Glacial geomorphology of the Chirripó National Park, Costa Rica

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ABSTRACT

Several regions of tropical America show imprints of past glacial activity. These relict landforms can support the understanding of past climate conditions, such as during the Last Glacial Maximum (LGM), and the implications that these paleoclimatic conditions could have had on landscape change. Here, we present and analyze glacial morphologies for the Chirripó National Park in Costa Rica based on aerial imagery (1:25,000), detailed Digital Elevation Models, geomorphic mapping, as well as geomorphic assessments in the field to determine and validate landforms. This study adds valuable insights into the reconstruction of the maximum expansion of tropical glaciation during the LGM in Costa Rica and into tropical America glacial landscapes in general.

1. Introduction

Past fluctuations of tropical glaciers provide important paleoclimate proxies for regions where other forms of evidence are generally scarce (Benn et al., 2005). During the Last Glacial Maximum (LGM), numerous valley glaciers advanced above 3000 m asl in the tropics of America, and more particularly in mountain regions of Mexico, Guatemala, Costa Rica, the Dominican Republic, and along the Andes (Lachniet & Vázquez-Selem, 2005; Mark et al., 2005; Vázquez-Selem & Lachniet, 2017) (Figure 1).

Several past studies have focused on the description of Pleistocene and Quaternary glaciers in Costa Rica since the late nineteenth century when Henri Pittier described the presence of past glacial activity on the high peaks of the Cordillera de Talamanca (Castillo-Muñoz, 2010). More than half of a century later, Weyl (1955) used aerial photographs and field observations to document and explain the glacially molded landscape. Hastenrath (1973) mapped numerous glacier lakes and cirques at the top of Cordillera de Talamanca. Other studies such as those of Bergoeing (1977), Barquero and Ellenberg (1983), Shimizu (1992), and Wunsh, Calvo, Willsher, and Seyfried (1999) presented large-scale maps derived from aerial photographs to illustrate the glacial morphology of Cerro Chirripó. Lachniet and Seltzer (2002) and Lachniet, Seltzer, and Solis (2005) mapped large glacial extensions of late Pleistocene glaciers as well as some erosive and depositional morphologies of the glacial valleys in the surroundings of the Cerro Chirripó. These authors mapped 35 km² of the Cerro Chirripó area and mention that the local ELA (equilibrium line altitudes) was located at 3500 m asl. Nevertheless, they also suggested that in surrounding areas, the ELA may have descended to 3200 m asl. More recently, Quesada-Román and Zamorano-Orozco (2018) described the glacial geomorphology of the Upper General River Basin, whereas, Li et al. (2019) mapped 22.1 km² of the surfaces with glacial remnants around Cerro Chirripó.

In recent decades, most studies focused on the dating of these glacial-like geomorphic features. For instance, Horn (1990) used charcoal and pollen analysis to determine the end of glacial dynamics in the largest lake of Valle de las Morrenas at ca. ∼10 ka. Orvis and Horn (2000) concluded that deglaciation occurred between 12.36 ka and before 9.7 ka, which then ultimately ended at ca. 8.580 ± 70 BP. More recently, Potter, Li, Horn, and Orvis (2019) used 36Cl, whereas Cunningham, Stark, Kaplan, and Schaefer (2019) utilized 10Be cosmogenic nuclides to determine that the maximum glacial extension age in Chirripó National Park corresponds with the LGM (∼26.5–19 ka). These novel studies agree with previous work that estimated ELA during the LGM were at 3500 m asl around Cerro Chirripó.

Despite the plethora of studies in the region, a detailed glacial geomorphic map for the entire protected area of the Chirripó National Park has not
been realized so far, which therefore limits the understanding of the glacial extent and its dynamics during the LGM in one of the least studied regions of the world. In this study, we therefore aim at conducting a geomorphic mapping of the entire Chirripó National Park at a scale of 1: 25,000, with a focus on glacial erosion and deposition landforms, as a basis for further studies of this tropical mountain region and a better understanding of climatic implications of these paleo-landforms in a more regional context.

2. Materials and methods

2.1. Regional setting

The study area is located in the Cordillera de Talamanca, the most prominent mountain system in Central America extending 175 km from the central-southern portion of Costa Rica to the eastern sector of Panama (Marshall, 2007). The Chirripó National Park, established on 19 August 1975, is located in the central part of the Cordillera de Talamanca (Figure 2).

The landscape of the study area is the result of the subduction processes between the Cocos and Caribbean plates, which has implications in terms of regional volcanism and seismicity (Alvarado et al., 2017; DeMets, Gordon, & Argus, 2010). In SE Costa Rica, the collision of the Cocos Ridge, a sequence of an oceanic crust growth from the Galapagos hotspot, stopped volcanism in the Cordillera de Talamanca some 2 Ma ago (Dzierma et al., 2011; Morell, Kirby, Fisher, & Soest, 2012). Consequently, this region has experienced high uplift rates ranging from 1.7 to 8.5 m kyr$^{-1}$ (Gardner, Fisher, Morell, & Cupper, 2013). Geology of the national park includes andesitic volcanic rocks of Upper Miocene volcanism (17-11 Ma), granodioritic plutonic rocks of the Mid-Upper Miocene (12.5–7.5 Ma), and plutonic alkaline rocks of post-intrusive magmatic pulses from 5 to 2 Ma (Alfaro, Denyer, Alvarado, Gazel, & Chamorro, 2018). Two faulting systems control Chirripó National Park, the first one consists of reverse component faults with NW heading; the second contains sinistral heading displacement faults, towards the NE (Alfaro et al., 2018). Vegetation in the national park includes different types of mountainous forests and peatlands. At elevations exceeding 3000 m, páramo landscapes prevail, a grassy or shrub-dominated ecosystem typical
of cool and wet upper hills of tropical mountains, above the tree line (Kappelle & Horn, 2016). Along these landscapes in the higher mountains of Costa Rica, hundreds of palustrine and lacustrine wetlands deliver paramount hydrological and ecological functions (Esquivel-Hernández et al., 2018; Esquivel-Hernández et al., 2019; Veas-Ayala, Quesada-Román, Hidalgo, & Alfaro, 2018).

Local climate is controlled by northeastern trade winds, the latitudinal migration of the Intertropical Convergence Zone, cold fronts, and the seasonal influence of Caribbean tropical cyclones (Alfaro, Quesada-Román, & Solano, 2010; Campos-Durán & Quesada-Román, 2017; Quesada-Román, 2017). These circulation processes produce two rainfall maxima, one in May and one in October, which are interrupted by a relative minimum between July and August known as the Mid-Summer Drought (Quesada-Román, 2016; Zhao, Oliver, Ballesteros, Vargas-Hernández, & Holbrook, 2019). Along these mountains, the active regional and local tectonics, in addition to intense rainfall, favor the occurrence of landslides (Quesada-Román & Zamorano-Orozco, 2018).

2.2. Geomorphological mapping

The Main Map was realized in three phases beginning with pre-mapping aerial photo interpretation (API) followed by fieldwork and finishing with GIS post-mapping (Chandler et al., 2018; Smith, Paron, & Griffiths, 2011). During pre-mapping, the morphogenetic map was generated based on aerial photo interpretation at a 1:25,000 scale from the CARTA project (Costa Rica Airborne Research and Technology Applications), a NASA mission which mapped Costa Rica between 2003 and 2005 (CARTA, 2005). These aerial photographs were georeferenced and processed to accomplish the geomorphic mapping. The method allowed to map the genesis, dynamics, morphology, evolution, and age of the different erosional and depositional glacial landforms (Verstappen, Zuidam, Meijerink, & Nossin, 1991) and digital graphic techniques to develop the final cartographic product (Bishop, James, Shroder, & Walsh, 2012). The fieldwork was conducted during four ground truthing missions in July 2016, July 2017, and January 2018 to verify the different landforms dynamics and limits using a preliminary morphogenetic map at a 1:25,000 scale. During the final stage of the post-mapping, the legend and the color election for each landform were genetically chosen (Gustavsson, Kolstrup, & Seijmonsbergen, 2006). Finally, the map was edited within a Geographic Information System (ArcGIS 10.3).

3. Results and discussion

3.1. Glacial erosional landforms

The movement of ice masses molded the landscapes in the higher summits of the Cordillera de Talamanca, leaving rounded hills. These surfaces sum 29.7 km²
over 3500 m asl. We distinguish two types of volcanic slopes modified by glacial action, namely (i) subhorizontal surfaces in the lowest parts of glacial valleys and on mountaintops with slopes <15°, and (ii) edges of the continental divide with steeper morphologies and slope angles of up to 36°. The latter morphologies correspond with the exposed rocky terrains where glaciers left characteristic scars, p-forms, and striations. One such landscape can be found on Cerro Chirripó, the highest peak of Costa Rica with 3820 m asl (Figure 3a). The different dating procedures applied around Cerro Chirripó indicate that ELA during the LGM were never lower than 3500 m asl.

The volcanic slopes molded by periglacial action represent extensive surfaces located around the glacial molded hillslopes. According to Orvis and Horn (2000) and Lachniet and Seltzer (2002), ∼9 °C below present temperatures prevailed during the LGM on the summits of Chirripó National Park. These slopes were presumably affected weathering, frost action, mass movement, nivation, and frozen ground. Periglacial dynamics affected 51.6 km² of the area during the LGM or previous glaciations that could not be determined by radiometric dating so far. These surfaces are, however, rarely are located below 3000 m asl. Along these surfaces, rocky terrains are dominant with random presence of whalebacks, striations, p-forms, and scars. Both glacial and periglacial volcanic slopes sum 91 km², nowadays covered by páramo vegetation.

Cirques, by contrast, are defined by their amphitheater-like morphology induced by glacial abrasion on those slopes located close to the peaks (Figure 3b). Circles alignment have a clear tectonic control by local faulting with NW and NE orientation. The concave geometry is the result of LGM ice pressure on Miocene plutonic rocks and the resultant abrasion of bedrock; frost action and hillslope processes have molded these landforms ever since as Cerro Urán. In Chirripó National Park, two types of cirques can be found, namely continuous and discontinuous cirques. Continuous cirques are limited in extent, occupy small areas (individually), and are elongated or in the shape of arcs. Continuous cirques are well preserved, either because of their recent age or as a result of their altitudinal position. Continuous cirques tend to persist in the landscapes because of a lack of fluvial energy; therefore, they can be recognized without difficulty in the field. Continuous cirques developed between 3500 and 3820 m asl, with a clear majority located on the Caribbean side, probably because rainfall is smaller as compared to the Pacific side (3500 mm/year), which allowed preservation of this type of relief as Cerro Chirripó Grande.

Discontinuous cirques are arcs (typically ‘boomerang-shaped’) with concave slope geometries. These cirques contain well-developed fluvial systems and significant post-LGM fluvial erosion. The extent to which fluvial erosion has acted explains the discontinuity of these cirques. The fluvial headwaters and their tributaries have reached the basin divides and therefore interrupted or eroded the glacial cirques. Discontinuous cirques are much frequent on the Pacific slope where rainfall exceeds 5000 mm annually as the division between Valle de los Conejos and Laguna Ditkevi. This precipitation regime exacerbates erosion and mantles original landforms. The position of discontinuous cirques varies from 3450 to 3820 m asl.

Arêtes form when glacial erosion acts on two adjacent cirques, thus resulting in a narrow and sinuous crest, usually constituted by fresh, exposed bedrock with a convex shape or debris. Their existence depends on glacial activity in the first place, but also on bedrock competence (Figure 3c). At the study site, arêtes can be found at the continental divide and on the Caribbean side of the divide at elevations ranging from 3320 to 3780 m asl, typically on flat (<15°) summits of the Cordillera de Talamanca. Arêtes with sharp (rocky) geometry can, by contrast, be found in positions where two or more peaks join. Vegetation is generally absent on sharp geometry (rocky) arêtes, and this morphology is located on the highest elevations of the national park. Arêtes represent 35 units with variable areas ranging from 2793 to 135,028 m²; over 2840 m asl.

Riegels are large rock barriers sitting across a valley and are usually formed by resistant rock outcrops. In some cases, riegels create natural dams of lakes. They represent broad steps and are slightly inclined. A good example is Laguna Ditkevi, a glacial lake blocked by a riegel shaped by glacial abrasion (Figure 3d). Glacial valleys are found in riegels and characterized by their steep slope surfaces with a transition toward semi-plane relief with inclinations below 15°. The altitude of the riegels varies between 3000 and 3520 m asl and a total of 7 units were recorded in this study, four on the Caribbean and three on the Pacific slope.

Roches moutonnées are present in the valley bottoms, as traces of glacial abrasion that can be found in the form of striations, p-forms, scars and steps. One such example of roches moutonnées is Cerro Terbi with 0.32 km² (Figure 3e). A total of 18 roches moutonnées units (occupied by glacial lakes at present) could be found in Chirripó National Park at altitudes ranging from 3320 to 3680 m asl. These landforms are found on slopes <25° and are located mostly on the Caribbean side, within Miocene plutonic bedrock.

3.2. Glacial depositional landforms

Morphologies issued by the accumulation of glacial sediments at Chirripó National Park include moraines, till deposits, and glacial lakes. These forms are usually situated on convex slopes with ridge morphologies.
Some of these depositional landforms are rather ephemeral, whereas others are also well defined with considerable widths and lengths, especially in the case of lateral moraines.

Lateral moraines are found at the margins of glacial valleys; a vast majority (76%) of these moraines are on the Caribbean slopes (32 of 42). This finding is most likely related to the smaller rainfall totals on the Caribbean side of the summits, which has resulted in less erosion over time and in the preservation of moraines. The best preserved and most obvious moraine is the Valle Talari moraine with a length of 655 m and a width of 70 m (Figure 4a). In general terms, lateral moraines are located between 3140 and 3660 m asl and occur on slopes ranging from 8° to 35°. Various studies recognized the presence of lateral moraines in Chirripó National Park (Bergoeing, 2017; Hastenrath, 1973; Lachniet & Seltzer, 2002; Orvis & Horn, 2000; Weyl, 1955), but with much less detail due to the 1:40,000 or even less detailed aerial photos examined.

Till deposits often consist of poorly sorted debris without stratification, thus pointing to sediment bodies that have lost their original morphology. Indeed, material is arranged as a mantle in the valley bottoms that currently without defined morphology, or with a significant process of dismantling as in Valle de las Morrenas (Figure 4b) or Valle de los Conejos (Figure 4c). By contrast, the position within the glacial cirque supports the hypothesis that the small bodies of water found in these poorly distinct environments are indeed relict glacial lakes originating from the impoundment of glacier meltdown waters. A total of 15 till deposits have been identified in the glacial valley bottoms with slopes below 25° at elevations between 3100 and 3600 m asl.

The glacial lakes are interpreted as kettle ponds, cirque lakes, paternoster lakes, or ice-marginal lakes. They originate from glacial scouring processes leaving transversal depressions in the parent material. Twenty-one of these lakes are identified between 3480 and 3660 m asl, in areas with slopes <10° like in Valle de las Morrenas, Lago Chirripó (Figure 4d), and Laguna Ditkevi. Horn, Orvis, and Haberyan (2005) identified 19 glacial lakes (of which 17 match with the lakes mapped in our work), but with the objective to determine their physical and chemical conditions. Horn and Haberyan (2016) reported about 30 glacial lakes.
that occupied glacially molded surfaces of the Chirripó National Park.

4. Conclusions

Different studies of the glacial geomorphology of the Chirripó National Park and surrounding areas have been developed since the 1950s but this study gives, for the first time, a mapped area of \(~90 \text{ km}^2\) with detailed information (1:25,000 scale) of glacial and/or periglacial landscapes of the highest summits of Costa Rica was made. The present work also provides a geomorphic analysis of seven erosional landforms (volcanic slopes modified by glacial action and periglacial action, glacial cirques, arêtes, riegels, and roches moutonnées) and three depositional landforms (lateral moraines, till deposits, and glacial lakes). The Main Map provides new insights into LGM activity in tropical high altitude landscapes of Costa Rica, and can also serve as a base map for geographical, ecological, hydrological, climatological and geoheritage studies.

Software

ESRI ArcGIS 10.3 was used for map production including data management, digitizing and final layout generation of the geomorphological map.

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