert a pronounced influence on the present-day relief (Fernandes, 1991; Hasui et al., 1978). In the Serra de Paraitinga sector, which represents the higher and more dissected portion of the plateau (900–1,600 m a.s.l.), the lithology is dominated by these syntectonic granitic bodies, locally associated with migmatitic gneisses and, toward the northwestern margin, by mica schists and quartzites along the Cubatão Shear Zone (Fernandes, 1991; Hasui et al., 1978). To the east, the plateau is abruptly interrupted by the Middle Paraíba do Sul Tectonic Depression, a Paleogene sedimentary basin associated with the development of the Continental Rift of Southeastern Brazil, whose main tectonic phase involved the formation of an ENE-oriented half-graben (Riccomini et al., 2004). The Paraitinga River watershed encompasses the southeastern slopes of this rift valley.

Under a current humid tropical climate (Köppen classification Cwa), which can be further described according to Novais & Galvani (2022) as "tropical ameno úmido" and "subtropical úmido" in the higher altitudes (free translation: humid mild tropical and humid subtropical), the region lies within the core area of the "Mares de Morros" (Sea of Hills) Morphoclimatic Domain (Ab'Sáber, 1966), characterized by rounded hills and a thick weathering mantle resulting from deep, widespread rock weathering, also influenced by fractures and joints (Ab'Sáber, 1966; Mousinho & Bigarella, 1965). Although part of this morphoclimatic domain, the plateau presents locally higher relief amplitudes and steeper slopes than typically observed in the "Mares de Morros" landscape.

The plateau relief is thus marked by elongated ridges, lineaments, and valleys that follow the regional NE–SW structural grain. Drainage organization and valley orientation commonly reflect this structural control, resulting in subparallel and rectilinear drainage segments aligned with foliation and fracture systems (Almeida, 2018). The predominance of foliated granitoids and the presence of intersecting shear directions have generated slope asymmetry and guided differential denudation (Ab'Sáber, 1966;

Mousinho & Bigarella, 1965), producing a rugged landscape of steep slopes, narrow valleys, and ENE- to NE-aligned ridges typical of the Paraitinga Plateau. The regional hydrography is dominated by structurally guided rivers with youthful profiles, numerous rapids and waterfalls (Almeida, 2018), and limited alluvial plains development, constrained at drainage confluences and upstream of knickpoints (Ab'Sáber, 1966).

The weathering mantle supports *Latossolo Vermelho-Amarelo* (Ferralsol) on hills near the Paraitinga River, *Argissolo Vermelho-Amarelo* (Lixisol) on higher elevations of the right margin, and *Cambissolo Háplico* (Cambisol) across most of the upper basin and drainage headwaters, with *Gleissolo* (Gleisol) and *Cambissolo Húmico* (Umbric Cambisol) occurring in specific zones (Rossi, 2017, pedological map at 1:250,000 scale).

The removal of the original vegetation cover, initially continuous from interfluves to valley bottoms, represents the most visibly altered landscape feature. Deforestation resulted from coffee plantation expansion in the early 19th century. Currently, only fragments of secondary Dense Ombrophilous Forest (Atlantic Rainforest) remain on the steepest slopes and some hilltops, with extensive cattle grazing pastures now predominating (Freitas Junior & Marson, 2007).

Between late 2009 and early 2010, during a rainy summer, intense rainfall affected the Paraitinga River basin, causing unprecedented historical flooding that severely impacted local populations and historical heritage (Moradei, 2016). During the same event, widespread mass movements were triggered across nearly 1,000 km² of the basin's left margin (Stabile & Colângelo, 2017), demonstrating both the intensity and spatial extent of precipitation (Figure 7). Stabile and Colângelo (2017) mapped over 2,000 landslide scars and recorded rainfall accumulations exceeding 300 mm over 96 hours, with estimated intensities surpassing 50 mm/hour on January 1, 2010, when most landslides likely occurred.

Landslide processes have been described in other compartments of the Paraíba do Sul Valley, particularly in mountainous or hilly convex–concave landscapes in Bananal region. These slumps, responsible for landscape evolution by shaping amphitheater-like hollows with narrow lower ends, are typically triggered in association with headwater channel initiation due to seepage erosion, tunnel collapses and gullying (Avelar & Coelho Netto, 1992; Coelho Netto, 1999; 2003) Subsequent

erosion, including short-distance debris flows, may lead to slope retreat beyond original watershed divides, and in some cases, promote headward gully propagation that can capture adjacent valleys through groundwater-driven processes (Coelho Netto, 1999).

In contrast, landslides in the Paraitinga Plateau as observed during the 2009/2010 event, were mainly shallow landslides triggered predominantly disconnected from the drainage network, which in some cases, generated downslope debris or mud flows that incised and modified channels, illustrating a particular type of geomorphodynamic response under extreme rainfall conditions. Previous studies about the 2009-2010 landslide event in the Paraitinga Plateau have shown that landslide occurrence and landslide size distributions are strongly influenced by controlling factor such as rainfall, lithology, slope gradient, upslope area, and land cover (Stabile & Colângelo, 2024; Stabile et al., 2025). They also indicate that landslide occurrence and severity (SL) follow a nonlinear response to precipitation, with critical rainfall thresholds marking abrupt transitions to widespread landslide activity. Below these thresholds, small landslides dominate, primarily controlled by local topography, upslope area, and vegetation cover. Above the thresholds, the probability of large landslides increases, particularly on slopes greater than 0.56 m/m and during rainfall exceeding 180 mm, with lithology (schist, quartzite) associated with larger scars, and soil saturation contributing to more extensive mass movement and debris flows (Stabile & Colângelo, 2024; Stabile et al., 2025). The present study was conducted in four sub-basins located within the zone of highest landslide severity, where landslide frequency increased abruptly and debris flows were also triggered.

3 METHODS

Building upon the mapping framework established by Stabile and Colângelo (2017, 2024) and Stabile et al. (2025), we selected four drainage headwaters, each a few km² in size, located in different sectors of the Paraitinga Plateau for geomorphological mapping: Rincão, Mato Dentro, Tremembé, and Catioca (Figure 1). The resulting maps, focusing on landforms generated by contemporary geomorphological processes (Coltrinari, 1984; Dramis, 2011; Verstappen, 1977), particularly those formed during the 2009/2010 event, were designated as Geomorphodynamic Maps.

Despite the availability of high-resolution aerial imagery with appropriate temporal coverage that offers strong potential for investigating slope process morphodynamics, most landslide inventories remain insufficiently detailed, producing simplified catalogs without a geomorphological perspective on process connectivity (Cooke & Doornkamp, 1990; Dramis et al., 2011; Pasuto & Soldati, 1999).

To advance the interpretation of landforms, processes, and deposits from high-magnitude events beyond conventional landslide inventories, this study integrated approaches from:

• Geomorphological mapping methodologies developed by the University of São Paulo's Geography Department (including works by Aranha & Ferreira, 2020; Coltrinari, 1982; Coutard et al., 2020; Pinheiro & Ferreira, 2020; Pinheiro & Queiroz Neto, 2016; Portela, 2015). These mappings were originally conducted at scales ranging from 1:25,000 to 1:50,000 and are characterized by the conceptual framework of their legends, which integrate landforms across different scales, distinguish inherited from active features, and associate landforms with the processes responsible for their formation. In this study the geomorphological mapping was not applied as a synthetic interpretative product of a region, but rather as an analytical tool to understand other elements of the landscape – similarly to the approach adopted in other works cited by Pinheiro & Ferreira (2020) – specifically, the geomorphological meaning of the 2009/2010 extreme event.

• Hack and Goodlett's (1960) seminal mapping of 1949 debris flow impacts and subsequent changes in Little River Valley (Appalachians, USA);

• Loye et al.'s (2016) mapping of contemporary geomorphic processes in Manival Basin (French Alps).

3.1 Mapping scale and data

Scale represents a critical factor in process geomorphology mapping (Coltrinari, 1984; Dramis et al., 2011; Verstappen, 2011). We conducted mapping at 1:1,000 to 1:2,000 scales (presented at 1:4,000), exceeding standard detail-scale definitions (e.g. Coltrinari, 1984; Verstappen, 2011) and qualifying as hyper-detailed mapping. This resolution enabled documentation of metric-scale features including shallow landslide scars, lobate debris deposits, scoured channels, textural variations in depositional units.

Photointerpretation utilized multi-temporal datasets, including aerial photographs, satellite

images, and an orthophoto (Table 1). All datasets were georeferenced and orthorectified in ArcGIS 10.2 using the orthophotos as basemaps, with direct digital mapping implementation.

The image selection captured three critical periods:

• Baseline conditions (pre-2009/2010 event);
• Immediate post-event status (~ 4 months post--triggering);
• Decadal-scale landscape evolution.

Notably, the 1962 and 1973 aerial photographs, as well as the 2023 satellite imagery, possess lower spatial resolutions than other datasets, constraining detailed geomorphic features mapping. For the year 2023 and intermediate study periods (2017 and 2021), complementary field campaigns were conducted to verify diagnostic geomorphic features, validate process classifications, and ground-truth geomorphodynamic interpretations.

3.2 Interpretation keys and legend structure

The geomorphodynamic mapping prioritized landforms generated by recent and sub-recent mass movements, while also incorporating other geomorphic processes (e.g., fluvial bank erosion, linear erosion). Wherever possible, we employed polygons corresponding to the exact boundaries of mapped features. Additionally, we mapped fundamental landforms essential for understanding geomorphological dynamics, including: hydrographic features, erosional landforms - amphitheaters and other denudational features, rock exposures, depositional features - alluvial fans, floodplains, and other accumulative forms, anthropogenic modifications etc. Slope gradient and morphology were represented exclusively through contour lines. Appendix I presents the complete feature inventory and primary interpretation keys.

The selection of landforms was guided by geomorphological studies addressing the evolution of headwater valleys in mountainous regions. Two main interpretative frameworks are recognized. The first emphasizes a paleogeographic or inherited origin, in which amphitheater-shaped valleys and hollows are considered remnants of large-scale or deep-seated slope processes influenced by climatic and tectonic fluctuations during the Late Quaternary (Bigarella et al., 1965; Coelho Netto, 1999; Hiruma et al., 2013; Meis & Moura, 1984; Modenesi, 1988). In this view, Coelho Netto (1999) described structurally controlled bedrock hollows affected by seepage erosion and tunneling, processes that may have originated under past environmental conditions but can be reactivated after deforestation, when increased groundwater flow and headward incision trigger landslides and channel extension. The second framework stresses contemporary hillslope–channel coupling, in which recurrent shallow landslides and debris flows actively incise and maintain headwater valleys during extreme rainfall events (Cruz, 1972; Dietrich & Dunne, 1978; Hack & Godlett, 1960; Stock & Dietrich, 2003, 2006).

Regarding the interpretation keys used for process mapping, it is essential to emphasize the inherently interpretive nature of geomorphological mapping. The processes themselves are not directly observable but must be inferred from landform characteristics (Verstappen, 1977). Crucially, distinguishing between different processes often requires (when possible at all) detailed field analyses of morphology and stratigraphy. As a result, only the maps for the Mato Dentro and Catioca areas can be considered fully validated. In the Rincão and Tremembé areas, accessibility constraints prevented us from conducting complementary field analyses with the same level of detail. Furthermore, certain diagnostic features – particularly rock abrasion

TABLE 1 – Datasets used in Geomorfodynamics Mapping

Data Type	Time Period	Resolution Scale	Source/Providers
Aerial photographs	1962	1:25,000	Instituto Agronômico/Instituto de Pesquisas Tecnológicas do Estado de São Paulo – IPT Archives
Aerial photographs	1973	1:25,000	Secretaria de Agricultura/Instituto Geológico do Estado de São Paulo – IG Archives
Orthophotos	2010	1 m	"Mapeia São Paulo" Project (Empresa Paulista de Planejamento Metropolitano – EMPLASA)
Satellite imagery	2006-2020	0.5-2 m	QuickBird-2, GeoEye-1 (via Google Earth/Maxar Technologies/CNES-Airbus)
Satellite imagery	2023	3-4 m	Rede MAIS/MJSP, includes material © 2023 Planet Labs Inc. All rights reserved.

forms and sediment arrangement patterns – are only visible at scales finer than those employed in this mapping effort.

For temporal attribution of features, those associated with the 2009/2010 event were primarily identified in April 2010 satellite imagery. The key diagnostic indicators included: (1) the distinctive coloration of freshly exposed soil in scars and deposits, and (2) the absence of these features in pre-event imagery. While some features may have formed at slightly different times during the 2009/2010 summer season, all certainly postdated the beginning of this period. Subsequent image analysis revealed that exposed soils in depositional areas were rapidly recolonized by pasture grasses, thereby confirming the recent formation of features identified in the April 2010 imagery.

Features related to processes occurring prior to the 2010 event (including landslide scars, linear and marginal erosion, and other mass movement types) were included in the legend under the "Preterit Geomorphodynamics" category. These features may thus represent processes active in pre-2009/2010 imagery, as well as inactive features that remain identifiable through photointerpretation.

4 RESULTS AND DISCUSSION

The geomorphodynamic mapping results from the four study areas (Appendix II) provide a robust framework for understanding mass movements and their role in landscape evolution. Our integrated analysis revealed recurring patterns in the spatial distribution and typology of these processes, while enabling inferences about their frequency, dynamics, and associated erosional/depositional landforms linked to past geomorphological evolution.

We organize and discuss our key findings along two main themes: detailed characterization of mass movements; relationships between current processes and relict landforms as geomorphological archives of past events, with implications for disaster prediction. Collectively, these results advance our understanding of geomorphodynamic processes in the humid tropical environments of the Atlantic Plateau, while identifying promising avenues for improving applied mapping techniques and geological risk management strategies.

4.1 Dynamics of mass movements during the 2009-2010 event

Understanding mass movement dynamics benefits from geomorphologically-based mapping – herein termed geomorphodynamic mapping – that transcends broad classifications typically used in inventories and connects current processes to inherited landforms. The classification of landslides by scar size (Stabile & Colângelo, 2024), combined with morphologic differentiation between depositional and flow processes, allowed us to capture the continuum of mass movements and landscape response to the 2009/2010 high-magnitude event in Paraitinga Plateau.

The 2009/2010 event triggered landslides of varying sizes across all study areas. Their division into rollover and tail types based on magnitude-frequency analysis (Stabile & Colângelo, 2024) and field evidence suggests distinct triggering mechanisms between smaller and larger magnitude landslides, consistent with Stark and Guzzetti (2009). Generally, rollover-type landslides were shallower (< 1 m depth) with failure surfaces at soil-bedrock or slightly weathered regolith contacts, while tail-type landslides showed deeper failure surfaces (1.5-5 m) not reaching bedrock (Figure 2).
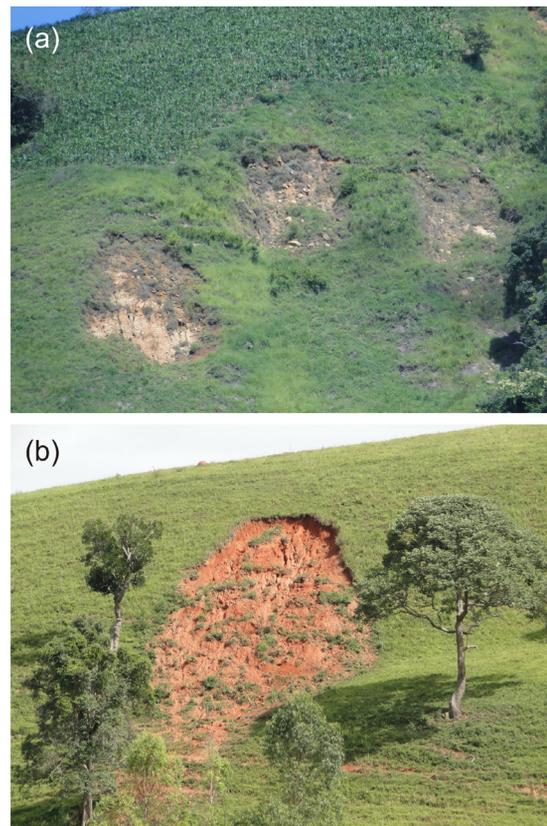

FIGURE 2 – Rollover-type landslide near Mato Dentro area (a) and tail-type landslide near Catioca area (b). Source: IPT (2015) - Photos from Feb/2014.

Steep channels in slope-channel coupling zones showed significant morphological changes post-event (Figure 3). Substantial sediment erosion occurred downstream of higher magnitude (tail-type) landslides. Rollover-type landslides produced less intense scouring and distinct deposition patterns, with erosion products confined to channel beds. In contrast, channels downstream of tail-type landslides contained more voluminous deposits, often including boulders distributed along channels, lateral *levees* and forming debris lobes/fans, particularly at channel confluences or where channel confinement decreased like at debris cones.

These coarse-particle-rich lobes match classical debris flow deposits described in literature (Costa,
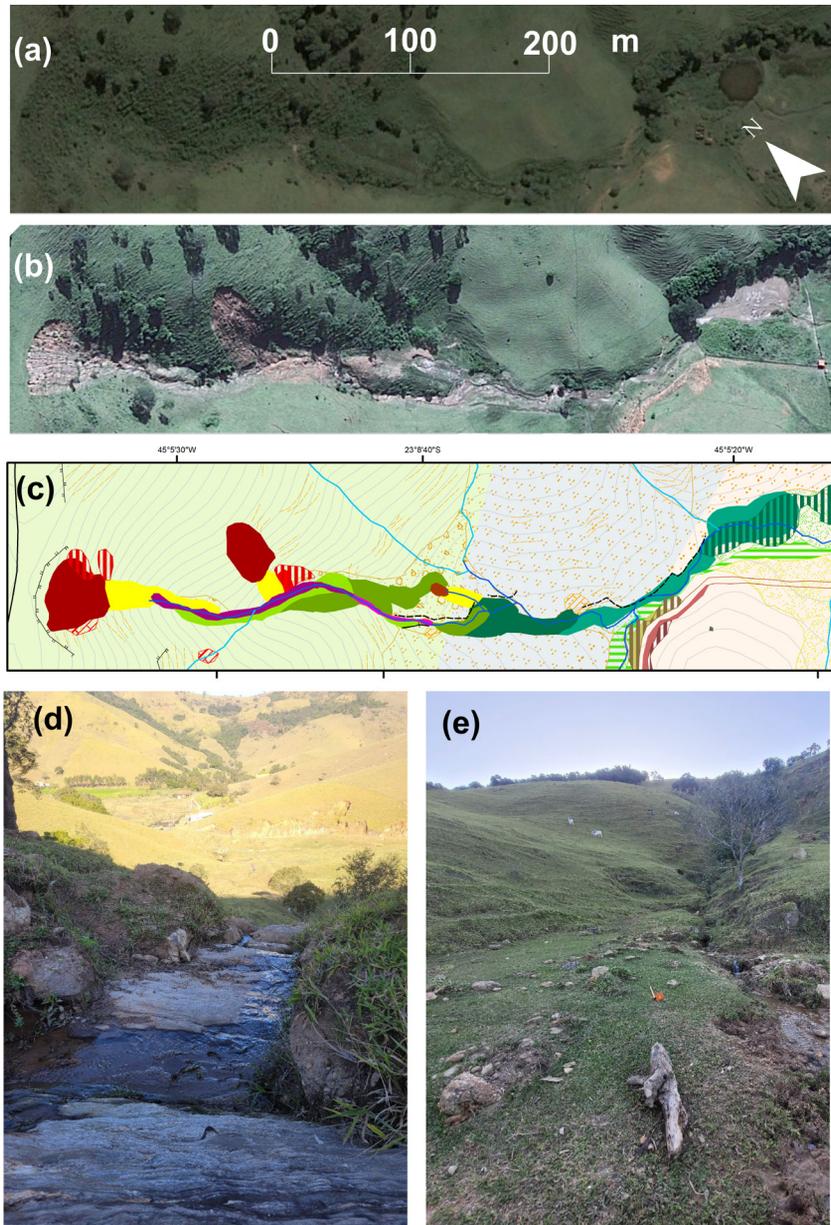
FIGURA 3 – Satellite images (a, b), geomorphodynamic map (c) and field photos (d, e) from the Catioca area showing changes associated with the 2009/2010 event. Satellite images from 03/02/2006 (a) and 04/17/2010 (b) highlight a landslide-triggered debris flow downstream, causing channel scouring (d) and subsequent debris lobe deposition, already degraded during the 2023 field survey (e). Satellite images: Google Earth. Field photos: 2023 field campaign. The complete geomorphodynamic map and its legend for Catioca are available in Attachment V.

1984, 1988; Dietrich & Dunne, 1978; Hungr et al., 2001; Reneau & Dietrich, 1987). Their characteristics - including coarse clasts in fine matrix (diamicton), debris levees, absence of primary sedimentary structures, convex surface topography, fragile clasts, and sometimes inverse grading or bimodal grain size distribution (Costa, 1984; Hungr et al., 2001; Pierson, 2005; Selley, 2000; Stock & Dietrich, 2003) indicate debris flow activity (Figure 4).

The strongest evidence for the erosive capacity of these flows at the mapped sites comes from observed morphological changes in the channels before and after the event. The observation that flows removed valley sediments is supported by three key field indicators: (i) abundant boulders and other coarse clasts in the deposits; (ii) the presence, albeit rare, of sub-rounded pebbles and cobbles among angular clasts, indicating that the debris flows also transported and incorporated fluvial sediments; and

(iii) bedrock channels lacking well-developed typical fluvial abrasion features.

Although it was not possible to characterize all scoured channels in the drainage headwaters that lacked debris lobes in the field, the absence of such deposits suggests intermediate processes between debris flows and fluvial flooding. In these cases, we identified the likely occurrence of either hyperconcentrated flows (when associated with fine or medium mixed deposits) or debris floods, characterized by coarser mixed deposits. From a process-based perspective, hyperconcentrated flows and debris floods differ fundamentally in sediment transport mechanisms: the former are dominated by suspended load supported by turbulence and high sediment concentration, whereas the latter are traction-dominated flows, capable of mobilizing and transporting coarse channel bed material (Church & Jakob, 2020).
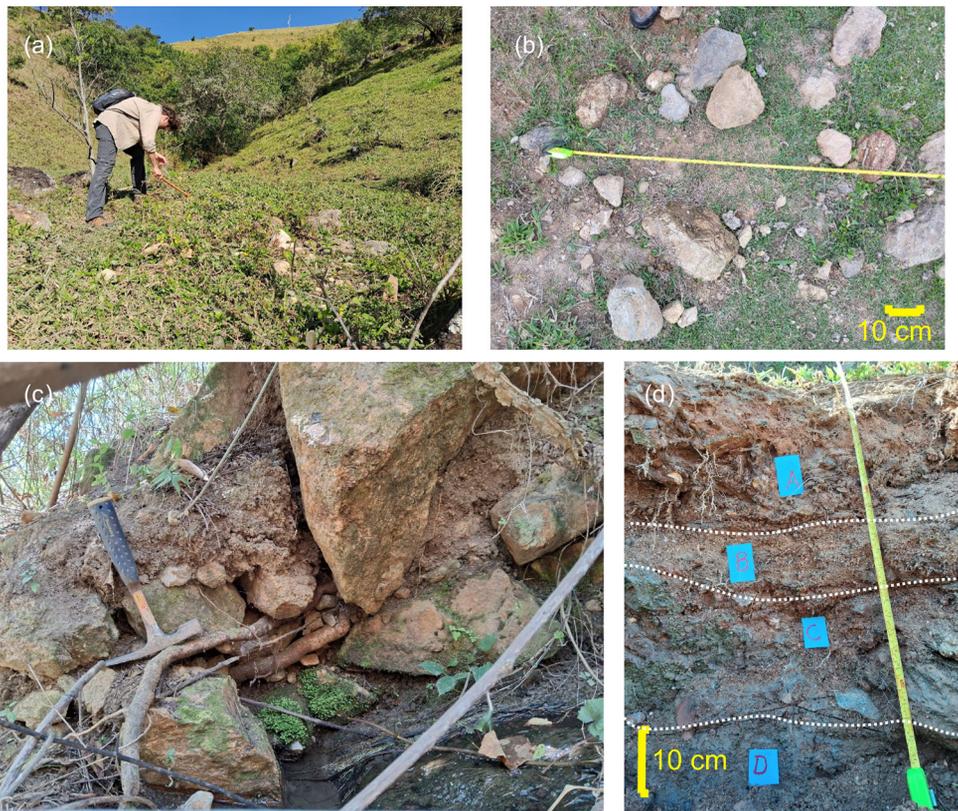

FIGURE 4 – Depositional features in steep channels associated with 2009/2010 event: (a) Debris lobe in Mato Dentro area, composed of angular boulders and cobbleswith sub-rounded pebbles in a clay-sand matrix;(b) Vertical view of debris lobe in Catioca area (same place as Figure 3e);(c) Debris levee on the right channel margin in Mato Dentro, consisting of angular boulders and cobbles in a clay-sand matrix; (d) Stratigraphic sequence on the left channel margin of the debris lobe in Catioca area; Layer A: Angular boulders and cobbles in clay-sand matrix; Layer B: Coarse sand and gravel without apparent stratification; Layer C: Angular boulders, cobbles and pebbles in clay-sand matrix; Layer D: Dark gray clay-sand with gravel inclusions. Photographs taken during 2023 field campaign.

A particular example was observed further downstream in the Mato Dentro area, where we identified an alternation between channels widened by the 2009/2010 event and deposits composed of angular boulders and cobbles coexisting with rounded and sub-rounded clasts. The absence of fine sediments, presence of sandy matrix, and predominance of sub-rounded clasts suggest the dominant process in these reaches was a debris flood, as characterized by Church and Jakob (2020) (Figure 5).

The deposits classified as "medium-grained mixed" or "fine-grained mixed" displayed a distinctive spatial organization, consistently occurring downstream of coarser deposits. While differing from Costa's (1988) classic description of hyperconcentrated flows – particularly in terms of clast fabric (open vs. matrix-supported) and the predominance of coarse sand - our study revealed deposits dominated by angular pebbles and granules within a fine-grained matrix (Figure 6). These deposits are therefore best interpreted as flow lobe

FIGURE 5 – Depositional features in the downstream portion of Mato Dentro area, consisting of complex deposits likely representing a mixture of slope-derived sediments - dominated by metric-scale angular boulders (*matacões*) from slope processes (landslides and rockfalls); and channel sediments – composed of smaller boulders, cobbles, sub-rounded pebbles and sand. These deposits were likely remobilized by a probable debris flood during the 2009/2010 event. Photographs taken during 2021 field campaign.
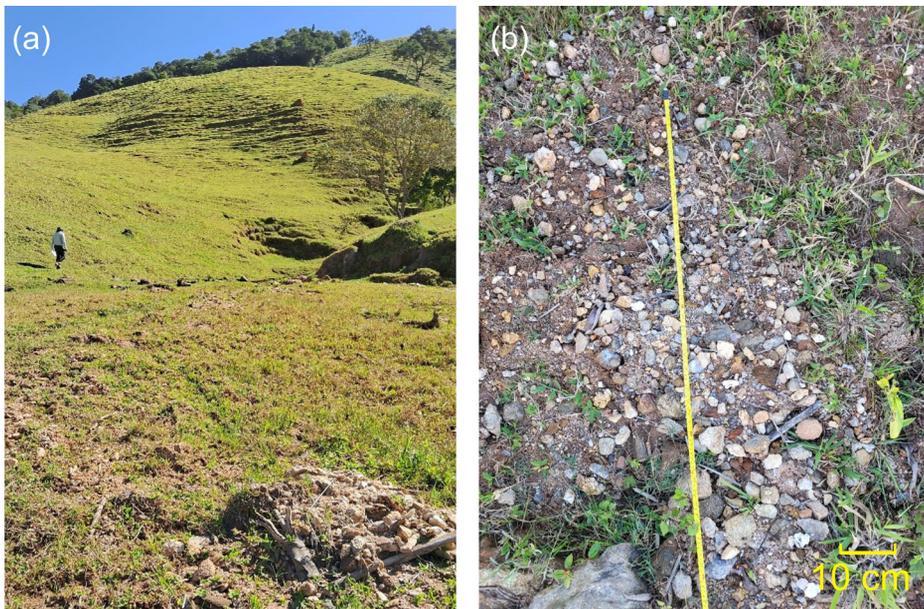

FIGURE 6 – (a) Area classified as "medium-grained mixed deposit" in the Catioca sector; (b) Close-up view of angular pebbles and granules characteristic of the deposit's fabric. Photographs taken during 2023 field campaign.

terminuses, demonstrating the longitudinal phase separation characteristic of debris flows (Costa, 1988; Pierson, 2005).

It is also important to note that the field observations were conducted more than a decade after the triggering event, and some deposits may have undergone partial degradation, reworking, or vegetation cover, possibly altering or obscuring diagnostic sedimentary features. For this reason, while we suggest the likely involvement of debris floods and hyperconcentrated flows, the mapped units intentionally retain descriptive terms ("fine-grained mixed," "medium-grained mixed," and "coarse mixed deposits"), reflecting observable sedimentological characteristics while acknowledging both the processual continuum among these flow types and the uncertainties imposed by post-event modification.

The discussion about the capacity of debris flows to excavate bedrock channels, contributing to landscape lowering, remains incipient (Buffington & Montgomery, 2013; Coelho Netto, 1999; Stock & Dietrich, 2006; Stock et al., 2005; Whipple et al., 2013). However, our observations do not contradict this hypothesis and may provide preliminary insights into the role of debris flows in bedrock channel scouring. In the Mato Dentro area, we observed a marked contrast between the granite channel beds in the downstream and upstream portions of the studied section. While the downstream areas displayed typical fluvial abrasion features (polished surfaces, flutes, potholes, and strath terraces), the upstream portions were dominated by plucking and dragging features, likely associated with debris flow activity (Figure 7). It should be noted that even in downstream areas, plucking features were present,

FIGURE 7 – Contrasts between bedrock channels in debris-flow scouring zones (a-c) and fluvially-dominated zones (d-f). (a) Bedrock channel sculpted by debris flows in Catioca area, showing characteristic erosional morphology; (b) Unpolished bedrock channel with plucking features; (c) Unpolished bedrock with linear abrasion (dragging) features; (d) Strath terraces displaying typical fluvial erosion features; (e) Polished bedrock with potholes and flutes from fluvial abrasion; (f) Flute marks indicating paleo-fluvial flow directions. Photos taken during 2021 and 2023 field campaigns.

though showing lower density and frequent polishing by subsequent fluvial abrasion.

In the Catioca section, within mica schist-dominated geology, we also observed an upstream transition dominated by plucking features and linear abrasion marks on rough channel beds, indicative of large clast dragging, extending to downstream reaches with well-defined fluvial pathways incised into bedrock, potholes, and probable strath terraces (Figure 7). In these areas, the geomorphodynamic mapping indicated widening and/or deepening of pre-existing channels during the 2009/2010 event. Satellite imagery reinforces this interpretation, revealing clearly expanded channel sections after the event, with exposure of bedrock surfaces previously covered by sediments.

While we cannot state with certainty that debris flows directly excavated the bedrock channel, it is undeniable that some of the currently exposed surfaces show no clear evidence of maintenance by fluvial processes. It is particularly noteworthy that many of the channels mapped as

being scoured or enlarged by the 2009/2010 event were already completely refilled with colluvial deposits at the time of fieldwork campaigns - an issue that will be discussed in the next section.

4.2 Geomorphological evidence and recurrence of high-magnitude processes

The geomorphodynamic maps (Appendix II) clearly indicate that, although subsequent landslide events have occurred, both the number of landslides and their downstream impacts differ significantly from those of the 2009/2010 event. Moreover, the size (area) of landslides varies markedly among pre-2009/2010 events, the 2009/2010 event itself, and post-2009/2010 events (Figure 8).

The primary explanation we identified for these distribution patterns relates to scar location. While pre-2009/10 landslides were mapped almost exclusively in granitic areas, portions of both the 2009/2010 and subsequent events also occurred in micaschist terrain. As demonstrated in the
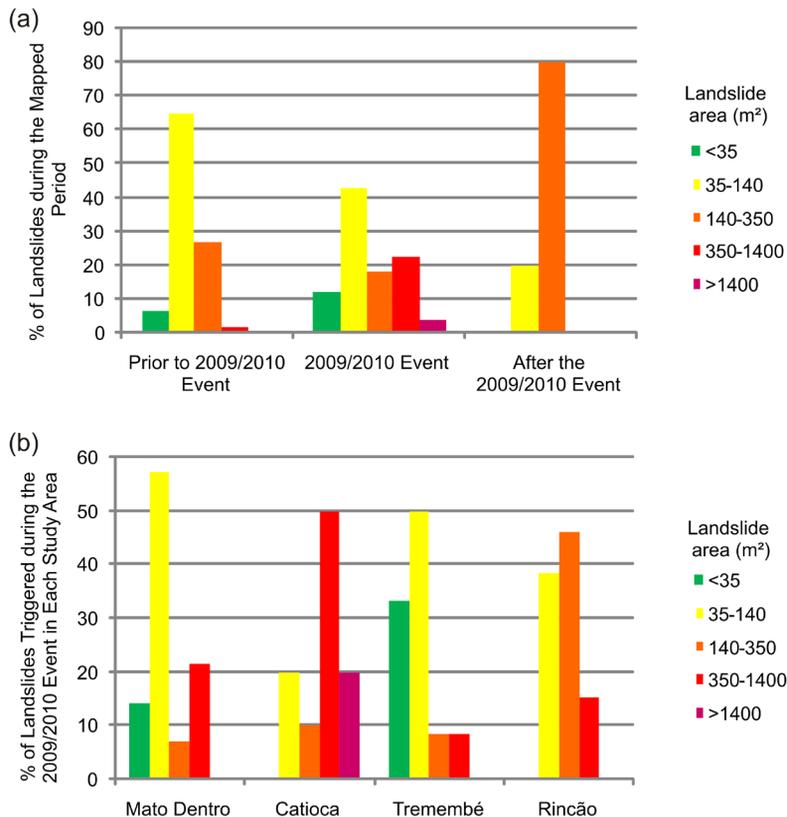

FIGURE 8 – Frequency distribution of landslide areas from the four study areas (aggregated data) according to triggering period: (a) pre-2009/2010 event, during the 2009/2010 event, and post-2009/2010 event; (b) Frequency distribution of landslide areas in the Rincão, Mato Dentro, Catioca, and Tremembé sectors during the 2009/2010 event.

magnitude-frequency spatial analysis by Stabile & Colângelo (2024), landslides in this lithology (mica schist) tend to be larger in scale - consistent with those observed during the 2009/2010 event in the Catioca sector (Figure 8). Factors such as the hydrological conditions at the time of landslide triggering and variations in the weathering mantle, which may be relevant to explain intra-basin differences in landslide scar size, were not addressed in this study.

In this sense, it is noteworthy that we have not mapped ancient landslide scars in the Catioca area. This area does not appear to be particularly less susceptible to frequent landslides, and indeed, several landslides triggered after the 2009/2010 event occurred there. One hypothesis to explain the absence of past scars is the intense soil creep, evidenced by the significantly greater density and depth of terracettes in the weathered schist mantle compared to that derived from granite, which would eventually cover and smooth out landslide scars over time. Another hypothesis is a likely predominance of shallow soil landslides, which would facilitate vegetation regrowth and the 'masking' of old scars compared to scars that occur at the boundary between the weathered mantle and intact bedrock, as observed mainly in areas with granitic bedrock.

It should also be noted that pre-2009/2010 landslides were mapped using aerial photographs (1962 and 1973, scale 1:25,000) and a single high-resolution satellite scene (2006, ~ 2 m). Differences in resolution and acquisition conditions across these periods may have influenced the detectability and delineation of older scars, potentially affecting their apparent size and spatial distribution. The rapid recovery of vegetation over landslide scars in the Brazilian tropical zone has already been demonstrated by other studies, such as that of Dias et al. (2025), and should be a concern in landslide susceptibility mapping based on or validated by scar inventories (Fell et al., 2008; Segoni et al., 2015; Reichenbach et al., 2018; Van Westen et al., 2006), given the potential bias arising from scar regeneration.

The confined channels, especially near the steep slopes closest to the valley heads, appear prone to sediment input from more frequent mass movement events. As we observed in the mapping, new landslides were recorded after the 2009/2010 event, primarily triggered as reactivations of landslides from that period. On the other hand, none of these subsequent events were capable of

causing significant erosion in the downstream valleys, at least not as debris flows. As a result, the valleys closest to the slopes may be currently classified as colluvial valleys.

The deposition pattern of sediments – with coarser clasts downstream and finer debris upstream – suggests a depositional sequence following the erosive event similar to that described by Dietrich and Dunne (1978), Benda (1990), and Benda and Dunne (1997) in the northwestern United States. In this sequence, the coarser debris increases surface roughness, reducing the erosive power of overland flow and promoting the deposition of progressively finer sediments. The more prominent colluvial fill in the upper parts of the channels, where they are more confined between steep slopes, highlights the importance of hillslope processes in this depositional sequence. Indeed, in valleys unaffected by the 2009/2010 debris flows, we observed a colluvial cover composed of a mixture of fine and coarse materials (Figure 9).

As can also be observed in Figure 8, landslides occurring after the 2009/2010 event are larger than those predating the high-magnitude event. This appears to happen because many of them are reactivations, primarily associated with the major landslides in Mato Dentro and Catioca. Further studies in other areas and over longer time periods are needed to confirm this pattern, but this finding can be explained by Samia et al.'s (2017) argument that landslides follow a trajectory (or occurrence pattern) dependent on areas previously affected by landslides, which remain more susceptible to new landslides for approximately 10 years. These authors also demonstrate that subsequent landslides tend to be larger than those triggered outside previously affected areas, which could, in part, explain why post - 2009/2010 landslides cover larger areas compared to those prior to the event.

The largest mapped landslides (> 350 m²) were triggered almost exclusively during the catastrophic 2009/2010 event (Figure 8), highlighting this event's unique capacity to generate large-scale slope failures. Regarding pre - 2009/2010 mass movements, it's possible that some large ancient scars were misinterpreted as secondary amphitheater-shaped hollows during mapping. This potential misclassification arises because a significant portion of landslides appears to contribute to the headward erosion of these landforms, ultimately blending with their contours.

Similar to the large landslides, debris flows were also only mapped during the 2009/2010
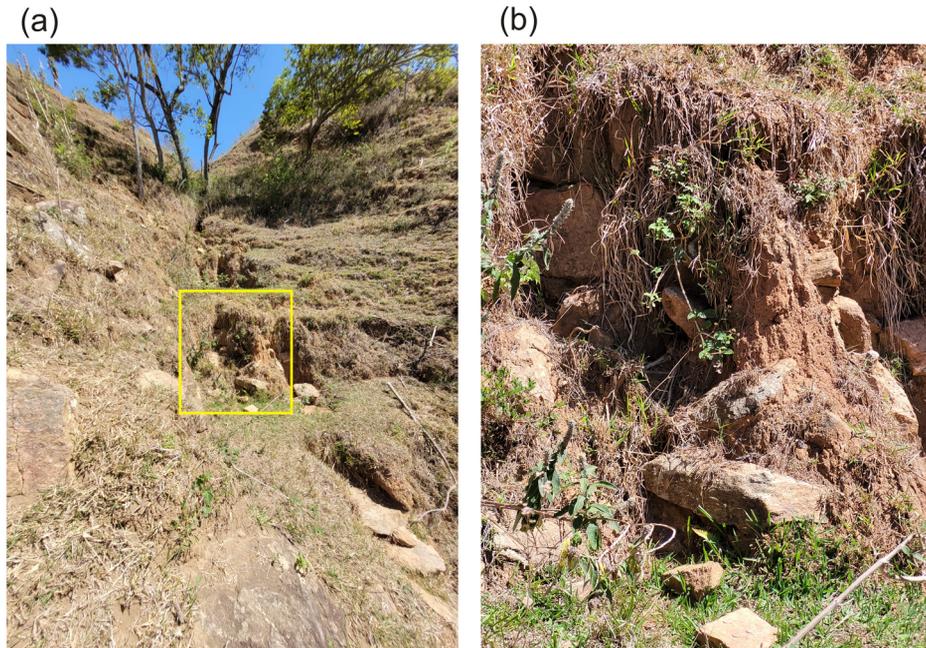
(a) (b)

FIGURE 9 – Valley unaffected by debris flows in 2009/2010 in the Mato Dentro area. These valleys are filled with sediments. Note how the valleys exhibit a stepped longitudinal profile filled with colluvial sediments. These small knickpoints are supported by coarser clasts (b). Photographs taken during 2021 field campaign.

event and not observed afterward. This suggests that the same hydrological triggers responsible for initiating the large landslides also led to the debris flows. It is noteworthy, therefore, that both large landslides and debris flows appear to occur in lower-frequency, higher-magnitude events compared to smaller-scale landslides.

The observation of at least one buried layer of boulders and angular cobbles within a fine-grained (clay-sandy) matrix beneath the Mato Dentro debris *levee* and the debris lobe on the debris cone in the Catioca area (Figure 4e) suggests that debris flow events had occurred in these areas prior to the 2009/2010 event. The recurrence of these processes in the same locations reinforces their role as geomorphic agents in the hillslope-channel coupling zones of the studied areas (Hack & Goodlett, 1960; Hungr et al., 2001; Stock & Dietrich, 2003), and demonstrates that debris cones should be considered not only as inherited landforms, but also as active features during high-magnitude events under current climatic conditions.

However, it is highly likely that the frequency of these processes has been accelerated by hydrological changes and alterations in soil properties caused by the removal of native vegetation (Coelho Netto, 1999; Meis & Silva,

1968). As previously noted by Stabile & Colângelo (2024), areas with native vegetation exhibited significantly lower landslide density compared to other areas during the 2009/2010 event. This does not mean that debris flows cannot occur in areas with native vegetation, as we observed in a granitic basement location approximately 2 km southeast of the Mato Dentro area. At this site, we identified a landslide and a likely debris flow downstream in a watershed predominantly covered by dense ombrophilous forest. This demonstrates that mass movements can also be triggered by intense rainfall in humid tropical environments even when forest vegetation is present (Coltrinari, 2003; Cruz, 1972; De Ploey & Cruz, 1979; Furian et al., 1999).

The dark clay layers (possible buried organic horizons) beneath debris levées along the channel in the Catioca area and buried by sediments interpreted as distal deposits from debris flows on the debris cone in the Mato Dentro area suggest significant sediment residence time in valley hillslope-channel coupling zones. Generally, paleosols indicate periods of stability with little or no deposition, allowing vegetation establishment, clay mineral leaching, and organic matter accumulation (Kraus & Aslan, 1995; Pierini & Mizusaki, 2007; Hiruma et al., 2013; Hiruma et al., 2016). Thus, these buried dark horizons would indicate past stability

in erosional and depositional processes, suggesting some form of hydrological control, potentially influenced by anthropogenic changes in triggering current debris flows (Bigarella et al., 1965; Coelho Netto, 1999; Modenesi, 1988;).

Studies focusing on the pedogenetic processes of dark horizons, detailed sedimentological analyses of depositional sequences, and their dating may help clarify these hypotheses in the future. Indeed, even in areas where debris flows are considered cyclical processes, their recurrence is estimated to be on the order of hundreds or thousands of years (Benda, 1990; Crozier et al., 1990; Dietrich & Dunne, 1978; Parker et al., 2016). A reasonable hypothesis is that debris flows are inherent processes in the hillslope-channel coupling zones of steep valleys in the Paraitinga Plateau, though their frequency has likely increased due to climate change or anthropogenic alterations.

Thus, landforms such as debris cones can be interpreted as morphological evidence of the recurrence - including recent occurrences - of high-magnitude processes in hillslope-channel coupling zones. The spatial coincidence between 2009/2010 debris lobes and ancient debris cones indicates a morphogenetic persistence of these areas as preferential zones for debris accumulation over time. Although further studies are needed regarding buried deposits within these features, the presence of diamicton layers with chaotic structure and fine-grained matrix interspersed with angular clasts suggests past occurrences of debris flows.

In this context, mapping the geomorphological dynamics of these areas emerges as an essential tool for understanding susceptibility to high-magnitude, low-frequency events - events that often escape collective memory as they exceed human lifespans or even multiple generations. Recognizing these landforms and their associated processes through a geomorphodynamic approach represents a crucial step for risk anticipation and strengthening prevention strategies, overcoming limitations inherent to traditional mass movement inventory analyses. Finally, it is important to highlight that this study represents a first approximation of geomorphodynamic mapping in the Paraitinga Plateau.

The maps were applied as an analytical tool rather than a synthetic interpretative product and raise additional questions that should be explored and confirmed by future studies.

5 CONCLUSIONS

The geomorphodynamic mapping significantly advanced our understanding of the mass movements triggered by the extreme 2009/2010 event in the Paraitinga Plateau. By integrating detailed morphological analyses with the interpretation of erosional and depositional evidence, we were able to not only distinguish between different landslide typologies but also identify features associated with processes such as debris flows, hyperconcentrated flows, and debris floods.

The link between debris flows and channel scouring, followed by deposition in debris lobes, underscores the importance of high-magnitude transport processes in recent landscape evolution. Evidence of scouring in steep channels, as well as the presence of complex deposits with varying degrees of sorting and granulometric organization, reveals a continuum of processes between hillslope and channel dynamics, with direct implications for landform evolution and sediment dynamics in humid tropical environments.

These findings reiterate the need for integrated approaches to characterize mass movements – ones that consider not only current features but also geomorphological evidence of past events. Such information is crucial for improving landslide inventories, understanding process recurrence and magnitude, and developing more effective geological risk management and mitigation strategies. Furthermore, the results highlight the relevance of geomorphology as a central tool in natural disaster analysis, particularly in high socioenvironmental vulnerability contexts such as southeastern Brazil.

Unlike conventional risk mapping approaches – which typically focus on slope susceptibility, stability thresholds, and factor of safety assessments – geomorphodynamic analyses emphasize the spatial and temporal evolution of landforms, offering a more comprehensive understanding of mass movement dynamics. This perspective contributes not only to the interpretation of past events but also to the anticipation of potential future scenarios, particularly in regions with limited historical records or technical monitoring. Therefore, the integration of geomorphological mapping constitutes a critical complement to risk-oriented strategies, enhancing both scientific understanding and practical responses to natural hazards.

Finally, it is important to note that this study represents a first approximation of geomorphodynamic mapping in the Paraitinga Plateau. The maps were applied as an analytical tool rather than as a synthetic interpretative product, and they raise additional questions regarding process recurrence, sediment dynamics, and landscape evolution that should be further explored and validated in future research.

6 ACKNOWLEDGMENTS

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