Geomorphology of the SW flank of the Doña Juana Volcanic Complex, Colombia: interplay of fluvial, denudational, structural, and volcanic processes

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ABSTRACT

In the SW flank of the Doña Juana Volcanic Complex, Colombia, the dynamic geomorphic system responds to the complex interaction between volcanic, climatic, and tectonic driving forces, where the recent landscape (last ~20 years) is being shaped as a function of denudational processes. Despite the rapid rates of landforms development, the geomorphology of this area is poorly documented. To overcome the lack of information we mapped the area using a GEO SAR DEM and an Unmanned Aerial Vehicle based DEM. This paper presents two maps, a 1:25,000 scale map and a 1:5,000 detailed map of landforms along the Humadal Creek. Detailed categorization of landforms (at 1:5,000) allowed us to identify geomorphic processes in the village of Las Mesas and rural areas that triggered hazards for the communities. The morphologic evolution interpretation of this volcanic tropical area serves as a tool for future geohazard assessment in inhabited areas with important information gaps.

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1. Introduction

Northern Andean volcano-sedimentary basins are of complex nature. They are the result of the interaction between intense crustal deformation, tectonic uplift (Gutscher et al., 1999) and highly variable tropical climate (Montgomery et al., 2001). As a consequence, steep topographic profiles with volcano summits – as high as 4000 m.a.s.l. – develop next to deeply incised river valleys outflowing into inter-Andean lowlands of less than ~500 m a.s.l. (Francis & Wells, 1988; Thouret et al., 1990). Deep exhumation and climate forcing induce not only high precipitation but enhanced erosion-deposition rates (Mora et al., 2008). At these active volcano-tectonic settings, strato-volcanoes and lava-dome complexes are highly prone to experience dry to water-saturated mass movements during their geological life span (Komorowski et al., 1997; Quesada-Román et al., 2019; Siebert, 2002; van Wyk de Vries & Davies, 2015). Fast changes on the landscape are reached when denudation processes compete against episodic events of rapid sedimentation rates that disturb the hydrogeomorphic balance of local drainage basins (e.g. Major et al., 2016; Pierson & Major, 2014; Pulgarín et al., 2004). That is, when volcaniclastic material is added during volcanic edifice collapses or when the system is being destabilized either by seismicity and/or rainfall triggers (Dykes & Welford, 2007).

The Doña Juana Volcanic Complex (DJVC), as part of the SW-Colombian Andes (Figure 1(A,B)) is a good example of a highly dynamic geomorphic system under mean annual precipitation rates (MAP +/- 1σ) of ~2048.6 +/- 363.3 mm/yr (estimated from San Bernardo station, 1973–2020; ideam.gov.co), active tectonics, volcanism (Figure 1(C); Pardo et al., 2019), and well-developed vegetation (Cajas & Yama, 2008). On the regional scale (~50 km²), the landscape evolves from overlapped volcanic edifices (Figure 1(C)) towards a landform mosaic (Figure 1(D)). While climate and vegetation are major factors in the generation of new landforms over inter-eruptive and post-eruptive periods (Alcalá-Reygosa et al., 2016), volcanic eruptions as well as non-eruptive (secondary) mass-wasting processes (Jones et al., 2017) may instantaneously add, bury, and erode pre-existing landforms, favoring rapid hydrogeomorphic changes (Pardo et al., 2021). In the last ~20 years, the increasingly fast formation of new landforms has been observed after gravitational processes occurred during...
intense rain periods and seismic activity. Examples are the 2009 rockfall and the 2014 flow that changed the geomorphic system limited by the Resina River watershed (Figure 1(B)), causing hazards for local communities (Pulgarín et al., 2016).

In the DJVC, long-term evolution (>10^3 years) of landforms and overprinting (Figure 1(D)) has been recognized through geological mapping, tephrochronology, and radiometric dating (Nuñez, 2003; Pardo et al., 2019). Short-term landscape development (<10^2 years), on the other hand, is poorly documented due to the lack of information on a detailed scale. This research aims to categorize the geomorphological units at the scale of the Humadal Creek tributary in the upper Resina watershed (Figure 1(B–E)) in two new maps, 1:25,000 (Figure 2) and 1:5000 (Figure 3). The classification involves the morphogenetic environment, the main developing process, the landforms as the basic mapping unit, the landform maturity, and the material from which the landform is shaped. Special emphasis is made on gravitational processes along the Humadal Creek, where major recent

Figure 1. Study area. (A) Central map illustrating the location of the Doña Juana Volcanic complex (red point) and the regional boundaries between administrative departments in the SW side of Colombia. Nariño department (left bottom), Cauca department (left upper), and Putumayo department (right bottom), all in grey. (B) Resina River watershed in pink, and the drainage system of the watershed highlighted in blue. (C) Detailed photograph of Young Doña Juana edifice, pre-Montoso and the rock avalanche of 1936. (D) Detailed landforms of the SW developed from the eccentric cone remnant named Pre-Montoso. (E) 3D image and profile showing the differences in the altitude and slope along the Humadal Creek.
mass movements have occurred. In the last decades, a significant migration to urban and peri-urban areas has been observed due to the disturbances produced by these events in Las Mesas village and rural areas (Figure 1(B)). Migration has led, consequently, to decreased soil fertility, high farm input costs and decreased farm income (Pardo et al., 2021). Therefore, this map will contribute to understanding long-term and short-term landscape changes, fundamental as a baseline for developing geohazard assessments. The map would also provide significant support in risk-informed policy-making (e.g. territorial planning, land administration); mainly, in an area where volcanic, denudational, fluvial, and tectonic processes combine to shape a complex volcano tropical landscape.

2. Geological setting

The Doña Juana Volcanic Complex (DJVC), located in the Andean region of southwestern Colombia (Figure 1(A)), belongs to an active volcanic arc of the Northern Andes (Pardo et al., 2019). The DJVC
lies in angular unconformity on top of the Late Cretaceous polymetamorphic basement of the Quebrada-grande Complex (Nivia et al., 2006). An $^{40}$Ar/$^{39}$Ar age of $\sim 1125.4 \pm 4.4$ ka, indicates that the calc-alkaline dacitic magmatic system was already established (Pardo et al., 2019), when the fill of the basin took place. Several eruptions covered a paleotopography defined between the Silvia-Pijao and Tablón faults to the ESE, and the San Jerónimo fault to the WNW (Pardo et al., 2019). During the Quaternary, the volcaniclastic transport and sediment yield have been mainly controlled by the Tajumbina River (tributary of the Mayo River) to the NE, and the Resina River (tributary of the Janacatú that flows later into the Juanambú River) to the SW (Figure 1(B)). The Mayo and Juanambú rivers merge into the E-W Patía River, which ultimately flows into the Pacific Ocean (Figure 1). Our study focuses on a tributary of the Resina River, the Humadal Creek, which records the highest frequency of mass movements in the last $\sim 20$ years.

Reconstruction of the Pleistocene-Holocene geological history indicates that the DJVC mainly generated lava-flows, lava-domes, pyroclastic density currents (PDCs), lahars, and large-scale mass-wasting processes related to volcano-tectonic collapses (Pardo et al., 2019).
et al., 2019). The volcanic deposits are thus a consequence of constructive (endogenic) and destructive (exogenic) processes of the multiple vents. As a result of constructive processes, three central and overlapping volcanic edifices have been identified and dated ($^{40}$Ar/$^{39}$Ar): The Santa Helena (1125–1097 ka), the Ancestral Doña Juana (878–312 ka), and the Old Doña Juana (231–77 ka) (Figure 2). Between the Santa Helena and Ancestral edifices, there are remnants of an undated eccentric cone named Pre-Montoso (Figures 1C and 2).

The consecutive sector and summit collapses of each edifice activated by volcano-tectonic processes lead to large-scale mass-wasting events. The last debris-avalanche registered is pre-Holocene. Landforms formed after avalanches, such as hummocks, have been reshaped towards terraces since the Pliocene by lahars and several denudational processes. Lastly, inside the most recent volcano-tectonic depression truncating the Old Doña Juana cone (Figure 2), the recurrent construction and destruction of lavadomes over the Holocene, including the latest 1897–1936(?)-eruption cycle (cf. Espinosa, 2012; Figure 1C) have been responsible for the evolution of the youngest and highest landforms.

3. Methods

The Main Map of the SW flank of the Doña Juana Volcanic Complex, Colombia, was developed in three stages. The first stage consisted of field work carried out during June-July of 2018 to prepare the landform inventory and to describe the deposits using the 1:50,000 geological map by Pardo et al. (2019). During the same campaign, flights were conducted on unmanned aerial vehicles. Subsequently, a classification scheme of the geomorphological units and a geomorphological pre-mapping were developed. Finally, during the field work of September 2019, a post-verification mapping of the units was followed through.

3.1. Mapping

The geomorphological mapping involved a division into spatial units and a morphogenetic classification based on the form and the genesis (or processes; Bishop et al., 2012; Quesada-Román & Zamorano-Orozco, 2019). The morphological attributes of the units at the 1:25,000 scale (Figure 2), were measured using a 5 m GeoSAR-based DEM combined with a 4-band PlanetScope Scene satellite image captured on 05 February 2020 by Planet Team (2017). The morphology of landforms at the 1:5000 scale was measured through the analysis of orthomosaics and a DEM obtained with the Unmanned Airborne Vehicle (UAV) flights (Figure 3).

As for the genesis, based on previous works and the fieldwork developed in 2018, we identified geomorphic processes using criteria such as the composition of the regolith, landform maturity (degree of incision and/or saprolite development), competence of the parent material, age of the deposits (when available, see Pardo et al., 2019), soil development, and stratigraphic relationships (Núñez, 2003; Pardo et al., 2019) Except for steep inaccessible areas, the map units were validated with fieldwork.

In both scales, the Colombian Geological Survey Guideline (SGC, 2017) was adapted to define the landform inventory and the landform description. The relief was divided into 19 landforms and grouped into four morphogenetic environments based on the dominant processes: denudational, fluvial, structural and volcanic. Table 1 summarizes the framework of the classification. Landforms created by processes that wear away the Earth’s surface, including gravitational processes (Huggett, 2011), conform the denudative morphogenetic environment. In the map, denudational processes are highlighted in yellow tones (Figure 3). The fluvial morphogenetic environment involves all the erosional and depositional landforms created by running water (Huggett, 2011) and are shown in blue. Structurally controlled landforms, whose shape is clearly dependent on geological structure (Ahnert, 1998), are grouped in the structural morphogenetic environment and are in red tones. Landforms controlled by volcanic processes define the volcanic morphogenetic environment and are in purple (Figures 2 and 3).

3.2. UAV Survey and data processing

High-resolution imagery was acquired with an unmanned airborne vehicle (UAV) during fieldwork campaign in June 2018. Using two DJI quadcopter Phantom 4 Pro, equipped with a 20 MP camera, we captured 4575 NADIR images with an approximated height of 120 m above ground level and a 70% overlap. We performed 20 flights, which covered a top-down elevation difference of ~900 m and a 5.5 km creek length. Measurements were staggered, considering the significant altitude differences along the Humadal Creek. We used the Pix4D software for processing the collected images. This processing resulted in a 90,673,712 points cloud with an average of 10.81 points/m². Finally, we developed an orthomosaic and a digital elevation model (DEM) with a 4.7 cm ground sampling distance (GSD). These data were used to calculate the morphometry and to define the geomorphological units.

4. Landform identification and interpretation

Table 1 summarizes the framework of the classification. Landforms are grouped into fluvial, structural,
Table 1. Geomorphological landform classification.

| Morphogenic environment                     | Processes                        | Landform                      | Symbol | Maturity characteristics | Diagnostic landform elements (attributes) | Type of parent material (rock, deposit, regolith, saprolite) |
|---------------------------------------------|----------------------------------|-------------------------------|--------|--------------------------|------------------------------------------|---------------------------------------------------------------|
| Denudational morphogenic environment        |                                  |                               |        |                          |                                          |                                                               |
| Surfaces and landforms created by denudational processes. | Gravitational (rock fall, rainwash, sheet erosion, etc.) | Talus cone                     | D_t_c  | Poorly dissected          | Slope angle and shape                    | Colluvial deposit                                              |
| Denudational processes are the sum of weathering, erosion, mass wasting (gravitational processes), and transport, that wear away the Earth’s surface (Huggett, 2011) | Gravitational | Debris cone                   | D_dc   | Poorly dissected          | Slope angle and shape                    | Debris flow deposit                                            |
| Denudational morphogenic environment        | Fluvial and gravitational        | Debris cone                   | D_s_dc | Highly dissected          | Dimension of the scarp wall (gulch)      | Either volcano-sedimentary Quebradagrande Complex (~100 to 125 Myr; Nivia et al., 2006), recent deposits, saprolite, o regolith. |
| Surfaces and landforms created by denudational processes. | Fluvial and gravitational        | Scarp or escarpment           | D_s_pd | Poorly dissected          | Dimension of the scarp wall (gully)      | Mostly in Quebradagrande Complex                              |
| Denudational morphogenic environment        | Fluvial erosion                  | Slope                         | D_sl   | Denuded (poorly dissected | Slope angle. Smooth roughness.           |                                                               |
| Denudational processes are the sum of weathering, erosion, mass wasting, etc.) | Fluvial erosion                  | Slow rate of erosion (sheet erosion, headward erosion, mass wasting, etc.) | D_h_pd | Poorly dissected          | Subendritic a subparallel                  |                                                               |
| Denudational morphogenic environment        | Eroded lobes                     | (Isolated) residual hills      | D_rh   | Volcanic landform relict  | Pseudo radial drainage                   | Old Volcanoclastic deposits. El Tablon (778.1 ± 6.7 ka; Pardo et al., 2019); debris-avalanche and debris flow deposits (<800 ka) |
| Structural morphogenic environment          | Removal of weathered material on a flattish surface | Mesas                          | D_m    | Volcanic landform relict  | Convex ridges of very low slope          |                                                               |
| Structural morpogenic environment           | Fluvial morphogenic environment  | Channels                      | F_ch   | Active landform continuing developing channels | Length and width of stream channels      | Pyroclastic density currents (PDCs) deposits                     |
| Structural controlled landforms are those whose shape is clearly dependent on geological structure (Ahnert, 1998) | Fluvial morphogenic environment  | Terrace scarp                  | F_ts   | Active landform continuing developing channels | Abrupt slopes in in Lateral wall of the fluvial terraces |                                                               |
| Fluvial erosion                             | Structural morphogenic environment | Terraces                     | F_t    | Active landform continuing developing channels | Shape and height to the channel          |                                                               |
| Structural controlled landforms are those whose shape is clearly dependent on geological structure (Ahnert, 1998) | Structural morphogenic environment | Fault line scarp               | S_fs   | Active faults (Holocene landforms) | Abrupt slopes | Either Quebradagrande Complex, recent deposits, saprolite or regolith. |
| Structural controlled landforms are those whose shape is clearly dependent on geological structure (Ahnert, 1998) | Structural controlled landforms are those whose shape is clearly dependent on geological structure (Ahnert, 1998) | Differential erosion            | S_ft   | Highly dissected          | Triangular facet that narrows upward | Quebradagrande Complex                                           |
| Structural controlled landforms are those whose shape is clearly dependent on geological structure (Ahnert, 1998) | Structural controlled landforms are those whose shape is clearly dependent on geological structure (Ahnert, 1998) | Flatiron                        |        |                          |                                          |                                                               |
| Faulting, fluvial and surficial erosion      | Structural controlled landforms are those whose shape is clearly dependent on geological structure (Ahnert, 1998) | Festooned spur                  | S_fs_pd| Poorly dissected          | Height <250 m and length of the spur axis < 250 m | Holocene volcanoclastic deposits (e.g. Las Mesas Fm. between 3210 ± 30 and 3100 ± 30 yr BP; Pardo et al., 2019), including PDCs and debris flows deposits (<6000 yr BP) |
| Structural controlled landforms are those whose shape is clearly dependent on geological structure (Ahnert, 1998) | Structural controlled landforms are those whose shape is clearly dependent on geological structure (Ahnert, 1998) | Volcanoclastic terrace          | V_t    | Relative ages are based on the height to the river. | Plane surfaces | Holocene volcanoclastic deposits (e.g. Las Mesas Fm. between 3210 ± 30 and 3100 ± 30 yr BP; Pardo et al., 2019), including PDCs and debris flows deposits (<6000 yr BP) |
| Structural controlled landforms are those whose shape is clearly dependent on geological structure (Ahnert, 1998) | Structural controlled landforms are those whose shape is clearly dependent on geological structure (Ahnert, 1998) | Volcanoclastic terrace scarp    | V_ts   | Relative ages are based on drainage density on the slope and the slope angle. | Slope | Holocene volcanoclastic deposits (e.g. Las Mesas Fm. between 3210 ± 30 and 3100 ± 30 yr BP; Pardo et al., 2019), including PDCs and debris flows deposits (<6000 yr BP) |
| Structural controlled landforms are those whose shape is clearly dependent on geological structure (Ahnert, 1998) | Structural controlled landforms are those whose shape is clearly dependent on geological structure (Ahnert, 1998) | Volcanoclastic lobe             | V_l    | Relative ages are based on dissection on the distal part | Lobular shape | Late Holocene (<6000 yr BP) volcanoclastic deposits of Loma Seca (312.1 ± 28.8 ka; Pardo et al., 2019); or Las Mesas Fm. (between 3210 ± 30 and 3100 ± 30 yr BP; Pardo et al., 2019) debris flow deposits |

Adapted from SGC (2017), Zinck et al. (2016) and Haskins et al. (1998). Lithostratigraphic units are taken from Pardo et al. (2019). The first column shows the morphogenic environment (genesis), followed by the main processes highlighted in the second column. The landforms, considered as the basic mapping units, are in column three. Landform maturity indicators are shown in column 5th. The diagnostic features that define the landform appearance such as altitude, length, width, curvature, gradient, convexity, slope longitude, and ruggedness are in column 6th; whereas the parent material and the geological unit are in column 7th. For details on the geology and stratigraphy, refer to Pardo et al. (2019).
volcanic, and denudational morphogenetic environments, based on morphological attributes and the dominant process involved in their genesis. Following, in this section, is the inventory and general description of the landforms and processes within each morphogenetic environment, and the interpretation of the morphological evolution of the SW flank of the Doña Juana Volcanic Complex. Special emphasis is made in the 2009 rockfall and the 2014 flow that occurred headwaters of the Humadal Creek and changed the geomorphic system limited by the Resina River watershed.

### 4.1. Fluvial landforms and processes

Fluvial terraces (F_t), escarpments (F_ts), and channels (F_ch) belong to the Resina River and the Humadal Creek. Channel sinuosity – on a detailed scale (1:5000) – is being locally determined by lithological contrasts between the metamorphic basement and the volcaniclastic deposits (Figure 3; Table 1). Several levels of fluvial terraces (between 300 and 3000 m²) and scarps (<3 m height) were recognized in both margins of the Humadal Creek; however, they are rare and only mappable at 1:5000 scale.

Rainfall variability – at intra and interannual timescales (e.g., Urrea et al., 2019) – is responsible for the periodical flooding, that has left in its wake, remnants of terraces (F_t), and escarpments (F_ts). Seasonal flooding has affected the boundary conditions of the river channel and the sediment supply in the Resina watershed. A good example is the 2014 event (See Section 4.5), where a combination of processes (triggered by precipitation) was enhanced by the fluvial drainage network. During this event, headwards erosion and mass wasting occurred in the basement height known as Cerro Montoso, increasing the sediment yield. Sediments were funneled towards the Humadal Creek, depositing and eroding bank materials on its path and propagating as a dilute suspension along the Resina River (e.g., mudflow, mudflood).

The main river channels are, thus, controlling the path traveled by mass flows, as well as PDCs. After deposition, the mass flows and PDCs that fill the paleovalleys are further incised by changes in the local base level during surface uplift. Several fluvi-volcanic episodes have affected the area in the last 5000 years (Table 1). The Main Map and Figure 2 show how fluvial incision affects mainly volcaniclastic lobes (V_l) developing several levels of volcaniclastic terraces (V_t; < 100 m height), which in terms of morphometry may be similar to fluvial terraces but of volcanic origin (Pardo et al., 2019). Examples of long-term fluvial incision are the river channels (F_ch) that form abrupt scarps. The scarps are shaped in Holocene deposits of Las Mesas Formation, in Pleistocene volcaniclastic deposits of Loma Seca and El Tablón Formations, and in the Late Cretaceous Quebradagrande Complex basement (Table 1). Because of the time of exposure, the steeper scarps (>35°) correspond more to the domain of denudational processes (section 4.4).

The combination of high precipitation rates, at an active volcano-tectonic setting, implies that after volcaniclastic events, landform evolution is largely influenced by fluvial erosion and deposition. Fluvial processes are further determined by the rock competence (e.g., degree of weathering), favoring the undermining at base of the scarps, promoting mass wasting, and giving rise to denudational processes.

### 4.2. Structural landforms and processes

The structural landforms are: fault line scarps (S_fl), festooned spurs (S_fs), and flatirons (S_ft). Fault line scarps and festooned spurs are recognizable at both scales, whereas flatirons are structural landforms exclusive to the 1:25,000 map. The triangular flatirons, located in the upper NE corner of the map (Figure 3), are developed by differential erosion of the steeply dipping volcanic-sedimentary sequence of the Quebradagrande Fm. The formative conditions involve both, the different resistance of the rock strata and the folding. Thus, evolution of this region is being controlled by regional tectonics and seismicity generated by the active NE-SW trending faults of El Tablón and San Jerónimo, that cover the entire studied area (Arcila & Muñoz, 2020). These faults are cross-crossed locally by an active ENE-WSW fault, which defines the main orientation and incision of the Humadal Creek and Resina River. The ENE-WSW fault is an active fault that records shallow (<15 km) seismicity (https://www2.sgc.gov.co/Noticias/Paginas/Boletines-mensuales.aspx) and is further controlling the fault line scarps (S_fl), the flatirons (S_ft), and the festooned spurs (S_fs).

Continuous uplift, together with high chemical weathering in the slopes, favor abrupt topographic gradients that smooth out by denudational processes in the short term. In fault scarps (landforms S_fs and S_fl; Figures 2 and 3), the steep – almost vertical – segment below the crest of the slope forms weathering-limited slopes (rate of erosion is higher than rate of weathering; Gupta, 2011), where landslides, debris avalanches, debris flows, mudflows, hyperconcentrated flows, and rockfalls are prone to happen (e.g., the 2009 rock fall of Cerro Montoso). With time, the straight debris slope (talus slope) increases in area due to material accumulation arriving from the top, eventually burying the scarp face (Gupta, 2011). Some remnants of the rockfall and flow deposits can be recognized in debris cones (D_dc) and talus cones (D_tc) at the 1:5000 scale map (Figure 3). After a slope declines, a transport-limited slope (rate of weathering is higher than the rate of erosion;
Gupta, 2011) grows and soil creep, through-wash, rainfall, rainsplash, and rillwash will dominate the hillslope development (Huggett, 2011). In the last case, the slope profile is modified to a convexo-concave appearance (Gupta, 2011). During this stage, festooned ends (\(S_{fs}\)) may develop.

4.3. Volcanic landforms and processes

The volcanic landforms are: volcanoclastic terraces (\(V_t\)); volcanoclastic terrace scarps (\(V_ts\)), and volcanoclastic lobes (\(V_l\)). Volcanic landforms in the DJVC form directly from volcanic processes during or after eruptive events, including non-eruptive (secondary) lahars and large-scale mass-wasting processes related to volcano-tectonic collapses (i.e. debris-avalanches). Both the lobes and the terraces are formed in pyroclastic material. The volcanoclastic lobes developed in the deposits of Las Mesas and Loma Seca Formations. The terraces were shaped exclusively in volcanoclastic deposits – including PDCs and debris flow deposits – of Las Mesas Formation (Table 1; see also Pardo et al., 2019). While terraces formed after deposition in a confined space, lobes developed at the unconfined flat surfaces on the roof of the terraces.

After volcanic events, PDC were deposited in the slopes of the volcanic forming lobes of long slopes with moderate to low angles and rounded fonts (i.e. \(V_l\)). These volcanoclastic lobes started to evolve towards denudative and fluvial landforms as a function of erosion, mass wasting, and fluvial incision. The superposition of events (i.e. paleovalley infilling, terrace, runoff, gulling, headward erosion, etc.) caused several generations of minor-sized landforms (~100 m² or less) such as volcanoclastic terrace scarps (\(V_ts\)) with slopes of moderate longitude and steep angle (Figures 2 and 3). Similarly, high-concentration PDCs were channeled into rivers and paleovalleys, which further incision formed several terraces of very low slope angle with longitudes varying between 100 m to 350 m and of ~10 m height (i.e. \(V_t\)).

Volcano-genetic landforms may therefore easily evolve to denudative landforms (mosaic landforms with higher complexity) upon increasing either the distance from the volcanic vent and/or the time elapsed from the volcanic event. In volcano-genetic and structural landforms, the material and geometric properties are closely related. In contrast, the material properties of volcanoclastic landforms are controlled by the balance between material added by volcanic eruptions and surface processes that transform/ remove it through regolith production and erosion. However, when new volcanic eruptions occur an instability is reached and the system input-output relationship is unbalanced, such as, for example, when the hydrogeomorphic response is magnified by rapid rates of volcanic material supply.

4.4. Denudational landforms and processes

The SW flank of the DJVC (Figure 2) is characterized by two large geomorphic units (~2 km²). One unit is a hill chain (modeled in Quebradagrande Complex basement) characterized by slope longitudes of ~300 m, moderate slope (~16–35°), and sharp summits. The landforms that conform this large unit are: slopes (\(D_sl\)), hills poorly dissected (\(D_h_pd\)), scarps poorly dissected (\(D_s_pd\)), scarps highly dissected (\(D_s_hd\)), and hill ridges (\(D_hr\)). The scarps of these hill chains are highly dissected and the drainage system is denser. The other unit is a hill chain characterized by short slopes ~200 m, high slope angles (~35–55 and even 74°), and flat summits, where scarps are less dissected and the drainage system is less dense. The landforms that conform this large unit are: \(D_s_pd\), \(D_s_hd\), \(D_m\), \(V_t\) and \(V_ts\). Despite \(V_t\) and \(V_ts\) are mainly of volcanic origin, they evolve towards mesas landforms (\(D_m\)) with time.

On a detailed scale (1:5000), cumulative landforms like debris cones (\(D_dc\)) and talus cones (\(D_tc\)), and erosive landforms such as scarps and landslide cirques (Figure 3) are indicative of recent activity. Slump and slide scars are very common on the scarps of the hill chains with flat summits (\(D_m\); Figure 3). Talus and debris cones and its associated deposits (Table 1), as depositional landforms, are more common in hill chains with sharp summits. Flat summits compared to sharped summits in the hill chains indicate that the summit amplitude is a function of dissection, rock hardness, and time of exposure. In highly dissected hills, the drainage system is denser and the summits are sharp. By contrast, in less dissected hill chains, the drainage system is less dense and summits are flat. This pattern suggests that slope gradients in highly dissected hills (sharp summits) have reduced with time due to mass wasting, as indicated by gradient values of less than ~35°.

In the evolution of slopes, the geometry of a slope reflects the balance between inputs and outputs of material (Renwick, 1992). \(V_ts\) is an example of a steep slope (>55°) that forms weathering-limited slope. However, weathering-limited slopes can also retreat maintaining a sharp gradient, depending on conditions at the slope base, such as transport capacity of streams (Huggett, 2011). Because scars and landslide cirques prevail in the scarp faces of \(D_m\) and \(V_t\) landforms, without talus or debris cones at the bottom, it suggests that transport is higher than weathering. Hence, mesas landforms (\(D_m\)) or volcanoclastic terraces (\(V_t\)) next to the Resina River may retreat keeping sharp scarps.

Soil profiles at the top of the hills (landforms \(D_m\) and \(V_t\)) are well developed. Similarly, in transport-limited slopes (landforms \(D_tc\), \(D_dc\); \(D_s_pd\), and \(D_hr\)) soil profiles may have some development.
Transport-limited slopes denote geomorphic stability and, consequently, thicker regoliths and soil profiles are prone to develop (Birkeland et al., 2003). By contrast, in the weathering-limited hillslopes of landforms V_ts, S_fl_s, and D_s_hd soil profiles are thin or absent.

4.5. Landforms connected with the 2009 and 2014 Montoso events

On May 21st, 2009, a rockfall was triggered at Cerro Montoso western flank (Figure 1(B)). According to the Colombian Geological Survey (SGC), the rockfall was probably related to seismic activity recorded 4 km northeast from Cerro Montoso (Pulgarín et al., 2016), along an ENE-WSE fault controlling the Humadal Creek. Two low-magnitude earthquakes were recorded by the Volcanological and Seismological Observatory of Pasto (OVSP) at 16:17, local time, on May 20th, and at 07:08 on May 21st of 2009 (2.8 and 2.7 in the Richter scale, respectively). The dry mass movement affected mainly the headwaters of the Humadal Creek.

A second mass-movement occurred on December 8th 2014 on the western flank of Cerro Montoso, reported as extremely noisy by the people inhabiting houses on terraces located at the Humadal headwaters. It was described as an ‘avalanche’ by locals to indicate that it was water-saturated. The OVSP recorded surface seismic waves on December 8th at 19:45 and 20:15 hours associated with the flow and excluded earthquakes as potential triggers. Instead, the event was likely triggered by soil saturation after intense and prolonged precipitations over previous days. This event has been the largest one recorded in the past decade, damaging local bridges and causing fear and abandonment of houses along the Humadal Creek. Three hours after the onset, the flow reached sectors near villages located more than 15 km away from its source areas on Montoso, probably as the result of temporary dams and the sequential mobilization of mass movements along the upper Janacatú River. Other minor and scattered mass movements have been perceived by the local inhabitants and witnessed during local geological surveys in 2017 and 2018, having similar source areas as the 2009 and 2014 events (Pulgarín et al., 2016).

The two major mass-wasting events that occurred during the dry season of 2009 and the wet season of 2014, resulted in a rock fall in the upper part of Cerro Montoso and a mass flow that transported material along the Humadal Creek towards the Resina River, respectively (see Figure 1). The 2009 rock fall consisted of blocks from the poorly dissected scarps (D_s捍d) identified in the southern flank of the Cerro Montoso (see Figure 3), mobilizing an estimated 21,000 m^3 and traveling an estimated horizontal run-out of 2.3 km over a total height variation of 1.0 km. The mobilized boulders traveled as a rock avalanche, depositing predominantly over the volcaniclastic lobe (V_l), with a few boulders reaching the Humadal Creek channel, and generating the alarm in the upper hill farmers (Pardo et al., 2021). The 2014 flow event resulted after an intense and prolonged rainy season, triggering two main landslides, of approximately 135,000 m^3 and 80,000 m^3 of accumulated material in the debris cone (D_d). The mobilized material traveled along the Humadal Creek, accumulating material from smaller landslides and eroding the creek banks on its pass. The nature of the chain reaction of these mass-wasting events challenges the interpretation of a single mass flow event. Consequently, three stages of the 2014 event can be differentiated. First, the released material from the main landslides traveled an approximated distance of 4.5 km as a debris flow, with a total drop height of 390 m. Then the incorporation of solids and accumulation of water transitioned the flow towards a hyper-concentrated flow over a distance of 1 km until reaching a narrow pass of approximately 10 m wide (see Figures 2 and 3), resulting in the accumulation of large boulders and the pass of a finer sediment suspension. After this point, the sediment suspension traveled potentially as a mudflow or a mudflood at least 2.8 km over the Resina River, being reported by inhabitants of the town La Victoria village and damaging a crossing bridge.

5. Conclusions

The geomorphological evolution of the SW flank of the DJVC is the result of complex interactions that involve not only tectonic and volcanic endogenic processes but also recent and ongoing fluvial and slope exogenic processes triggered by climate variables (i.e. precipitation seasonality). Gravitational processes and climate operate on short time scales (years). On long timescales (from thousands to millions of years), unroofing, and uplift may have had a major influence on channel incision. In the last ~20 years, short time events have been recognized within the upper Resina watershed, some of which documented by the community given the frequency and damage to crops, houses and roads, particularly along the ENE-WSW trending Humadal Creek valley.

On a broader scale, the prevailed landforms in the SW flank of DJVC are mainly of denudative nature created by processes such as weathering, erosion, mass wasting, and deposition. The intensity of denudation in younger landforms is closely related to the rock/sediment competence. By contrast, in relict landforms (where denudation occurs over structural, volcanic, fluvial or other landforms), time of exposure is the main factor influencing the intensity of denudation. Detailed mapping at 1:5000 scale enabled us to
evaluate the morphologic evolution of landforms following the rainfall and/or seismic events that have caused infrastructure and community hazards in Las Mesas village and rural areas (e.g. 2009 and 2014 Motoso events). By characterizing events that have affected the geomorphic system in the past, it is possible to establish if the continuity of the processes could affect the Resina watershed in the future. Thus, the map sets up a baseline for the study of future mass movement scenarios, allowing the validation of areas prone to slope instability. The baseline would, further, improve knowledge for detailed geohazard assessment and provide support on risk-informed policy-making (e.g. territorial planning, land administration) in this inhabited volcanic tropical area.

Software
ArcMap was used to compile and edit GIS datasets. ArcGIS Pro was used for the map design. Illustrator was used for final editing.

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Data availability statement
The dataset that compiles high-resolution digital elevation model acquired with an unmanned airborne vehicle is available in Zenodo DOI: 10.4211/hs.b314bb2c089744a8bc0dca01a31c9ee8. Derived data from the unmanned airborne vehicle, supporting the findings of this study, are available upon request from the corresponding author.

References
Ahnert, F. (1998). Introduction to geomorphology. John Wiley & Sons.
Alcalá-Reygos, J., Palacios, D., Juan, J., & Orozco, Z. (2016). Geomorphology of the amanto volcanic complex (Southern Peru). Journal of Maps, 12(5), 1160–1169. https://doi.org/10.1080/17445647.2016.1142479
Arcila, M., & Muñoz, M. (2020). Integrated perspective of the present-day stress and strain regime in Colombia from analysis of earthquake focal mechanisms and geodetic data. In G.-T. Pinilla-Pachón (Ed.), The geology of Colombia. SGC, Servicio Geológico Colombiano. https://doi.org/10.32685/pub.esp.38.2019.17
Birkeland, P. W., Shroba, R. R., Burns, S. F., Price, A. B., & Tonkin, P. J. (2003). Integrating soils and geomorphology in mountains – an example from the front range of Colorado. Geomorphology, 55(1–4), 329–344. https://doi.org/10.1016/S0169-555X(03)00148-X
Bishop, M. P., James, L. A., Shroder, J. F., & Walsh, S. J. (2012). Geospatial technologies and digital geomorphological mapping: Concepts, issues and research. Geomorphology, 137(1), 5–26. https://doi.org/10.1016/j.geomorph.2011.06.027
Cajas, D. R., & Yama, F. A. (2008). Caracterización de sistemas agroforestales en la vereda La Palma, Comunidad Indígena Yanacona, corregimiento de San Juan, municipio de Bolívar - Cauca. Universidad de Nariño. http://sired.udenar.edu.co/id/eprint/5518
Dykes, A. P., & Welford, M. R. (2007). Landslides in the Tandayapa valley, Northern Andes, Ecuador: Implications for landform development in humid and tectonically active mountain ranges. Landslides, 4(2), 177–187. https://doi.org/10.1007/s10346-006-0076-6
Espinosa, A. (2012). Erupciones históricas de los volcanes colombianos. In ACCEFYN (Ed.), Enciclopedia de desastres naturales históricos en Colombia (2nd ed., pp. 1840). Universidad del Quindio.
Francis, P. W., & Wells, G. L. (1988). Landsat thematic mapper observations of debris avalanche deposits in the Central Andes. Bulletin of Volcanology, 50(4), 258–278. https://doi.org/10.1007/BF01047488
Gupta, A. (2011). Tropical geomorphology. https://doi.org/10.1017/CBO9780511978067
Gutscher, M. A., Malavieille, J., Lallemand, S., & Collot, J. Y. (1999). Tectonic segmentation of the North Andean margin: Impact of the Carnegie Ridge collision. Earth and Planetary Science Letters, 168(3–4), 255–270. https://doi.org/10.1016/S0012-821X(99)00060-6
Haskins, D. M., Correll, C. S., Foster, R. A., Price, A. B., & Tonkin, P. J. (2011). Fundamentals of geomorphology. Routledge Fundamentals of Physical Geography Series (third, Vol. 11). https://doi.org/10.1137/101923310385829
Jones, R., Manville, V., Peakall, J., Froude, M. J., & Odber, H. M. (2017). Real-time prediction of rain-triggered lahars: Incorporating seasonality and catchment recovery. Natural Hazards and Earth System Sciences, 17(12), 2301–2312. https://doi.org/10.5194/nhess-17-2301-2017
Komorowski, J. C., Navarro, C., Cortés, R., Saucedo, R., Gavilanes, J. C., Sieb, C., … Rodríguez, S. (1997, January 19–25). The Colima volcanic complex. 1. Quaternary multiple debris-avalanche deposits; 2. Historical pyroclastic sequences (1913, 1991, 1994). In IAVCEI (Ed.), International Association of Volcanology...
and Chemistry of the Earth’s interior – General assembly Puerto Vallarta. Volume fieldtrip guidebook No. 3 (pp. 37–69). Gobierno de Jalisco.

Major, J. J., Bertin, D., Pierson, T. C., Amigo, Á., Iroumé, A., Ulloa, H., & Castro, J. (2016). Extraordinary sediment delivery and rapid geomorphic response following the 2008-2009 eruption of Chaitén Volcano, Chile. Water Resources Research, 52(7), 5075–5094. https://doi.org/10.1002/2015WR018250

Montgomery, D. R., Balco, G., & Willett, S. D. (2001). Climate, tectonics, and the morphology of the Andes. Geology, 29(7), 579. https://doi.org/10.1130/019-7613(2001)029<0579:CTATMO>2.0.CO;2

Mora, A., Parra, M., Strecker, M. R., Sobel, E. R., Hooghiemstra, H., Torres, V., & Jaramillo, J. V. (2008). Climatic forcing of asymmetric orogenic evolution in the eastern Cordillera of Colombia. Geological Society of America Bulletin, 120(7–8), 930–949. https://doi.org/10.1130/B26186.1

Nivia, A., Marriner, G. F., Kerr, A. C., & Tarney, J. (2006). The Quebradagrande Complex: A Lower Cretaceous ensialic marginal basin in the Central Cordillera of the Colombian Andes. Journal of South American Earth Sciences, 21(4), 423–436.

Nuñez, T. A. (2003). Cartografía geológica de las zonas Andina Sur y Garzón-Quetame (Colombia). Reconocimiento geológico regional de las planchas 411 La Cruz, 412 San Juan de Villalobos, 430 Mocoa, 431 Piamonte, 448; Monopamba, 449 Orito y 465 Churuayaco. Departamentos de Caqu. Memorias, INGEOMINAS, Internal Report, Bogotá, Colombia.

Pardo, N., Pulgarín, B., Pardo, N., & Betancourt, V. (2016). Informe de la geología y monitoreo volcánico del Complejo Volcánico Doña Juana (CVDJ), en los municipios de La Cruz y Tablón de Gómez, Nariño. Bogotá, Colombia.

Quesada-Román, A., Fallas-López, B., Hernández-Espinoza, K., Stoffel, M., & Ballesteros-Cánovas, J. A. (2019). Relationships between earthquakes, hurricanes, and landslides in Costa Rica. Landslides, 16(8), 1539–1550. https://doi.org/10.1007/s10346-019-01209-4

Quesada-Román, A., & Zamorano-Orozco, J. J. (2019). Geomorphology of the upper General River basin, Costa Rica. Journal of Maps, 15(2), 94–100. https://doi.org/10.1080/17445647.2018.1548384

Renwick, W. H. (1992). Equilibrium, disequilibrium, and nonequilibrium landforms in the landscape. Geomorphology, 5(3–5), 265–276. https://doi.org/10.1016/0169-555X(92)90008-C

SGC. (2017). Guía metodológica para la zonificación de amenaza por movimientos en masa escala I: 25.000. Servicio Geológico Colombiano.

Siebert, I. (2002). Landslides resulting from structural failure of volcanoes. In GSA reviews in Engineering Geology catastrophic Landslides Volume XV (pp. 209–235). Geological Society of America. https://doi.org/10.1130/ REG15-p209

Thouret, J.-C., Salinas, R., & Murcia, A. (1990). Eruption and mass-wasting-induced processes during the late holocene destructive phase of Nevado del ruiz volcano, Colombia. Journal of Volcanology and Geothermal Research, 41(1–4), 203–224. https://doi.org/10.1016/0377-0273(90)90089-X

Urrea, V., Ochoa, A., & Mesa, O. (2019). Seasonality of rainfall in Colombia. Water Resources Research, 55(5), 4149–4162. https://doi.org/10.1029/2018WR0233316

van Wyk de Vries, B., & Davies, T. (2015). Landslides, debris avalanches, and volcanic gravitational deformation. In H. Sigurdsson (Ed.), The encyclopedia of volcanoes (pp. 665–685). Elsevier. https://doi.org/10.1016/B978-0-12-385938-9.00038-9

Zinck, J. A., Metternicht, G., Bocco, G., & del Valle, H. F. (2016). Geopedology, an integration of geomorphology and pedology for soil and landscape studies. Geopedology. https://doi.org/10.1007/978-3-319-19159-1