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Debris-flow occurrence in granite landscape in south-southeast Brazil

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Abstract

The widespread occurrence of Granite Massif landscapes in the Serra do Mar Range, south-southeast Brazil, is also connected with high incidence of debris-flow events. In recent years, the debris-flow events in Serra do Mar Range have caused many deaths and great infraestructure losses. These events occur in high gradient watersheds covered by a thin regolith. This paper intends to analyse the connection between debris-flows-prone watersheds and granitic regolith. These rocks, quite abundant along the mountain chain, are resistant to weathering, and present large vertical gradients. In addition, they generate porous and cohesive regoliths, which support infiltration to the rain water. When saturated, these regoliths can generate shallow landslides, which can liquefy and flow along channels, depositing this material in colluvial fans in piedmont areas. From this point of view, we analysed two watersheds in a granitic terrain, both of similar size and that recently suffered catastrophic events of debris-flows: 1) the Guarda-Mão creek watershed in Itaoca region, which had an intense meteorological event in January 2014; 2) the Gigante creek watershed, in Serra da Prata, which suffered an event with nucleation of debris-flows in March 2011. Both basins present themselves a thin regolith and rock outcrops in higher areas, grading to thicker regoliths and colluvium deposits in the foothills, where the gravels are deposited in the colluvionar fan. Both basins have soil densities (γs) between 2.4 and 2.7 g/cm³, reflecting the presence of primary (quartz, feldspar) and secondary minerals (illite, kaolinite, montmorillonite and iron oxides). Both materials are porous (32% to 44%), with plasticity indices (PI) between 1% and 17%. Most materials have low plasticity, although the Gigante creek watershed is even lower, between 1 and 5%. The analysed watersheds are typical of granite/granitoid terrains in Serra do Mar Range, and present great similarity. Further studies should consider the morphometric characteristics of these basins, the mechanisms of rupture and the regoliths liquefaction processes, besides modelling the deposition in fan areas. This understanding could bring improvements to disaster risk management strategies throughout the Serra do Mar region.

Keywords: debris-flow, granitic regolith, geotechnical properties

1. Introduction

Serra do Mar is mountainous landscape associated with escarpments fault that span for over 1,500km alongside the Brazilian south and south-eastern coast (**Fig. 1**), reaching an elevation of 2,000 m" (Vieira and Gramani, 2015). Most of that landscape is associated with granitic and/or gneissic rocks substrate. Because of these gradients, topography and slope materials, the Serra do Mar Range often presents flow-type slides, especially debris-flows, (Vieira and Gramani, 2015; Fernandes et al., 2004; Kanji et al., 2017), causing serious damages and loss of lives (**Table 1).**In recent years, a series of catastrophic events occurred throughout the region, forced the Brazilian government to change the legislation, besides promoting a more integrated disaster risk approach. Meanwhile this approach was progressing,

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turned it out evident the relationships among debris-flow, Serra do Mar watersheds and granitic/gneissic regolith. Based on estimates, more than half of the debris-flows in the Serra do Mar range occur in granitoid or orthogneisses rocks of the same composition.

The abundant Archaean to Cambrian granitic and granitoid rock bodies in Serra do Mar Range are mostly situated in the hilltops, given their resistance to weathering (Modenesi-Gaultieri et al., 2002; Hiruma et al., 2008). The resultant granite-derived regolith has a generally silty-clayey to sandy-silty composition, with the common development of blocks (corestones) in deeper zones (Picanço et al. 2019; Scott and Pain, 2009). Understand these relationships could improve the mapping methods now in progress.

However, these connections are not easily perceived. Most of the watershed geomorphological and geotechnical data are geographically disperse and difficult to gather. To start the comprehension of these relationships between granitoid terrains and debris-flows in Serra do Mar range, we proposed the comparative discussion of two typical debris-flow occurrence areas.

The chosen areas where occurred flow slide events consist of sub-basins with more than 90% in granite substrate: the Gigante creek watershed in the Serra da Prata region (March/2011) and the Guarda-Mão creek watershed near the Itaoca town (January/2014) (**Fig. 1**).

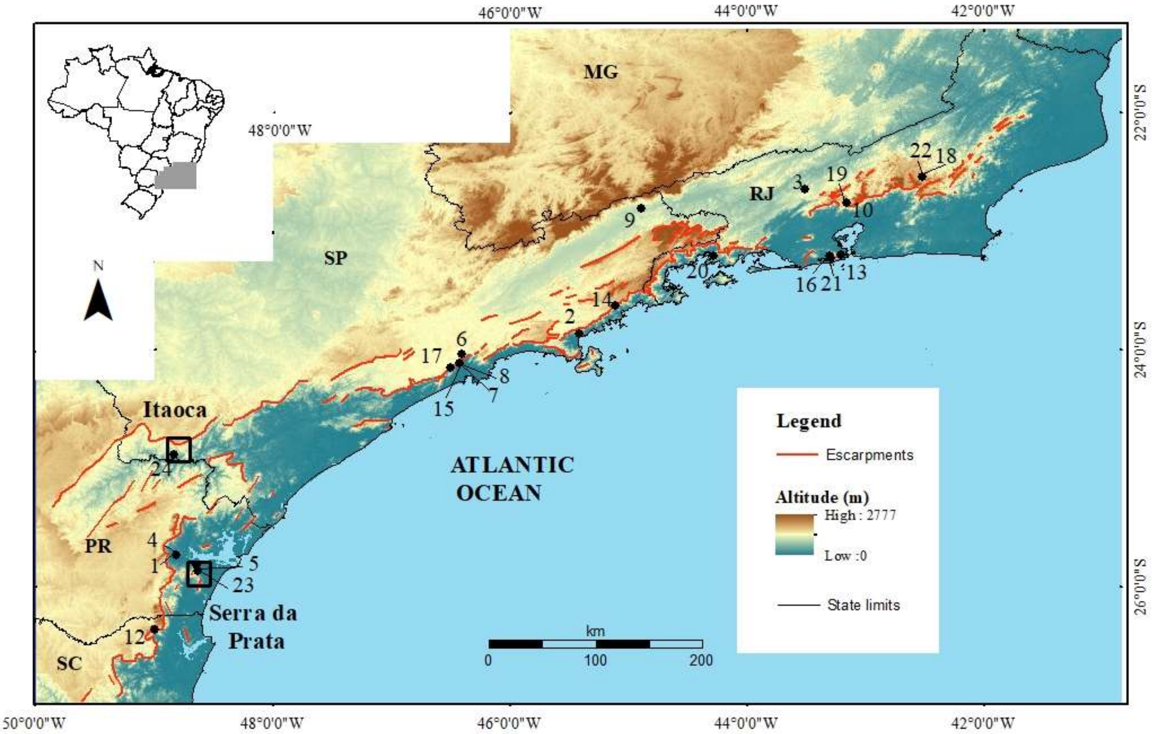


Fig. 1 - The Serra do Mar Range in south-southeast Brazil, showing the main escarpments. The investigated areas, Itaoca and Serra da Prata are localized in the map. The filled circles are related to main events associated to debris-flows recorded in the literature. Each number corresponds to events displayed in Table 1. SC: Santa Catarina State; PR: Paraná State; SP: São Paulo State; MG: Minas Gerais State, and RJ: Rio de Janeiro State.

Table 1. Selected debris-flow occurrences in the Serra do Mar range.

N°	Year	Area, State	(Deceased People) and material losses	Lithotype	Ref.
1	1888	Morretes (PR)	(8) Floods and landslides	Granite, gneiss, schists	1
2	1967	Caraguatatuba (SP)	(120) 400 houses and highways destroyed,	Migmatite, granite-gneiss, mafic rocks	2
3	1967	Serra das Araras (RJ)	(>1,200) > 100 houses destroyed, highways damaged, destruction of hydroelectric plant	N/d	2
4	1969	Morretes (PR)	Floods and landslide	Granite, gneiss, schists	1
5	1975	Paranaguá	(3) Debris-flow occurence	Granite, gneiss, schists	1
6	1975	Grota Funda (SP)	Damage to railway pillars	Gneiss	2
7	1976	Cubatão (SP)	N/d	Gneiss, granite, migmatite	2
8	1976	Cubatão (SP)	N/d	Gneiss, granite, migmatite	2
9	1986	Lavrinhas (SP)	(11) houses, bridges and highways destroyed	N/d	2
10	1988	Petropolis	(171) 5,000 displaced, 1,100 houses interdicted	Granite, gneiss, migmatite, schist, quartzite marble	2
11	1994	Cubatão (SP)	N/d	Gneiss, granite, migmatite	2
12	1995	Quiriri (SC)	Houses destroyed, higway interdicted	Granite, gneiss, schists	1
13	1996	Quitite/Papagaio (RJ)	(62) 200 houses destroyed	Gneiss, granite, tonalites, quartzite	2
14	1996	Ubatuba (SP)	Highway damaged, need for slope stabilization, water capture facility damaged	Schist, filonite/migmatite gneiss, foliated granite	2
15	1996	Cubatão (SP)	N/d	Gneiss, granite, migmatite	2
16	1996	Soberbo Highways, RJ	N/d	Gneiss, migmatite, granite	2
17	1999	Via Anchieta Km 42 (SP)	200 m of affected road, traffic stopped for several weeks, water capture facility affected	N/d	2
18	2001	Rio de Janeiro, Petropolis (RJ)	(40) 164 wounded people	N/d	2
19	2002	Petropolis (RJ)	(88) Houses destroyed	Granite, gneiss, migmatite, schist, quartzite, marble	2
20	2010	Angra dos Reis (RJ)	(53) 800 displaced people, houses destroyed	N/d	2
21	2010	Rio de Janeiro (RJ)	(253), 1,410 displaced people, and 338 dislodged	N/d	2
22	2011	Nova Friburgo (RJ)	(772) >300 disapeared, genereralized destruction	Granite, gneiss, schists	2
23	2011	Serra da Prata (PR)	(3) 221 wounded, 33 dislodged, highway interrupted, houses and crops destroyed	Granite, gneiss, schists	3
24	2014	Itaoca (SP)	(27) 3 disapeared, houses destroyed	Granite, quartzite	4

Data sources: 1) Picanço et al., 2017; 2) Vieira and Gramani, 2015; 3) Picanço and Nunes, 2013; 4) Brollo et al., 2015.
N/d: non-available data.

2. Regolith profiles

The Guarda-Mão creek watershed in Itaoca area (**Fig. 2a**) has substrate constituted by Proterozoic granites, with a small portion in the highest hilly area capped by fine quartzites. The basin height is 657 m. The granitic rock is grey to pink, medium to coarse granulometry, homogeneous and massive texture, locally with porphyritic crystals. The granite has some portions with hydrothermal alteration. It presents a thin residual regolith in the regions of steeper slopes. This regolith is deep in the less inclined slopes and associated with colluvial material. Fluvial material occurs near the slope base. Locally, sand and gravel strings could be observed, derived from older debris-flows and debris floods.

In the Serra da Prata area, the Gigante creek watershed (**Fig. 2b**) has the largest part of its substrate formed by Proterozoic granitic rocks, with small occurrences of filonites, schists, and Mesozoic basic dykes (Cury, 2008). The granites vary from grey coarse-grained, porphyritic granites with biotite and hornblende to pinkish, medium- to fine-grained equigranular granites. The coarser granites are more weathering resistant and consist the highest part of the mountains. The watershed gradient is 665 m high. The residual regolith is a thin veneer in the upper portions of the watershed, with thicknesses of up to 5 m in the lower areas. Based on their geological and geotechnical characteristics, the residual regoliths (**Tab 2)** were separated in a) collapsed saprolith; b) saprolith; and c) saprock, in the transition to bedrock (Scott and Pain, 2011). The transported material was referred as colluvium.

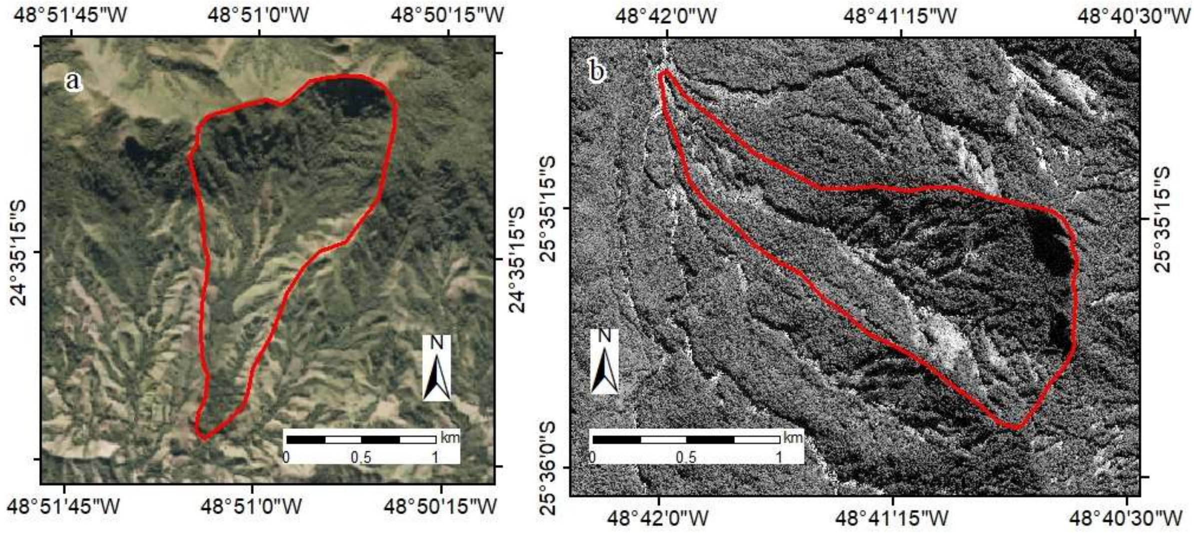


Fig. 2. (a) The Guarda-Mão creek watershed, in Itaoca region, before the debris-flow episode; (b) The Gigante creek watershed, in Serra da Prata area, with the main debris-flow zone areas.

The analysed regoliths in Guarda-mão creek watershed shows a sandier profile **(Fig. 3a)** than the regoliths from Serra da Prata watersheds. On the other hand, the weathering profile in the Gigante creek watershed (**Fig. 3b**) begins with a clayey-silty texture (sample 106A in the **Fig. 3b**), while the least weathered materials in depth are silty-sandy (sample 106D in the **Fig. 3b**). The presence of blocks and boulders increases in the transition from saprolite to altered rock. Colluvium materials in the watershed are more common downstream. Regolith materials also increase their thickness downstream. The colluvium material in these areas is very similar to the collapsed saprolith/regolith intermediate material (sample 108 in the **Fig. 3a**). This is due to the transport processes, which mixture materials during the colluvium formation (King, 1996).

The Guarda-Mão watershed regolith has liquid limits data (LL) between 38 and 44% (**Tab. 2**), whereas plasticity indices (PI) values fall between 12.4 and 17.5%. Colluvium materials from Guarda-Mão watershed have PI values slightly higher than the PI values of saprolith data. The LL data for the Gigante creek range from 32 to 37%, while the PI values vary from 1.5 to 5.0 %. The data of the granitic saprolite and the associated colluvium in the Guarda-Mão watershed fall close to the line A (CL field) in the plasticity chart (**Fig. 4**) (Bain 1970; Casagrande, 1948). The saprolite and colluvial data of the Gigante creek watershed regolith plot in the ML field near the boundary of the CL-ML field.
A saprolite sample fell further in the MH field.

The Guarda-Mão porosity data values range from 46% at the upper quartile and 42% at the lower quartile (**Fig. 5a**). The mean is 44.55% and the median is 45%. An outlier reached 40%. Gigante creek watershed regolith samples have porosity between 35 and 41%, with a 42% at the upper quartile and 28% at the lower quartile (Silva, 2017). The mean is 37.6% and the median is 38.5%.

The soil density data (γ) for both watersheds overlaps between 2.4 and 2.77 g/cm^3. The Gigante creek watershed has γ values vary from 2.45 to 2.71 g/cm^3, with the upper quartile of 2.6 g/cm^3 and the lower quartile of 2.5 g/cm^3. The mean is 2.53 g/cm^3 and the median is 2.51 g/cm^3. The values of γ of the Guarda-Mão creek regolith are between 2.77 and 2.45 g/cm^3, with the upper quartile of 2.70 g/cm^3 and the lower quartile of 2.55 g/cm^3. The mean is 2.63 g/cm^3 and the median is 2.65 g/cm^3.

Table 2. Geotechnical data of selected samples in Guarda-Mão and Gigante watersheds.

sample	localization	material	Porosity (%)	γ_s (g/cm³)	LL (%)	PI (%)	ref
01-P10	Guarda-Mão watershed	collapsed saprolith	42	2.7	39.4	12.4	1
02-P10	Guarda-Mão watershed	saprolith	61	2.7	-	-	1
03-P11	Guarda-Mão watershed	collapsed saprolith	37	2.8	-	-	1
04-P11	Guarda-Mão watershed	saprolith	35	2.6	-	-	1
05-P12	Guarda-Mão watershed	collapsed saprolith	41	2.7	-	-	1
06-P12	Guarda-Mão watershed	colluvium	39	2.7	44.1	17.5	1
07-P12	Guarda-Mão watershed	saprolith	37	2.7	-	-	1
08-P36	Guarda-Mão watershed	colluvium	42	2.8	-	-	1
09-P17	Guarda-Mão watershed	collapsed saprolith	38	2.6	-	-	1
10-P19	Guarda-Mão watershed	collapsed saprolith	61	2.7	-	-	1
11-P15	Guarda-Mão watershed	collapsed saprolith	38	2.5	40.9	13.2	1
14-P20	Guarda-Mão watershed	Colluvium	31	2.6	42.7	14.4	1
15-P21	Guarda-Mão watershed	collapsed saprolith	31	2.5		-	1
16-P37	Guarda-Mão watershed	collapsed saprolith	28	2.4	38.7	13.1	1
PF 001	Gigante watershed	saprolith	45	2.5	34.6	4	2
PF 010	Gigante watershed	collapsed saprolith	46	2.5	24.4	1.5	2
PF 033	Gigante watershed	collapsed saprolith	46	2.5	26.9	1	2
PF 96 A	Gigante watershed	saprolith	42	2.6			2
PF 96 B	Gigante watershed	saprolith	45	2.5			2
PF 97 B	Gigante watershed	saprolith	45	2.5			2
106 A	Gigante watershed	collapsed saprolith	46.0	2.5	46	4.86	3
106 B	Gigante watershed	saprolith	44.5	2.6	44.5		3
106 C	Gigante watershed	saprock	45.3	2.5	45.3		3
106 D	Gigante watershed	saprock	43.6	2.6	43.6		3
108	Gigante watershed	colluvium	45.8	2.5	45.8	4.38	3
109 A	Gigante watershed	collapsed saprolith	40.4	2.7	40.4	5.05	3
109 B	Gigante watershed	saprolith	45.0	2.5	45	4.87	3

References: 1) Silva, 2017; 2) Sturion et al., 2015; 3) Melo et al., 2015.

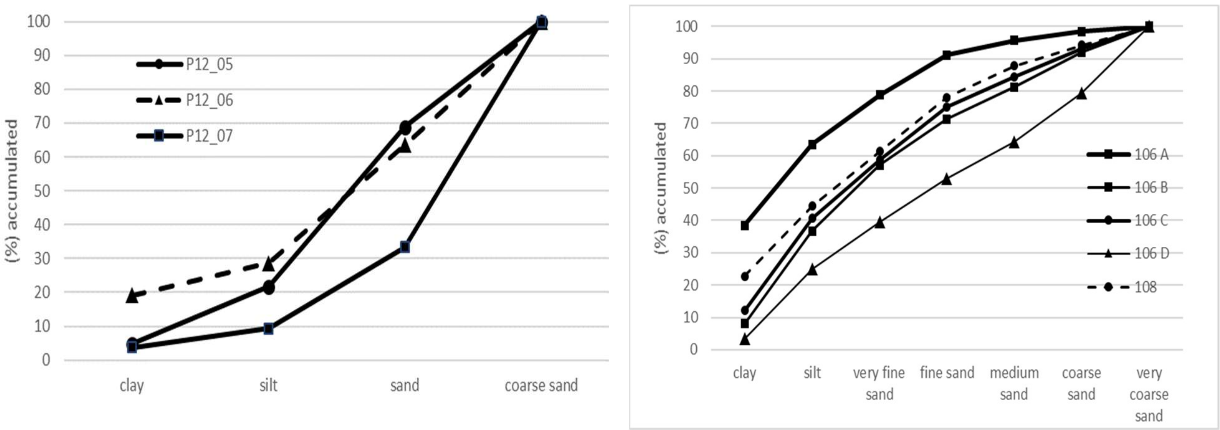
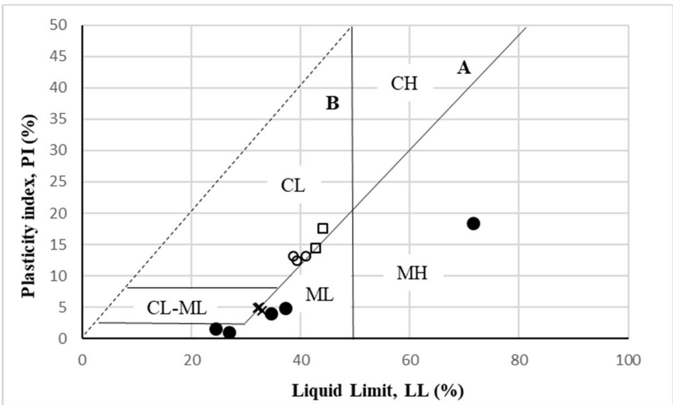


Fig. 3. (a) Granulometric chart of the regolitic profile of Guarda-Mão creek watershed; (b) Granulometric chart of the regolith profile in a landslip scar in the Gigante creek watershed. The samples 106 A-D are saprolite material and the sample 108 is a colluvium material.



Fig, 4. Plasticity chart from Guarda-Mão watershed saprolites (open circles) and colluvium (open boxes), and samples from Gigante watershed saprolites (filled circles) and colluvium (X). Plasticity chart: CL – low strength clays; CH: high strength clays; ML: low strength. A-line: PI=0.73LL-14.6, B-line=50%LL (Casagrande, 1948; Bain, 1970)

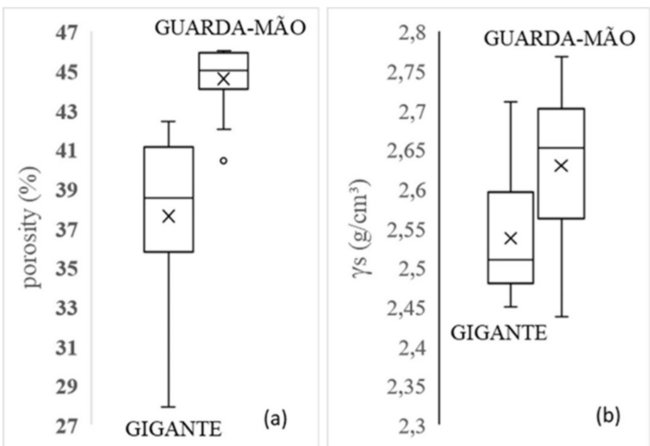


Fig. 5. (a) box and whisker plots of the porosity data; (b) box and whisker plots of the soil density data (γs).

3. Debris-flow events

The debris-flow in the Guarda-Mão watershed, São Paulo State, occurred on January 14th, 2014 after an intense rainfall episode, that recorded 200mm in 2 hours (Gramani and Arduin, 2015; Gramani and Martins, 2016). Shallow landslides began on the escarpment near the contact between granite and quartzite sequence (**Fig. 6a**). The slides on rock and soil had initially small volumes. However, the material must have increased due to small dams along the channel. The bursting of these dams raised the energy of the flow, which ran downstream eroding the channel margins and forming an extensive ravine (**Fig. 6b**). The Guarda-Mão creek ravine attain 50 meters wide and 15 meters high (**Fig. 6c**). The coarse material, with blocks up to 4m³, was deposited near the village (**Fig. 6d**) killing 23 people (Brollo et al., 2015).

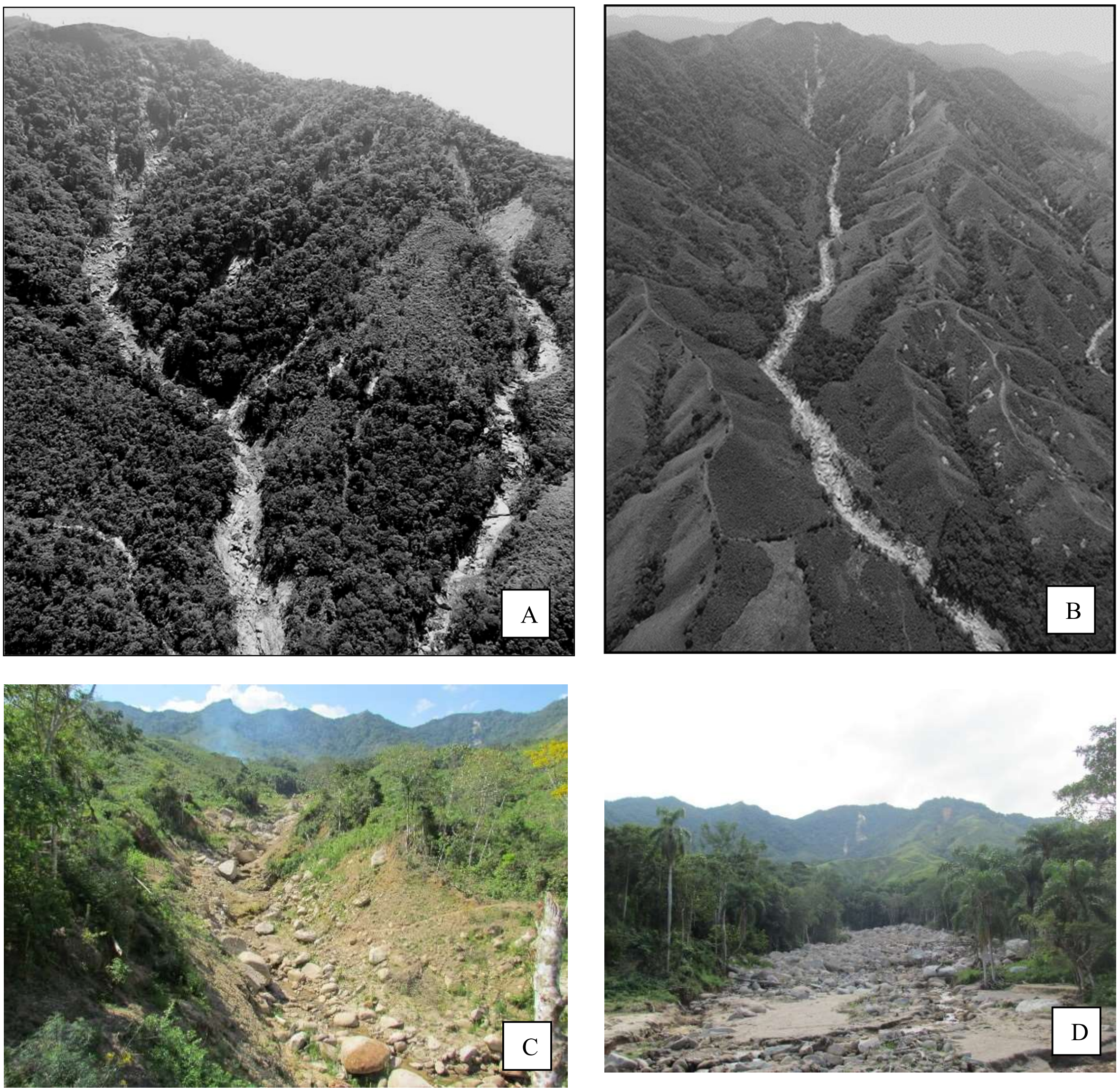


Fig. 6. (a) Panoramic view of Guarda-Mão creek. Observe the landslides scars and the severe river bank erosion. (b) View from the upper portion of the slopes of the Guarda-Mão stream basin. In this sector, predominated soil and rock slides with variable size and shape. (c) large ravine in debris-flow transport zone; (d) blocks and boulders in the deposit zone, Guarda-Mão creek.

The debris-flow of the Gigante creek occurred on March 11th, 2011 in Serra da Prata area, Paraná State. The 72h accumulated rain was 580 mm prior the onset (Picanço and Nunes, 2013). Almost all the ravines had the occurrence of debris-flows in the Serra da Prata western slope, where is situated the Gigante creek watershed. The scars were on soil and rock (**Fig. 7a**), and the initial ruptures occurred in the saturated regolith related to slope inflexion points.

The scars in the Gigante creek watershed are 2 to 3 meters deep, where the biggest ones on the ground reached an area of up to 44,000 m². According to residents' reports, there were natural dam occurrence along the thalweg, which increased the flow discharge and its downstream energy (Melo et al., 2015). The debris-flow energy was raised, and eroded the regolith deepening the ravines (**Fig. 7b, c**). The coarse material deposit and aligned blocks in lateral bars extended to the entire alluvial fan area (**Fig. 7d**).

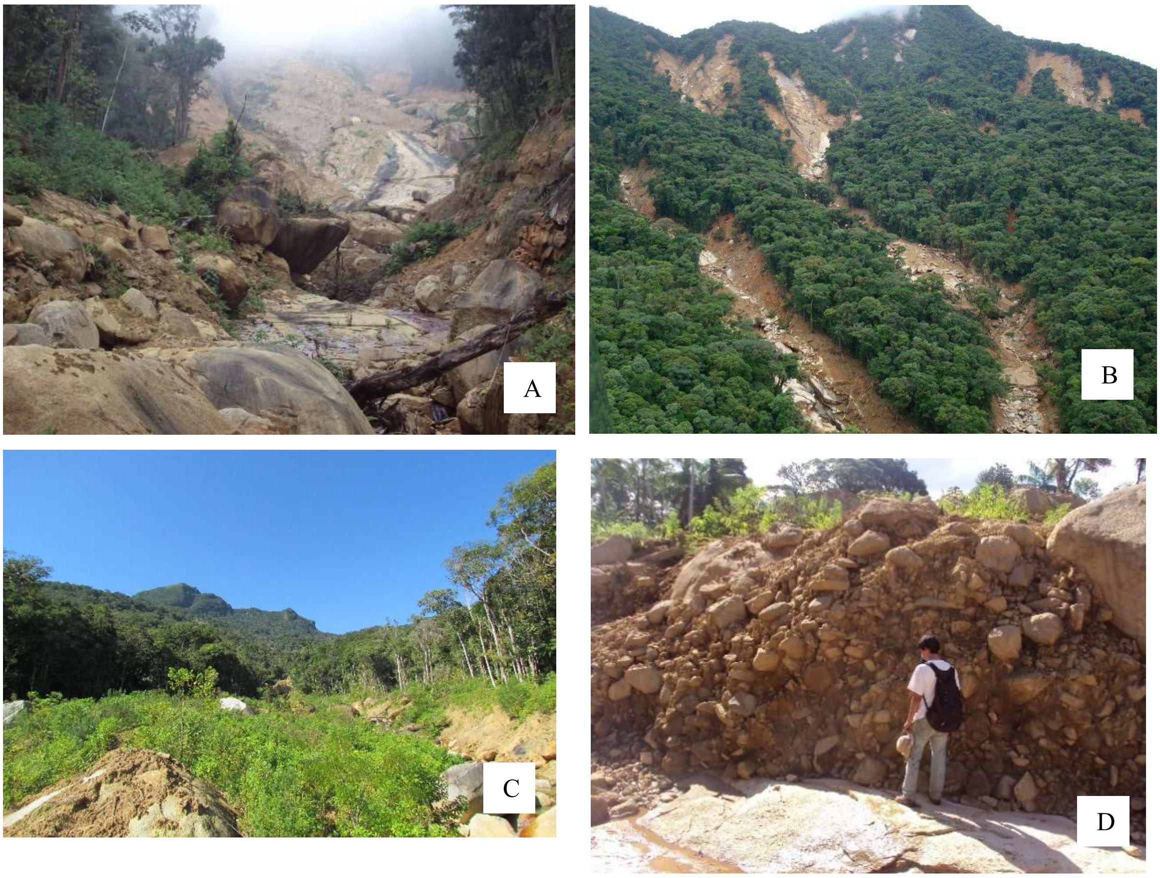


Fig. 7**.** (a) Scar in bedrock, Serra da Prata area; (b) Serra da Prata large scars and transport zone ravines, photo; Renato Lima; (c) Deposition zone, Gigante creek, in Serra da Prata area; (d) Debris-flow deposit, Serra da Prata, photo Flavio Sturion.

4. Discussion

The occurrence of debris-flows in Serra do Mar is not only related to granitic/gneissic substrate watersheds, but also there might be some relation with its typical landscape. Some of these links has a geomorphological signature, as basin shapes and vertical gradients. Other probable links come from geology and geotechnics that correspond to characteristics from parental rock and weathering profiles.

We could verify that both investigated areas have similar watershed shapes, gradients and lengths (**Fig. 2**). Not surprisingly, both debris-flows were similar in detritus type, block sizes and runout area (Sturion et al., 2015; Melo et al., 2015; Silva, 2017). Their analyses of morphometric parameters are quite analogous as well (Gramani and Martins, 2015; Picanço et al, 2016; Silva, op. cit.). Therefore, this kind of morphometric analyses could be useful to compare watersheds of similar features, but with no historical record events. This approach is necessary because the debris flow-prone watershed areas in Serra do Mar have low frequency of debris-flow occurrence (Picanço et al., 2017).

The frequency of these events is largely reliant on the presence of thick regolith in steep areas, and areas covered by dense vegetation, as both analysed watersheds. This condition could be attained in some areas when large meteorological events occur, generating the great episodes of debris-flow development, as shown in **Table 1**.

Areas with granitic substratum present a geomorphological evolution by shallow landslides rather than an erosion dominated runoff, as observed by Gaertner et al. (2004) in British Columbia. In contrast, the Gigante watershed samples present greater variation in terms of porosity than the samples of the Guarda-Mão watershed (**Fig. 5a**). While the former is lower and better distributed, the latter occur within a narrower range. In any case, the porosity differences are small and quite similar between the two areas.

The Gigante creek material presents low PI values. Some saprolite and colluvium samples are very close to the CL-ML field in the plasticity chart (**Fig. 3**). The LL values are very similar between the two areas. In the plasticity chart, the materials are very close to the beginning of the line A, and classified as CL or ML depending on its position relative to the line A.

The regolith of both areas have soil densities (γ) within the same range (**Fig. 5b**). The Gigante creek watershed regolith has an average density of 2.5 g/cm^3, close to the density of primary minerals, as quartz and feldspar, and newly formed minerals, such as illite, kaolinite and gibbsite. The soil density of the regolith material from the Guarda-Mão creek watershed may suggest the additional presence of heavier mineral phases, such as iron oxides.

The occurrence of large rock blocks in the regolith is linked to translational landslides involving soil and rock, as observed in the analysed watersheds (**Fig. 6, 7**). The development of small landslides of this type may, however, trigger the liquefaction of more sandy and porous materials downstream as colluvium and talus deposits. The material able to be entrained in debris-flow path is highly dependent of the regolith formation rate (Jakob, 2005). These deposits could be then incorporated in the channel and increase the material volume to be deposited downslope (Sassa and Wang, 2005).

The general characteristics of granitic regolith, such as granulometry, porosity and mineral content, are obviously present in both Guarda-Mão and Gigante watersheds. All these characteristics suggest that granitic watersheds of similar type could generate very similar pebbly debris-flows. However, this assumption is not very well constrained, and the data are not enough to sound deductions. More comprehensive analyses must be done to prevail upon these initial propositions.

5. CONCLUSIONS

The analyses of regolitic material of the two discussed watersheds are important for the evaluation of the flow type movements occurred in granitic terrains of Serra do Mar Range. The characteristics of this granite regolith generate porous and low PI soils susceptible to rupture and liquefaction. In this way, the granite regolith is susceptible to an evolution marked by the translational landslide's occurrence. The fluidification of these materials and their entrainment in the gullies could give rise to debris-flows.

Notwithstanding, this relationship between debris-flows in granite-derived regolith is still poorly understood. The morphometric characteristic of some granite-related basins should be more developed. There is still a need for further studies in the Serra do Mar area concerning the rupture mechanisms of these materials beyond the Wolle and Hachich (1989) model. It is important, for example, the inclusion of dense vegetation in slope stability calculations. The understand of the behavior of these granitic regolith in the soil liquefaction and in the channel entrainment processes is another interesting topic.

As high slope terrain is largely supported by granite and granitoid rocks *lato sensu* as granitic gneisses, the Brazilian mountain range is a place where this type of flow movements is common in extreme weather events. The study of the characteristics of these lands can yield developments for many useful information to reduce the vulnerability of the population that lives in these areas.

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