A study case of a rockfall event in a geomorphosite from the Corumbataí Geopark Project, state of São Paulo, Brazil

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ABSTRACT: Many geomorphosites are under a natural risk scenario, as those from the Corumbataí Geopark Project, state of São Paulo, Brazil. This paper shows a rock fall event in the Camelo Hill geomorphosite. The area is used by walkers, climbers, mountaineers and civilians in general as a touristic spot in the Geopark domain. In October 2022, a boulder fell from the cliff and destroyed many trees along the slope until stopping at the dirt road used for local tourism. Herein, we have identified the rock detachment source area using field investigations and UAV mapping; an inventory of rockfalls was created and compared to the recent event. Characteristics of the rock travel distance were raised to guide the local authorities. This study also presents a new kind of source area, a rock fall conceptual model for tropical conditions, created to elucidate the mass movement to civilians.

Keywords: Rock fall, drone, conceptual model, travel distance, geomorphosite, geopark.

1 INTRODUCTION

Several conceptual models are found in the literature to elucidate gravitational mass movements (landslides). Varnes (1978) presented around thirty types. Cruden & Varnes (1996) continued developing the classification. Hungr et al. (2014) made an update from previous studies, introduced relevant concepts related to failures and added 3 landslide-type keywords. In general, totaling at least 32 models for geological phenomena recognition and description.

For rock falls and correlated processes, since the 1960s, the Ritchie model (Ritchie 1963) has served as a basis to the phenomenon characterization for engineering purposes. It shows the geometric contours related to free fall, rebound, rolling and sliding (Figure 1a). Varnes (1978) presents around three models for this type of gravitational process, once other typologies can transform into a rock falling down a hill, such as topple and/or block slide (Figure 1b). In a broader perspective, some models show ruptures that are involved in the detachment of rock blocks from their source areas, and, as Ritchie model, subsequent propagation down slope.

In Brazil, Augusto Filho (1992) simplified Varnes classification into four main groups of gravitational mass movements: creep, landslides, rock falls and flows. The gravitational process can be reclassified based on its geometry, for example: shallow and rotational landslides. The simplified classification (i.e., conceptual models) makes part of the guidelines for susceptibility mapping defined by the Technological Research Institute (IPT) (Bitar 2014). And, currently, applied by the Geological Survey of Brazil in cities under summer natural disasters (Fernandes et al. 2018).

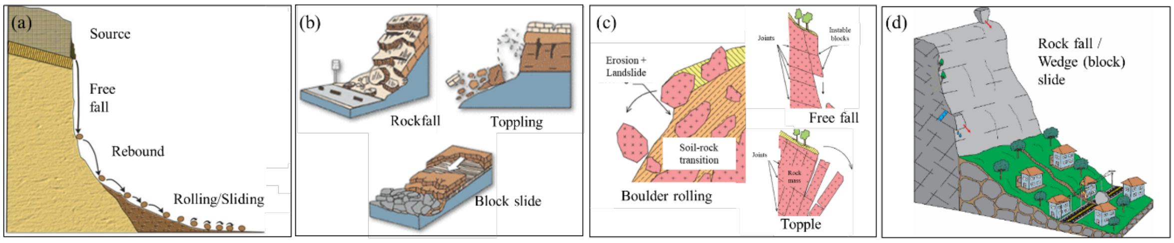

Figure 1. Rock fall conceptual models according to (a) Richie (1963), (b) Varnes (1978), (c) Augusto Filho (1992) and (d) Fernandes et al. (2018).

Four conceptual models are presented for rock falls and correlated process in Augusto Filho (1992). For each one, processes involved in the block detachment are indicated, such as: the alterability, the erosion and landslides in weathering profile for blocks rolling, and discontinuity sets for toppling and free fall (Figure 1c). But, controversially, the Geological Survey of Brazil, through the Program for Strengthening the National Strategy for Integrated Management of Natural Disasters, Project Gides (Fernandes et al. 2018), seems to use only one model for rock fall risk analysis (Figure 1d). In this dubious context of Brazilian guidelines, rock fall events and correlated typologies were reported in tourist destinations and their accesses throughout the national territory (e.g., Praia da Pipa, BR 277, Capitólio Canyons geosite, etc.) which partially, exposes the need for continuous studies and focusing on recreation areas, such as: parks and geoparks, and their accesses, such as: roads, highways, trails and rest areas, etc.

Here, a rock fall event was recorded in October 2022 at the Camelo Hill, a geomorphosite of the Corumbataí Geopark Project, state of São Paulo, Brazil. We mapped the rock detachment source area using field investigations and UAV mapping before and after the event. An inventory of rock falls was created and compared to the records. The inventory of sandstone and basalt blocks were used to estimate the rock travel distance, aiming to guide local authorities in an emergency land use management. Through this task, a new kind of rock fall source area appeared to be harmful as cliffs formations. Then a conceptual model was constructed to elucidate the mass movement to civilians and to help the development of rock fall analysis under tropical conditions.

2 ROCK FALL MAPPING IN THE CORUMBATAÍ GEOPARK PROJECT

The Corumbataí Geopark Project is a former plan of the São Paulo state geoscientist community. It is located between the geomorphological provinces, Peripheral depression and Cuestas. The second comprises a string of sandstone and basalt escarpments that divide the state of São Paulo into the Paraná Basin region (Abreu & Augusto Filho 2012). Many geomorphosites in this domain are under a natural risk scenario, as the Camelo Hill geomorphosite in the municipality of Analândia, where the rock fall was recorded in October 2022. This geosite has a peculiar natural aspect, a witness of escarpment retreat, whose scenic exuberance was classified as having strong touristic and educational appeals (Kolya 2019 and Garcia & Pinato 2021) (Figure 2a-c).

Civilians access the geosite by a dirt road and park their cars nearby to enjoy viewpoints, trails and leisure areas for picnics, etc. In this place, the Botucatu formation sandstone emerges as protuberant cliffs with 30 - 60 meters high (Figure 2 d), a rock feature easily recognized by literature conceptual models (Figure 1). However, among the Paraná Basin sedimentary rocks in the municipality of Analândia, Serra Geral formation rocks appear, beyond lower cliffs, in the form of domes and small hills related to sill and dike intrusions.

Due to strong erosion in initial layers of the weathering profile, hexagonal prismatic blocks emerge. This rock feature is usually characterized as block exhumation. Many basalt blocks are prone to rolling down slope, and for this currently land use, it may configurate a source area with a harmful effect for civilians on trails or in leisure time (Figure 2e).

In a technical perspective, block exhumation is not usually field mapped by classifications available in the literature, i.e., a rock feature not considered as a potential source area of rock falls. According to Perzl et al. (2018), around 25% rockfalls in Austria derived from sources without a cliff edge. Thus, based on current activities developed in the Camelo Hill geosite, it raised the need to elucidate these geology aspects to civil authorities aiming to avoid damage over the geosite users. The exhumed block conceptual model was elaborated from Goodman & Bray (1976), and Augusto Filho (1992) models (Figure 1c). It aims to highlight that a landslide is not vital, instead the vegetation (when present), soil erosion, creeping and lateral spreading process could play a key role on block toppling or sliding, as well as human activities, in a block detachment (Figure 2f).

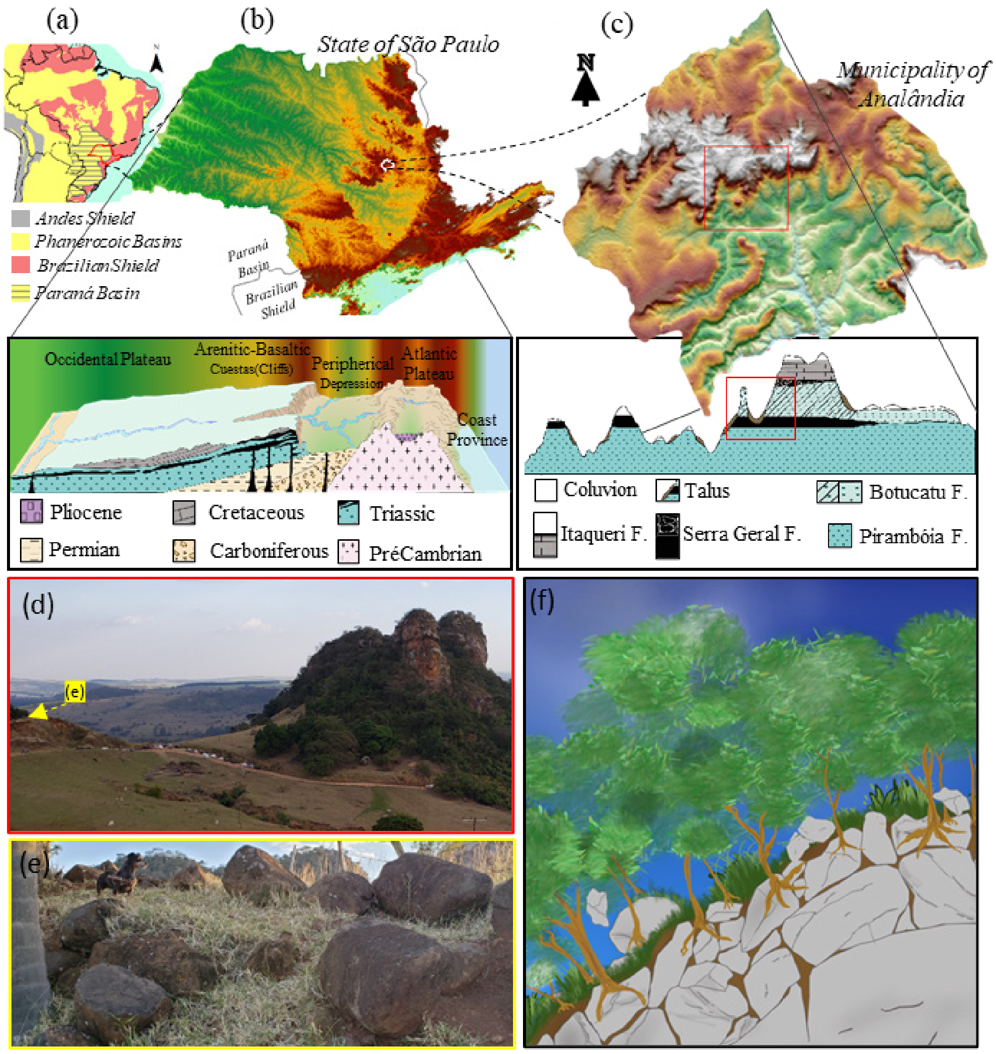

Figure 2. Study site: (a) Brazilian geological provinces, (b) digital elevation model for the state of São Paulo, (c) study site in the municipality of Analândia, (d) Camelo Hill geomorphosite panorama view, (e) basalt blocks and (f) a general conceptual model for block exhumation, an area prone to block rolling. (Note: geological sections modified from De Abreu 2012).

3 THE ROCK-TRAVEL DISTANCE

UAV equipped with antenna PPK® and supported by a RTK geodesic antenna were used to carry out flights in August 2021 and November 2022. Geotagged photos were processed in Agisoft®, a photogrammetric software. Orthophotos and digital terrain model (DTM) were elaborated with 0.2- and 1-meter resolution, respectively. The georeferenced products served to compare the recent event scar with older block deposits as well as served for updating the local SIG database. We created the first rock falls inventory for Cuestas geomorphological province in Brazil (Monticelli in press).

Then, the farthest sandstone and basalt blocks were checked by field investigations to correctly identify the most probable rock trajectory and its profile. The blocks run-out were calculated by empirical approaches, (α) reach angle and (β) shadow angle (Corominas et al. 1990; Evans & Hungr 1993; Wieczorek et al. 2008; Copons et al. 2009; Jaboyedoff & Labiouse 2011). Basically, the two methods are developed in topographic profiles extracted from DTM.

More than 780 blocks were surveyed, totaling around five thousand cubic meters. Sandstone blocks represented over 95% rock fall deposit, meanwhile the basalt blocks, less than 5%. Particularly for the recent event, 240 m^3 detached from the cliff, and immediately after the first impact with the talus body at the escarpment base, a rock splash in a semi-radially format happened. It was counted five block trajectories with 54.2 m^3, emanating from the impact zone. These blocks rolled down the slope throughout the trees, some of them stopped in the bush jungle (cerrado), but three boulders with 22.5 m^3 reached the dirt road (Figure 3a). Only 9% volume of block detachment represented a hazard, the trees were responsible for stopping 13% volume, and the rock fragmentation in the first impact represented the major factor for energy dissipation. Also, the Brazilian bush jungle had a dissipation energy effect, but comparatively to coniferous and broadleaves trees (Dorren et al. 2007), its value still completely unknown.

Concerning the DTM data, critical attention is needed to raster resolution when rock falls processes are under analysis. In the Cuestas province, UAV products were extremely useful to properly collect the terrain surface characteristics (Figure 3a). In contrast, the raw Alos Palsar data, used for risk mapping in Brazil, could not properly characterize the cliff formation (Figure 3b). Besides that, for empirical methods, it may be quite difficult to identify the talus apex for the shadow angle calculation. Roughly, only the reach angle may be applied for the Alos Palsar raster.

The profile extracted for the sandstone cliff did not produce well-formed escarpment. Also, there was no significant difference in reach angles between the event and the farthest boulder presented in the inventory (Figure 3b). Moreover, its value is out of the usual range reported in literature. For basalt exhumation, values were extremely low. In fact, a 12.5-meter resolution raster could not proper extract the topographic surface characteristics for the application of empirical methods related to rock fall analysis in the Cuestas Province in the state of São Paulo. It may overestimate the travel-distance creating misleading results.

Depending on characteristics involved in the rock fall process, reach angles may vary between 38 and 52°, while shadow angles, between 28° and 32° (Corominas et al. 1990; Evans & Hungr 1993; Wieczorek et al. 2008; Copons et al. 2009; Jaboyedoff & Labiouse, 2011). Concerning UAV data, for the sandstone cliff, the inventory farthest boulder showed angles within the literature range, while for the rock fall event, only the shadow angle was out of it (Figure 3a). In parts, these results reinforce that it is necessary to make an inventory to analyze an isolated case of rock fall. Taking isolated cases into account may underestimate the travel distance covered, especially for empirical methods.

For basalt block exhumation, it was expected that the reach angle value (23.3°) would be out of the literature range (Figure 3b), since the empirical methods applied were idealized for cliff formations. Compared to the sandstone cliff, what calls attention is the difference between reach angles, around 15° less. Usually, low values of reach and shadow angles are related to a greater rock travel-distance in cliff formations. However, it is not the case for the Camelo Hill geomorphosite, block exhumation is located in a gentle slope, and depending on the cross-section analyzed, it can produce an intercept close to the source area, given smaller travel-distances compared to the sandstone cliff.

Major sandstone blocks (100-0.1m^3) can travel up to 200 m from the source area, while basalt blocks (< 1m^3) can travel less than 100 m. Its consensual that the lithotype and joint sets play a fundamental role in the shape of boulders detached from the source area, as the block falling down the slope hits the topography many times, depending on the incident angle, and may gain momentum energy and velocity, or lose them (Wagner et al. 2020). Moreover, the highly dense vegetation can still produce dissipation effects on the block, reducing its propagation (Dorren et al. 2007). The basalt boulder outcrops like a prismatic hexagonal shaped, is rounded by weathering, and its source and propagation areas are covered with grass, meanwhile, sandstone blocks are roughly cubic, with higher gravitational potential. Its propagation zone is a talus body sloped with partial forest vegetation. These are aspects that also have influenced the travel distance in the Camelo Hill geomorphosite. Simulations were planned, and it would expect to shed a light on these topics (Monticelli in press).

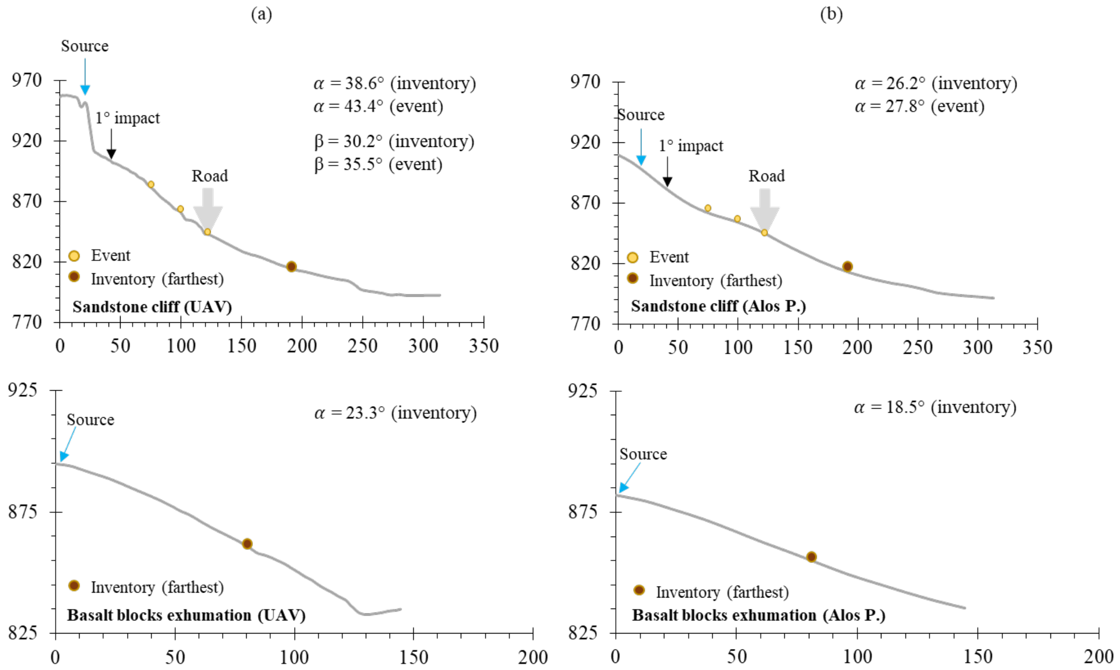

Figure 3. Profiles showing rock-travel distance measurements in a sandstone cliff and basalt block exhumation with (a) UAV DTM and (b) Alos Palsar DTM. (α: reach angle, β: shadow angle).

4 CONCLUSION

In the Camelo Hill geomorphosite domain, belonging to the Corumbataí Geopark Project in the state of São Paulo, Brazil, we mapped two kinds of rock fall source areas (i.e, two conceptual models), a rock cliff and a rock block exhumation. Both may produce blocks with travel-distances between 200 and 100 meters, respectively. Simple approaches were conducted to measure block travel distance, the results stressed three points for local authorities: i) the importance of closing road access especially on summer rainy days, once it is under the reach or shadow zones, a hazard area; ii) the need for deeper studies covering geotechnical solutions and projects (e.g., barriers, road path changes); and iii) the need for establishing guidelines for a proper land use in areas for recreation, leisure and outdoor activities, aiming at risk prevention for geosite users.

In a general perspective, empirical methods can be used as simple procedures for delimiting hazard areas in the Corumbataí Geopark Project domain, as well as in the Paraná Basin. For updating Brazilian risk analysis guidelines, we can summarize three relevant topics: i) recognition of dangerous source areas depending on the use of conceptual models (i.e., landslide-type keywords). Block exhumation may be a source area for boulder rolling and it has to be mapped; ii) the use of UAV products (i.e, dense clouds, orthophotos, and high resolution DTM) should be a rule for susceptibility, hazard and risk analysis for municipalities prone to summer disasters in Brazil; iii) raw Alos Palsar data are not recommended for rock fall (and correlated processes) analysis if used for application of empirical methods (geometric), a raster post-processing may be required to overcome limitations pointed out herein.

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