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To cite this article: Adolfo Quesada-Román & José Juan Zamorano-Orozco (2019) Geomorphology of the Upper General River Basin, Costa Rica, Journal of Maps, 15:2, 95-101, DOI: [10.1080/17445647.2018.1548384](https://doi.org/10.1080/17445647.2018.1548384)

To link to this article: <https://doi.org/10.1080/17445647.2018.1548384>



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Published online: 29 Nov 2018.



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Geomorphology of the Upper General River Basin, Costa Rica

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ABSTRACT

In spite of the geomorphological diversity of Central America and Costa Rica, there are few detailed geomorphological maps. A 1:25,000 scale map of the Upper General River Basin (UGRB) in Costa Rica is presented, based on the interpretation of aerial photographs and field geomorphological mapping. A total of 43 types of landforms divided genetically into endogenic (tectonic features), and exogenic (fluvial, gravitational, and glacial features) are mapped for an area of 1560 km². This cartography is important in terms of disaster prevention and mitigation (floods and hillslope processes), as well as for land use planning.

ARTICLE HISTORY

Received 3 June 2018
Revised 7 November 2018
Accepted 12 November 2018

KEYWORDS

Geomorphological mapping; fluvial geomorphology; mass movements; glacial geomorphology; Pérez Zeledón; Central America

1. Introduction

The UGRB basin has been examined in a number of aspects including geology (Alvarado, Barquero, Taylor, López et al. 2009; Alvarado, Barquero, Taylor, Mora et al., 2009), glacial landforms in summit areas above 3000 m (Bergoeing, 1977; Barquero & Ellenberg, 1983; Horn, 1990; Orvis & Horn, 2000; Lachniet & Seltzer, 2002), mapping of alluvial fans (Kesel & Spicer, 1985; Bergoeing, Brenes, Fernández, & Ureña, 2010), and its geomorphology (Quesada-Román, 2016; Quesada-Román, 2017). In this case we present a 1:25,000 scale geomorphological map of the Upper General River Basin (UGRB) in Costa Rica.

The UGRB is located in south-central Costa Rica, 80 km southeast of the capital San José, where the city of San Isidro del General stands out as the most important town. This is where the Cordillera de Talamanca, the General River valley, and the Fila Brunqueña merge in an area of 1,560 km² (Figure 1). The topography and geomorphology of the UGRB results from a complex tectonic interaction between the Cocos, Caribbean, Panama, and Nazca plates, as well as the subduction of the submarine volcanic cordillera of Cocos, also known as the Coco's Ridge which stopped the volcanism and provoked an intense uplift of Cordillera de Talamanca (DeMets, Gordon, & Argus, 2010).

The study area is divided into two morphotectonic sectors associated with the subduction dynamics of the Cocos under the Caribbean plate, known as the fore arc (sedimentary basins of the General and Fila Brunqueña rivers) and the inner arc (Cordillera de Talamanca) (Marshall,

2007). The Cordillera de Talamanca is composed of andesitic volcanic rocks of Mio-Pliocene age and largely of granodioritic plutonic rocks of Miocene age. On the SW flank of the Fila Brunqueña a mountainous complex of Oligocene-Miocene turbidite shales, conglomerates, and sandstones can be found (Alvarado, Barquero, Taylor, López et al. 2009; Alvarado, Barquero, Taylor, Mora et al., 2009; Denyer & Alvarado, 2007).

Different exogenic processes dominated by water, ice, temperature, and vegetation have shaped the landforms of this territory. In the mountain zones above 3,000 m a.s.l., there are landscape features associated with paleoglacial landforms that developed during the Last Glacial Maximum, LGM (Lachniet & Seltzer, 2002; Orvis & Horn, 2000). Both seasonal and cyclonic rains trigger fluvial processes that constantly modify the landforms (Alfaro, Quesada-Román, & Solano, 2010; Alfaro & Quesada-Román, 2010; Campos-Durán & Quesada-Román, 2017). Here, the mean annually precipitation is over 2500 mm and can reach 5500 mm (Quesada-Román, 2017). These processes combine with strong rates of soil loss as well as chemical weathering to sculpt the landscape (Pincus, Ryan, Huertas, & Alvarado, 2017; Villatoro-Sánchez, Le Bissonnais, Moussa, & Rapidel, 2015).

The different landforms of the UGRB are the result of the interaction of both endogenic and exogenic processes, such as active tectonics, Miocene to Pliocene volcanism, glacial dynamics during the LGM, mass movement processes, and fluvial activity that have physically modified the Cordillera de Talamanca, the Fila Brunqueña, and the General Valley. [The Main Map](#)

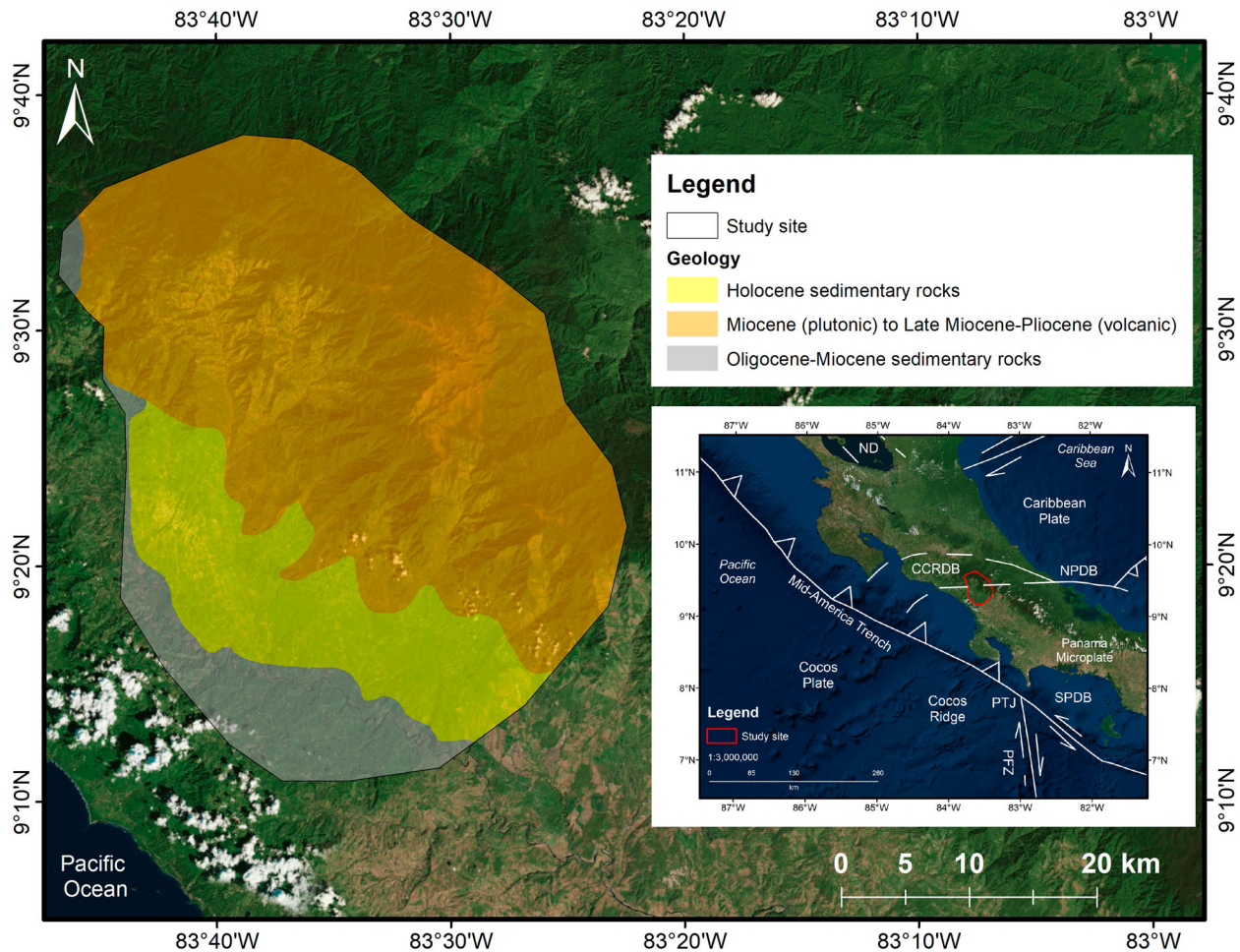


Figure 1. Localization, tectonic and geological setting of the UGRB in the Costa Rican context (Source: ArcGIS Online Basemap; Projection GCS; Datum WGS84). ND: Nicaragua Depression; CCRDB: Central Costa Rica Deformed Belt; NPDB: North Panama Depression Belt; SPDB: South Panama Depression Belt; PFZ: Panama Fracture Zone; PTJ: Point Triple Junction; SJ: San José; SI: San Isidro del General (DeMets et al., 2010; Morell, 2016).

is a base map to model the hillslope processes and floods that constantly affect different communities of the Pérez Zeledón municipality. This document may be important for disaster mitigation and to enable more orderly development of the land-use planning for this territory.

2. Materials and methods

The Main Map was conducted in three phases beginning with pre-mapping Aerial Photo Interpretation followed by fieldwork and finishing with GIS post-mapping to refine the end product (Otto & Smith, 2013). During the pre-mapping the morphogenetic map was generated based upon Aerial Photo Interpretation (API) at 1:25,000 scale from the CARTA project (Costa Rica Airborne Research and Technology Applications, 2005), a NASA mission which mapped Costa Rica between 2003 and 2005. These aerial photographs were georeferenced and processed to accomplish the geomorphological mapping. The method allowed to map the genesis, dynamics, morphology, evolution, and age of the different landforms and its processes using various manual and digital graphic techniques to develop the final

cartographic product (Bishop, James, Shroder, & Walsh, 2012; Otto, Prasicek, Blöthe, & Schrott, 2018).

The fieldwork was conducted during four ground checks made between 2011 and 2013 to confirm or correct the different landform dynamics and limits using a preliminary morphogenetic map at 1:25,000 scale. During the final stage of post-mapping, the legend for the geomorphological map of the UGRB, which divides the landforms genetically into endogenic (tectonic) and exogenic (fluvial, gravitational, and glacial), was developed. The exogenic features are mainly erosional features whereas the exogenic structures are separated into erosional and depositional forms (Gustavsson, Kolstrup, & Seijmonsbergen, 2006). Finally, the map was created within a Geographic Information System (ArcGIS 10.3).

3. Results

3.1. Endogenic landforms

3.1.1. Tectonic landforms

These landscapes comprises uniquely tectonic landforms associated with a strike-slip fault identified in



Figure 2. Yellow dashed lines indicate a couple of shutter ridges close along the strike-slip fault close to Unión town.

the SE of the study area. This study was able to analyze the spatial distribution, arrangement, variety, and morphology of escarpments, fluvial deflections, shutter ridges, and sag ponds. The morphology, design, length and width of the escarpments vary between 20 and 150 m and it's a direct surface expression of the strike-slip fault dynamics. The fault escarpment is discontinuous and fragmented in five parts that varies between 540 m to 1750 m cut by different river valleys and fluvial deflections. 41 shutter ridges were identify along the fault trace with axis between 300–460 m, with predominant orientations NW-SE, altitudes from 550 to 740 m, and symmetric and elongated morphologies over fluvial-proluvial detritus (Figure 2).

3.2. Exogenic landforms

3.2.1. Fluvial landforms

Erosional fluvial landforms (i.e. volcanic slopes dissected by a dense drainage network, sedimentary slopes dissected by fluvial activity, <20 m deep valleys, >20 m deep valleys, and rocky bed valleys), are the result of the action of rivers and their tributaries, which have played an important role in the formation of valleys in concordance with hillslope processes (Figure 3a). The volcanic slopes dissected by a dense drainage network affect extensive areas located on Cordillera de Talamanca where the high rainfall and intense weathering rates facilitates the erosion and modeling of these landforms between 1000 and 3000 m. On the other hand, below 1000 m, the sedimentary slopes dissected by fluvial activity are composed of sedimentary rocks of the Fila Brunqueña modified by fluvial and gravitational activity. The <20 m deep valleys are incipient

ravines along the headwaters, the >20 m deep valleys are well-developed V-shaped erosional landforms, and rocky bed valleys are high energy incisions dominated by boulders. The valleys are not isolated landforms; they are linked to other fluvial forms such as scarps (both active and inactive), headwaters, ravines, and gullies.

Depositional fluvial landforms appear when the slope of the river's longitudinal profile decreases, especially in the transition between the mountains to the floodplains or the piedmont, or when the channel approaches its local base level. In either case, the streamflow loses its erosional and competitive capacity to deposit debris in alluvial fans, floodplains, flood terraces, and alluvial cones.

Alluvial fans form when the channel encounters a significant slope change, which enables the deposition of the suspended load. The origin and evolution of these landforms are directly conditioned by tectonics and climate. The intensity and velocity of the depositional processes are linked to the uplift of the Cordillera de Talamanca during the Quaternary with rates from 1.7 m/k.y. to 8.5 m/k.y. (Gardner, Fisher, Morell, & Cupper, 2013). These conditions favored the development of wide alluvial fans well preserved in comparison with the rest of the country and its erosion rates. This situation is consistent with the presence of extensive floodplains more than 100 km from its base level in the Ocean Pacific where this river, as Terraba River deposits tons of sediments (Acuña-Piedra & Quesada-Román, 2016).

The influence of past climate is evident at elevations above 3000 m (Lachniet & Seltzer, 2002). These elevations were under the direct influence of glacial



Figure 3. Fluvial landforms: (a) >20 m deep valleys, (b) braided floodplain, (c) alluvial fans in the background, (d) transition from anabranching to meandering patterns in the union of the Pacuar and General rivers.

conditions during the LGM (Horn, 1990; Orvis & Horn, 2000). The existence of glacial landforms like the volcanic slopes modified by glacial action is a geomorphological inheritance of these past climate conditions that is composed of debris (depositional) and clear granodiorite surfaces due the glacier movement (erosional). These materials were then reworked by the river erosion, which dismantled, transformed or destroyed them. The rivers transported debris through the glacial valleys, which in some cases transformed or removed the glacial landforms.

Most of these materials became part of extensive alluvial fans in the foothills of the Cordillera de Talamanca, with at least 14 fans and a total area of 213.8 km² (Figure 3c). In general, they maintain a slope <10°, with a mean NE – SW orientation, mean altitudes of its apexes at 881 m a.s.l. and they were classified according to their relative age and stratigraphic position into late, intermediate, and early forms (Kesel & Spicer, 1985). The late fans are active and over the intermediate fans, meanwhile the latter are above stratigraphically and geomorphologically the early and older fans. Another significant feature is the lateral displacement of up to 2.3 km of five alluvial fans, caused by a right-lateral strike-slip fault that affects this zone with its lateral movement. The inactive alluvial fans are divided in two dynamics: the eroded ones by a dense river drainage and the buried below the active and younger fans letting some relicts of its presence.

The floodplains occupy the bottom of broad valleys, which in many cases are flood areas in the rainy season or in extraordinary periods of rainfall, such as tropical

cyclones. These areas were classified as braided, anabranching, and meandering (Figure 3b, 3d). The floodplains alternate with fluvial terraces that are characterized as being asymmetrical and three orders of terraces were recognized. The 1st order fluvial terraces are located between 360 and 1580 m, with a length from 330 to 2200 m and a width of 40–140 m active during annual floods. The 2nd order fluvial terraces are between 360–1480 m, some are inclined until 15° with lengths from 660 m to 2.2 km, and widths from 20 to 250 m its dynamics are associated with extraordinary rainfall events as extensive rainy seasons. The 3rd order fluvial terraces are located between 460–1420 m, with lengths from 190 m to 2.7 km, widths from 45 to 720 m, and are related with the tropical cyclones impacts. These characteristics reveal erosional dynamics of lateral and vertical erosion associated with intense neotectonic movements.

3.2.2. Gravitational landforms

These landforms are located on slopes steeper than 15°, and where the substrate is poorly consolidated, as in the case of fractured rocks, and weathered debris or soils. The presence of disjunctive structures favors the development of these landforms, which can be triggered by seismic events and intense rainfall, which exceeds 2500 mm per year and magnifies their dynamics. The extensive areas covered by these erosional landforms are the volcanic slopes affected by creep and gully erosion, and the volcanic slopes shaped by landslides and fluvial activity located between 1000 and 3000 m. Under this scenario, the scarps associated with 150 landslides (Figure 4a), 956 falls (Figure 4b), 70

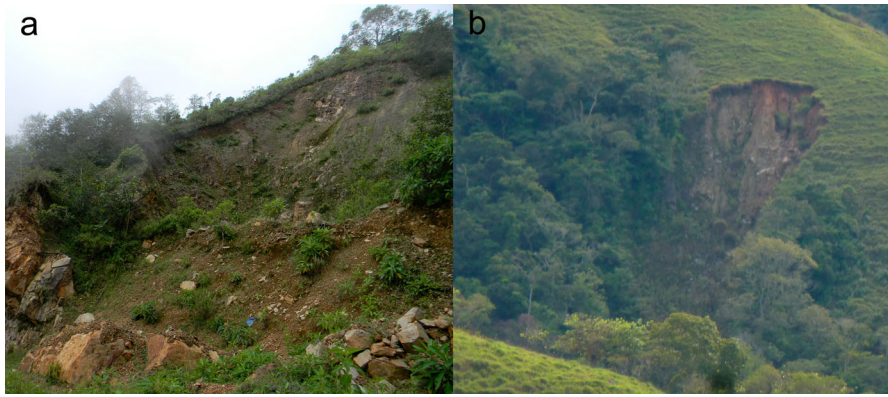


Figure 4. Gravitational features: (a) rotational landslide, (b) fall, in the volcanic slopes shaped by landslides and fluvial activity.

rock flows, and 25 mudflows can be explained, as well as the depositional landforms resulting from the exogenic dynamics that influences their development. These include the accumulations associated with slides with staggered and lobular morphologies, and mudflows with lobular morphology, and colluvial deposits.

3.2.3. Glacial landforms

These landforms originated during the phase of glaciation/deglaciation through the Last Glacial Maximum until the Younger Dryas (Horn, 1990; Lachniet & Seltzer, 2002; Orvis & Horn, 2000). These paleoforms were formed as a result of the accumulation of snow and ice, resulting in processes of abrasion and polishing due to the downslope movement of the glacial ice masses. Among the erosional glacial landforms, volcanic slopes modified by glacial action, cirques, arêtes, riegels, glacial lakes, and *rôches moutonnées* (Figure 5), were defined. The volcanic slopes modified by glacial action are located over 3000 m in altitude, they were shaped by the colder conditions during the LGM. Here, straight and concave geometries predominate among the exhumation of polished, predominantly granodiorite rocks. The most representative depositional glacial landforms are the lateral and ground moraines which show the extent of glacial advances during the LGM. On these landforms rely are located 963 palustrine

and lacustrine wetlands landforms with a paramount hydrological and ecological importance (Esquivel-Hernández et al., 2018; Veas-Ayala et al., 2018).

4. Conclusions

A detailed geomorphological map (1:25,000 scale) is presented with 43 types of landforms classified genetically as endogenic (tectonic) and exogenic (fluvial, gravitational, and glacial) covering a 1560 km² area. The importance of this document lies in the new information of different geomorphological environments presented in the region with less geomorphological studies in the world. The glacial landforms over 3000 m cover around 80 km², and were mapped for the first time at this scale, with the detailed identification of glacial cirques, arêtes, riegels, glacial lakes, *rôches moutonnées*, till deposits, ground and lateral moraines. Also, an extensive number of hillslope landforms were identified and classified (i.e. 150 landslides, 956 falls, 70 rock flows, and 25 mudflows). These gravitational features are located along different volcanic and sedimentary mountain slopes modified and triggered by seismicity and extraordinary rainfall.

The fluvial landforms are prevailing in the volcanic slopes affected by creep and gully erosion as well as by dense drainage network that allows valleys of < 20 m

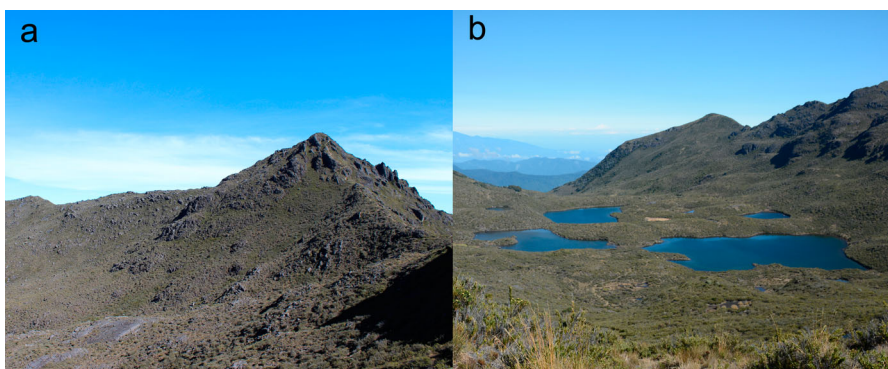


Figure 5. Glacial landforms: (a) glacial cirques and arêtes (Cerro Chirripó: 3820 m a.s.l.) on volcanic slopes modified by glacial action, (b) glacial lakes and till deposits.

and > 20 m deep, and rocky bed valleys. The high tectonic uplift rates coupled with intensive precipitation averages and a dense river network has favored accelerated erosion and with it, the transport and accumulation of significant coarse deposits in the lowlands. As a clear transition between mountain slopes and lowlands the alluvial fans were mapped and classified according its relative age and stratigraphic position into late, intermediate, and early fans covering 213.8 km².

A strike-slip fault presents clear a tectonic geomorphological response on the shutter ridges and fault escarpment dynamics along the SE of the alluvial fans. The fluvial landscape are controlled by braided, anabranching, and meandering floodplains, with the presence of three fluvial terraces orders and alluvial cones. This type of geomorphological maps can also be used for landforms evolution, detailed morphogenetic maps, disaster prevention and mitigation, as well as land use planning cartography.

Software

The software used was ESRI ArcGIS 10.3 to georeference, digitize, visualize the aerial photographs and generate the geomorphological map.

Acknowledgements

The final version of the manuscript and the map benefits from the observations of R.L. Losco, S. Allen, and the original Journal of Maps Referees F. Dramis, T. Karampaglidis, and T. Pingel. Also, the authors are grateful with the final reviewers J.P. Bergoeing, S. Bernard, D. Guida, and especially T. Piacentini for their valuable comments and suggestions.

Disclosure statement

There is no conflict of interest on the part of the authors.

Funding

Thanks to CONACYT (Mexico) and MICITT (Costa Rica) for post-graduate scholarships to the first author.

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