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Debris flows that affected Mocoa city, Colombia on March 31, 2017

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Abstract

On March 31, 2017 many landslides, rock falls and debris flows were triggered by high rainfall, which affected Mocoa city area, capital of Putumayo department in southern Colombia. These events killed more than 300 people, destroyed many houses, bridges, ways, water supplies facilities, the electric power plant and other infrastructure of Mocoa city. The greatest destruction was caused by debris flows generated at Taruca and Taruquita creeks and the Mulato and Sangoyaco rivers. This work is focused on the geo-environmental characteristics of these watersheds, also the debris flows causes are analyzed. The main conditioning factors, were the composition and quality of geological materials due to the cracking and weathering of the Mocoa Monzogranite; the high slope of the hillsides; the sloping of the middle and upper riverbed; the alluvial deposits in the riverbeds and colluvial deposits in riverbanks. The triggering factor was intense rainfall the day of the event in combination with precedent rainfalls, which generated damming and cascading failure of such clusters of landslide dams.

1 INTRODUCTION

Since the night March 31th to dawn of April 1st, 2017, many mass movements and fatal debris flows happened as a result of intense and prolonged rainfalls affecting Mocoa city, capital of Putumayo department, Colombia. The debris flows triggered at Taruca, Taruquita, San Antonio and El Carmen creeks and the Mulato and Sangoyaco rivers, caused 335 deads, and 398 wounded, according to official reports. Furthermore 7,484 families were affected, adding up 22,310 casualties, 48 neighborhoods and 1,461 homes were damaged, in accordance whit official information consolidated by the National Disaster Risk Management Unit (Unidad Nacional de Gestión de Riesgo de Desastre - UNGRD). The electric power plant of the Putumayo department was partially destroyed, besides two aqueducts, the water and gas supply systems and five bridges were destroyed.

The reconstruction plan of the National Government reaches US$3.5 million.

This paper shows the conditioning and triggering factors of the mass movements, especially debris flows that partially destroyed Mocoa city, based on studies made by the Colombian Geological Service.

2 LOCALIZATION

Mocoa city is located at Amazonian Foothill, north of Putumayo department, south of Colombia. The urban area belongs to the Mocoa River catchment, it´s located on its right bank, at west of Serranía de los Churumbelos. Four important drainages cross Mocoa city: (i) Mocoa River at east, flows from north to south; (ii) Mulato River at south and southeast, which flows from west to east; (iii) Sangoyaco River, flows southeastern-south parallel to Mulato River; (iv) Taruca and Taruquita creeks at north-northeast which flow to Sangoyaco River, with their effluent San Antonio and El Carmen creeks (Figure 1).

According to accounts of Mocoa city inhabitants, in June 1947 a debris flow at Mulato River damaged several houses, killed farm animals and destroyed crops in the rural area. The intense rainfall triggered many mass movements at upper basin hills generating temporary dams.

At December 1960 a debris flow at Taruca creek, happened as a result of intense and prolonged rainfall. The debris flow killed three people and farm animals on rural area. The topography of the area before and after the event was analyzed by aerial photographs of 1962. The geometry, mobilized volume, propagation path and deposit area is similar to 2017 event. Other debris flow events documented happened in 1972, 1989, 1994, 1995, 1997, 1998, 2010, 2011 and 2014 (SGC, 2017a).

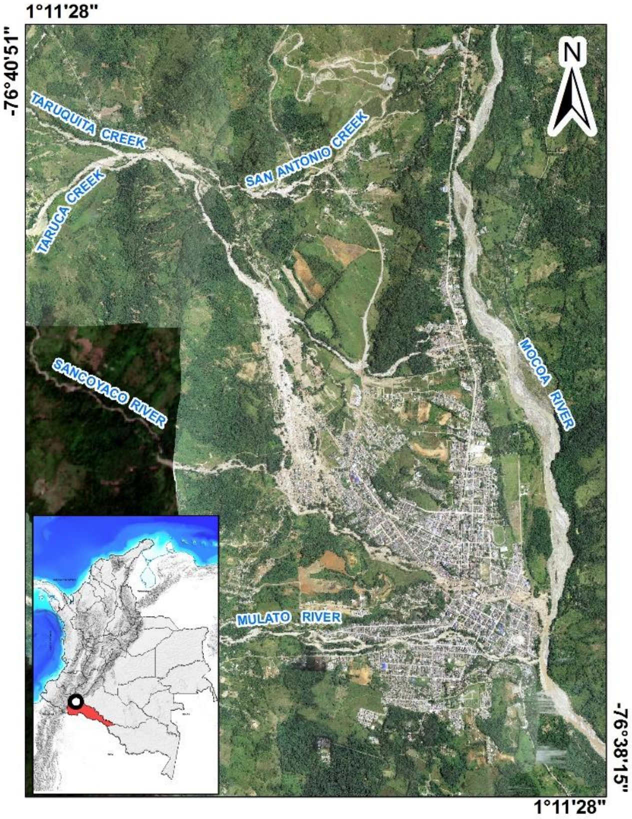

Figure 1. Location of the city of Mocoa.

3 CONDITIONING FACTORS

Debris flows are common in foothill areas due to a combination of favorable conditioning factors including basin geology and geomorphology and triggering factor like intense rainfall and occasionally earthquakes.

3.1 Geomorphology

Debris flows landforms exhibit classic morphology whit a distinct failure scarp, incised channel, channel levees, and toe deposits.

Mocoa city was settlement on ancient debris flows deposits preserved along channels of creeks and rivers, those have steep basins and V-shaped valleys. The deposits form fans *sensu stricto* if flow exceed the capacity of the channel and overflow or break it. On narrow and deeper channels, materials are deposited on slopes at different heights, showing different debris flows occurred historically. The Taruca and Taruquita creeks with their distributaries (San Antonio and El Carmen creeks) form a fan spanning approximately 15 km^2, as result of different debris flows events. At Mocoa city area four different deposits were identifying by their height to the riverbed, and the degree of weathering of boulders and state of conservation of matrix. Those deposits are classified as current fluvio-torrential flow (Ftac); undercurrent fluvio-torrential flow (Ftsa); old fluvio-torrential fan (Faan); and ancient fluvio-torrential fan (Faman) as shown in Figure 2.

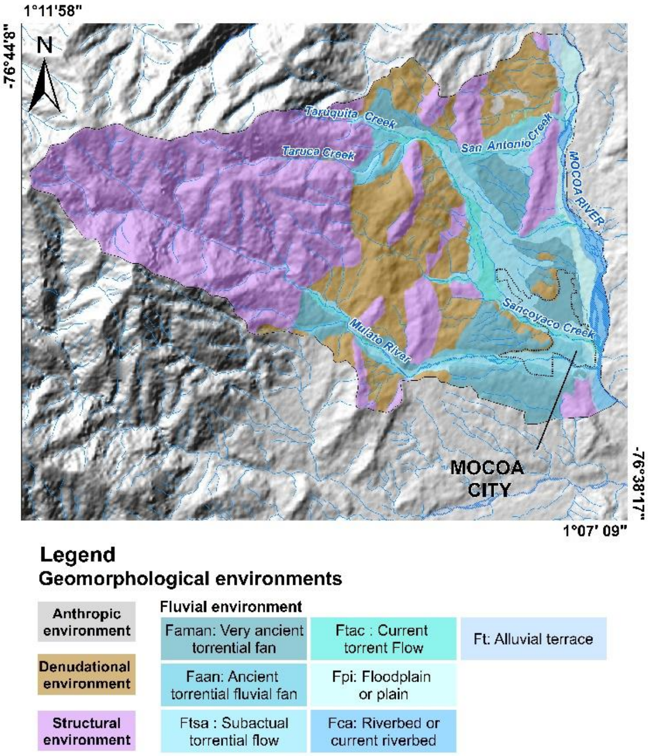

Figure 2. Geomorphology.

Taruca and Taruquita creeks deposits represent the highest torrentiality on area due to their thickness and extension characteristics. The Mulatos Chiquitos creek and the Mulatos River have a similar torrentiality with less deposits thickness (SGC, 2018).

The watersheds morphometric characteristics depict drainages development associated to tectonic activity. The results at hypsometric integral (HI) of Mulato and Sangoyaco rivers and Taruca Creek, shows the elevations through the basin area; the asymmetry factor (AF) shows tectonic tilts perpendicular to the main drain; the Stream Length-Gradient Index (SL) shows the relationship between the channel slope and the total length of channel; the elongation ratio (Er) represents the relationship between the shape of basin and a circle; and the relationship between the valley width and height and the sinuosity of the mountainous front (Smf) depicts the balance between erosive forces that cut into bays within the mountain front and tectonic forces that produce a straight front aligned to an active fault (SGC, 2018). These morphometric indices are useful to identify rapid tectonic deformation areas. They can be calculated as from topographic information, aerial photographs and satellite images and digital elevation models (DEM)s (Keller and Pinter, 2002, in Oviedo, 2015). The values obtained for the main basins are shown in Table 1.

Table 1. Morphometric Indices

Index	Name	Mulato River	Sancoyaco River	Taruca Creek
IH	Hypsometric Integral	0.49	0.47	0.44
AF	Asymmetry Factor	2.18	1.45	14.18
SL	Stream Length-Gradient Index	379	272	317
Er	Elongation ratio	0.47	0.43	0.42
Vf	Valley width / valley hight	0.2	0.31	0.76
Smf*	Sinuous of the mountain front	1.055	1.021	1.021

The geomorphological condition of these drainages is also characterized by steep slopes in the middle and upper basin and V-shaped section. The source of Taruquita creek is at 1,702 m.a.s.l, with a riverbed slope up to 45.5% (24.4°) as a result of the incision in fractured rock of Monzogranite. It flows from West to East at straight riverbed and width between 2 and 8 m. On the fan area it shows slight curvatures, with slopes of 14% (7.9°) and a widening channel (up to 25 m). The Taruquita creek fan is near 1.0 km length and 0.750 km wide shaped by fluvial-colluvial sediment levels from ancient landslides in upper basin.

The Taruca an Taruquita creeks longitudinal profiles have a convex-linear pattern with inflection zones at structural control sectors and by channel aggradation due to colluvial deposits from large landslides.

The mountain front at northwest, indicates the exhumation of the Mocoa Monzogranite as result of La Tebaida, El Carmen, Campucana and Mocoa Faults activity.

The La Tebaida-Mocoa Fault has post-Miocene activity, it has reverse-dextral movement with a great dip and associated short-cut faults with 30° dip and east vergence (Núñez, 2003). The weather conditions, high temperature and humidity whit intense periods of rainfall higher than 4000 mm/year (Robertson and Castiblanco, 2011), generate residual soils, which are re-mobilized and deposited downstream channel.

3.2 Geology and regional tectonics

Jurassic rocks outcrop in the area corresponding to an intrusive body known as the Mocoa Batholith or Mocoa Monzogranite (González & Núñez, 2001, in SGC, 2015). In fault contacts, upper Cretaceous rocks are observed that correspond to the Villeta and Rumiyaco formations of continental- and marine-shelf character with local marine intrusions, while the Paleogene-Neogene is represented by the Pepino Formation and the Orito Group of fluvial and coastal character, respectively (Figure 3). The Quaternary deposits are characterized by temporarily differentiable fluvio-torrential fans, colluviums and terrace deposits.

In this area, regional tectonics are controlled by the Algeciras-Garzón Fault System, the southern sector at Borde Llanero Fault system, that includes the Mocoa and Afiladores Faults and have tectonics of blocks lifted differentially along thrust and dextral-transcurrent fault planes (Robertson and Castiblanco, 2011).

Locally, the Mocoa-La Tebaida, Churumbelo, Cantayaco and Mulato Faults, along with La Taruca creek and Sangoyaco river paths, form a thrust faults system in N-S, NE-SW direction. According to stress field, this fault system has a regional compressive component likewise the regional tectonics of Cordillera Oriental foothills (SGC, 2017) (Figure 3).

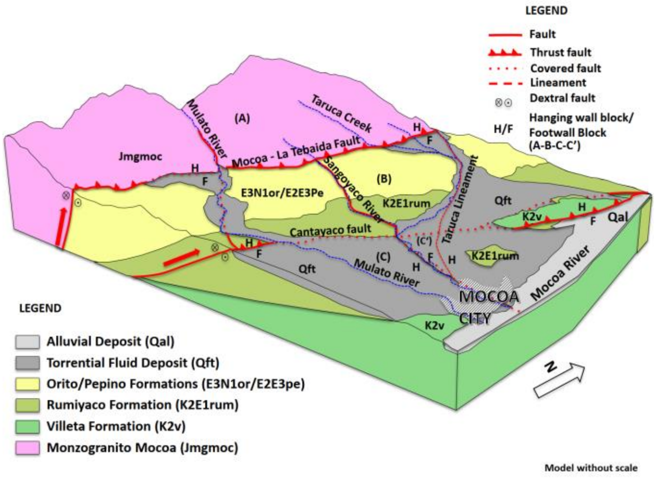

Figure 3. Regional and tectonic geology

3.3 Surficial geological units - UGS

Nine different soil-types and eleven rock types were identified as surficial geological units (UGS) at Mocoa city area.

The criteria to define rock units was the Rocky Massif quality, based on weathering degree (Dearman, 1979, in SGC, 2017), fracture index (Jv, ISRM, 1981, in QMS, 2017b) and Geological Strength Index (GSI, Marinos and Hoek, 2000, in QMS, 2017b), they were grouped according to predominant rock type (Table 2).

Table 2. Rock Units

Name	Acronym
Very Low Quality Rock of Orito Group Arcillolite	Rmbaro
Very Low Quality Rumiyaco Formation Arcillolite Rock	Rmbar
Very Low Quality Villeta Formation Lodolite Rock	Rmblv
Very Low Quality Mocoa Monzogranite Rock	Rmbmgm
Low Quality Orito Group Arcillolite Rock	Rbaro
Low Quality Pepino Formation, Middle Member Lodolite Rock	Rblpm
Low Quality Rumiyaco Formation Arcillolite Rock	Rbar
Low Quality Villeta Formation Lodolite Rock	Rblv
Intermediate Quality Pepino Formation Conglomerate, Upper Member Rock	Ricps
Intermediate Quality Pepino Formation Conglomerate Lower Member Rock	Ricpi
Intermediate Quality Mocoa Monzogranite Rock	Rimgm

Soil units were characterized according to their lithological and mineralogical composition, genesis, color, size and grain shape (texture), weathering of grains and matrix, consistency and relative density. Nine different types of transported soils were classified, corresponding to fluvio-torrential deposits of different ages and alluvial soils, especially associated with the Mocoa River and colluvial deposits (Table 3).

Table 3. Soil Units

Name	Acronym
Active Riverbed Transported Soil	Stfca
Anthropic Filling Transported Soil	Stalle
Alluvial Plain Transported Soil	Stflla
Colluvial Transported Soil	Stc
Current Fluvio-torrential Transported Soil	Stfac
Subcurrent Fluvio-torrential Transported Soil	Stfsac
Old Fluvio-torrential Fan Transported Soil	Staan
Ancient Fluvio-torrential Fan Transported Soil	Staman
Alluvial terrace Transported Soil	Sttal

4 MORPHODYNAMIC PROCESSES

4.1 Mass Movements

As a result of rainfall at Mulato and Sangoyaco rivers and the Taruca, Taruquita, San Antonio and El Carmen creeks basins, 276 mass movements were triggered as shown in Table 4.

Table 4. Mass movements that occurred on March 31, 2017

Sub-basin	Total Detonated	Contributed to the flow of debris	Volume of material contributed (m^3)
Taruca creek	158	65	126.128
Taruquita creek	21	19	61.703
Mulato River	132	47	34.009
Sangoyaco River	153	59	76.940
Total	276	190	298.780

In the Taruca creek basin, between its source and San Antonio sector, were triggered translational slides, debris flows and rock falls. The materials of these mass movements were transported downstream, producing accumulations 8 m in thickness at least and on Taruquita creek, occurred landslides in rock and residual soil. The material was transported downstream and generated fluvio-colluvial deposits up to 6 m thickness. On Sangoyaco River and affluents, at least three active mass movements were identified since 2002, which correspond to active soil and debris flows with deposits between 1 and 2 m thick. At source of Mulato River, there is an ancient retrogressive and widening landslide, reaching its greatest impact area at 2005, it was active at event time (SGC, 2017a).

As a result of the deposits generated by these mass movements, after the event at least five damming sites were recognized in the Taruquita creek basin and three in Taruca creek.

4.2 Bank deposition and erosion

The debris flows generated deposits that were classified according to boulders and matrix percentage (sand-sludge) and the textural variations in deposit zones, as follows:

- Type 0: Bottom and/or lateral scour zones in which material was not deposited significantly but remaining blocks can be found.
- Type I: Deposit zones of sandy-gravel material ± mud, which may have the presence of granitoid blocks lower than 5%.
- Type II: Deposit zones of sandy-gravelly material and sludge, with granitoid blocks between 5 and 25%.
- Type III: Deposit zones of sandy-gravelly material and sludge, with granitoid blocks between 25 and 50%.
- Type IV: Deposit zones of sandy-gravelly material and sludge, predominantly granitoid blocks more than 50%.

In upper Taruca creek basin, there was no significant material accumulation, scouring and arrangement of "relict" blocks predominated. Downstream the slope and channel direction change, causing scour in convex areas and at the same time shocks that leave relict blocks (Type I). Some remnants of the transported material remained at main flow path, categorized as Type II deposits, and generated lateral scour at pre-existing alluvial terraces. Type III and IV deposits were generated at approximately 400 m NW from the Junín electrical substation.

Throughout the Taruquita creek there are scouring, damming and deposition evidence that originated deposits categorized as type I and II, composed mainly by Mocoa monzogranite material.

The houses destruction was associated to bankment erosion the processes, generating the total or partial buildings collapse, while the human deaths are associated to transport and block deposition even though partial and sometimes total buildings destruction too.

5 TRIGGER

Debris flows are episodic events; they occur within a very short time, particularly with very heavy rainfall or by the rupture of permanent or temporary reservoirs that significantly increase the rivers or creeks flow.

Mocoa city area has a unimodal rainfall distribution. The rainiest months are May, June and July. Analyzing historical rainfall data reported by the Institute of Environmental Studies of Colombia, IDEAM, the rainfall of January and March 2017 exceeded the average monthly approximately 70%, while in February, they were below average comparing the multiyear monthly average for the months of January, February and March.

According to official data of IDEAM, the rainfall occurred on March 31, 2017 was 129.66 mm, and according to the analysis of historical rainfall data, tit´s the maximum daily rainfall in five years return period.

Based on the daily rainfall data, the 38 days cumulative precipitation was 600.6 mm which is exceeded more than once in a year, according exceedance values calculated per year. The accumulated rain saturated hillsides and triggering mass movements Taruca and Taruquita creeks basins.

Due to geological and geomorphological conditions at creeks and rivers basins crossing the Mocoa city area, mass movements occur in intense rainfall periods. The sediment produced in upper basins often does not inmediately migrate downstream, but is instead deposited at riverbed, producing channel aggradation. Mass movements can form steep dams and channel clogging by colluvial (ancient landslides) and fluvio-alluvial materials depositing. These materials generate debris flows such as the one occurred on March 31, 2017. Each damming represent potential energy accumulation, which is transformed into kinetic energy at breaking time, not only by increasing the flow velocity but also its capacity to re-mobilize boulders of riverbed (cf Zhou et al., 2013; Shi et al. al., 2015).

As already mentioned, at least five dam sites were recognized at Taruquita creek and three in Taruca creek. Due to the channels conditions, was estimated that reservoirs in the Taruca and Taruquita creeks was not up to 25,000 m^3; however, the sequential triggering of mass movements generated a large material volume and reached high speed in a short time (one hour) in short distance. The distance between sliding zone and the first dam is critical to understand the energetic transitions, i.e. the closer the dam is to sliding zone, the greater kinetic energy is dissipated by flow interaction with the dam base. (Zhou et al., 2013). the time

At first damming rupture, the granular material concentration increased and the transition from potential to kinetic energy made the flow to acquire speed and capacity to break the dams downstream, failing like dominoes generating debris flow.

6 ANALYSIS

According field observations, Taruquita creek generated at least three pulses that contributed large material volumes on Taruca creek riverbed. This material was later mobilized again by main flow at riverbed confluence of Taruca and Taruquita creeks.

Damming and obstructions observed in Taruquita creek indicate that scoured material lost its transport capability rapidly due to the low slope and the presence of obstructions, causing channel aggradation in Taruquita creek riverbed.

According to deposit thickness and flow height (obtained from exposed elements), variations at solids concentration can be estimated. Solid concentration of channel flow (water channel) is less than 10% vol (or up to 40%), at hyper concentrated flow is between 40 and 60% vol and at debris flows is > 60% (Costa and Schuster, 1988; Benvenuti and Martini, 2002; Pierson, 2005).

At Taruca and Taruquita creeks took place concentration and dilution processes which correspond to body transformations, i.e., the development by variations from laminar to turbulent flow or vice versa without loss of interstitial fluid, caused mainly by sediment addition as a product of bottom scour and lateral scour in riverbed and terraces, as well as slopes ruptures (Fisher, 1983; Benvenuti and Martini, 2002).

7 CONCLUSIONS

The destruction generated by debris flow occurred on March 31, 2017, was originated by materials involved at event, the largest blocks correspond to Mocoa Monzogranite, the sand- and clay-sized materials to Villeta and Rumiyaco formations and finally to old fluvio-torrential deposited at riverbeds, where had been built many houses.

The debris at Taruca and Taruquita creeks and the Mulato and Sangoyaco originated by their torrential regime as shown their geomorphological characteristics.

The weather conditions at Mocoa city area was the trigger of different mass movements occurred at basins of creeks and rivers going across urban area.

The study of debris flows must include geological, geomorphological and climatological conditions of basins as the same as historical evidence of ancient events.

Authorities must be aware of physical conditions of territories prone to occurrence of debris flows due to their destructive nature.

8 ACKNOWLEDGMENTS

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