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A review on the origins and controlling factors of the Santa Lucía landslide, Chilean Patagonia

Una revisión sobre los orígenes y factores controladores del deslizamento de Santa Lucía, Patagonia Chilena

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ABSTRACT: In December 2017, a catastrophic landslide affected the small town of Villa Santa Lucía, in the Chilean Northern Patagonia, killing 22 people and destroying nearly half of the village and a section of the main Highway 7. The landslide was first identified as a debris flow, to be later recognized as a rock slide-rock avalanche-debris flow sequence that started on the headers of Río Burritos valley, over 7 km away from the village. In this paper, we summarize a series of studies focused on understanding the failure mechanisms and controlling factors on the origin of the 2017 initial rock slide, which took place in an altered volcanic rock sequence and reached a volume of ca.9-12 million cubic meters. Through the combination of fieldwork, structure-from-motion photogrammetry, geotechnical tests, 2D and 3D numerical modeling, and kinematic analysis of the slope, we can propose a retrogressive, progressive failure mechanism combined with a kinematically favorable rock mass structure. The failure was favored by rock mass damage induced by stress changes due to recent deglaciation in the Burritos valley and triggered by heavy rainfall during an atmospheric river event that produced high saturation of the slope. This case study highlights the importance of combined geological and geotechnical analyses for the understanding of complex rock slope failures in paraglacial mountain settings.

KEYWORDS: Landslides, rock slides, paraglacial processes, numerical modeling.

1 INTRODUCTION

Mountain slope collapses such as large rock slides and rock avalanches are major geological hazards in high mountain environments. While they are less frequent than smaller landslides such as shallow soil slides, rock falls, or debris flows, they can still produce major damage given their large magnitude. Further, commonly the presence of ice, snow, or water in the slide initiation area in many cases produces the initial rock slides to derive into long-runout rock/ice avalanches and/or debris flows, which have a higher chance of impacting infrastructure and communities even if the failure occurs in a remote area (e.g. Guthrie et al. 2012, Shugar et al. 2021), as well as affecting ecosystems (e.g. Geertsema et al. 2022).

In Chilean Patagonia, large rock avalanches can be triggered by different causes, such as earthquakes (Sepúlveda et al. 2010) or heavy rainfall (Duhart et al. 2019, Sepúlveda et al. 2024). The presence of steep glaciated valleys, in many cases with retreating glaciers, active tectonics, and wet climates favor the occurrence of landslides. A recent example of a large rock slide that derived into a fatal debris flow is the case of the Santa Lucía landslide in December 2017, which caused 22 fatalities and the destruction of a large part of the small town of Villa Santa Lucía, Palena province, as well as a section of Highway 7 (“Carretera Austral”). In this paper, we summarize the results of a series of engineering geological studies carried out between 2020 and 2023 (Burgos 2022, Palma 2022, Singh & Sepúlveda 2023 and 2024, Ochoa-Cornejo et al. 2024) to analyze the initial rock slide that originated the Santa Lucía disaster. Other studies (e.g. Duhart et al. 2019, Somos-Valenzuela et al. 2020, and references therein) have focused on the debris flow stage and its consequences, which are not covered in this paper.

1.1 Study area

The 2017 landslide originated in the headers of the Río Burritos valley, southwest of Yelcho Lake, about 70 km south of the city of Chaiten (43.36°S - 72.43°W, Figure 1). The river runs through a glacial valley in SE direction and then turns into a narrow NS valley, reaching an alluvial fan area where the village of Santa Lucia is emplaced, about 8 km from the landslide source (Figure 1). The initial slide is located in the Cordon Yelcho mountain range, with intense glacial activity during the last glaciation, and which is still partly covered by glaciers. One of these glaciers, named CL111023182 in the official Dirección General de Aguas glacier inventory is located in the headwaters of Río Burritos, with ice remnants that can be observed in the landslide toe area and the main glacier body a few hundred meters upstream (Figures 1 and 2).

The rock slide originated in a sequence of volcanic rocks of the Cordón Yelcho Volcanic Complex, mainly lapilli tuffs and breccias of andesitic to dacitic composition, which present an intense, pervasive hydrothermal alteration (Sernageomin 2018, Duhart et al. 2019). The volcanic sequence overlays a tonalitic intrusive, cut by significant metric-width basaltic dikes (Sernageomin 2018, Duhart et al. 2019). The volcanic layers are arranged sub-horizontally and exhibit marked sub-vertical fractures. The Liquiñe-Ofiqui fault zone is the main structure in the region, though no fault trace is observed locally in the landslide source area.

The initial rock slide had an estimated volume, using the SLBL method, of ca. 9.1 Mm3 for the main failure, and up to 12.5 Mm3 when secondary failures are included (Singh & Sepúlveda 2023; 2024). The rock slide derived into a rock and ice avalanche and then into a debris flow (Figures 1 and 2), of which about ca.2 Mm3 impacted the village of Santa Lucía (Duhart et al. 2019). The landslide was triggered during a Summer atmospheric river that lasted 2 days, with 122.8 mm in the 24 hours before the slide and a high 0°C isotherm over the mountain tops (Palma 2022, Sepúlveda et al. 2024).

2 PREPARATORY AND CONDITIONING FACTORS

The initial rock slide (Figure 2) took place in a paraglacial environment (Ballantyne et al. 2002, McColl 2012) with a recent glacial retreat (Palma 2022, Ochoa-Cornejo et al. 2024). The landslide is a reactivation of an older rock slide and has been shown through numerical modeling that geotechnical conditions of the volcanic rocks, the rock mass structure, and deglaciation history can be identified as key conditioning or preparatory factors (Palma 2022, Ochoa-Cornejo et al. 2024, Singh & Sepúlveda 2024). Conditioning or preconditioning factors are those static and inherent to the slope, such as lithology and structure, while preparatory factors are dynamic and reduce the stability of the slope over time, without actually starting movement (McColl 2012).

2.1 *Lithology and geomorphology*

As mentioned above, the rock slope failure took place in hydrothermally altered pyroclastic rocks. The argillic alteration reduced the rock strength of these rocks (Figure 2), making them prone to instability in steep slope conditions, such as the old landslide scarp where the failure took place, with slopes of up to 70-80° and ca. 350 m height in an amphitheater-shape scarp, laterally unconfined on the west side (Figure 2). Laboratory tests in blocks of tuffs returned a compressive strength of 35 MPa and a tensile strength of 7 MPa (Palma 2022), which can be considered as upper bounds for the altered rocks.

Figure 1. (A) and (B) Location of the Santa Lucía landslide in the southern tip of South America (Patagonia) and the Palena province. (C) Extension of the landslide from the initiation rock slide zone (yellow circle), through the Río Burritos valley and down to Villa Santa Lucía (red star).

2.2 *Rock mass structure*

The rock mass in the slide generation area is moderate to highly fractured, with average GSI values around 40 for the volcanic rocks (Palma 2022, Ochoa-Cornejo et al. 2024). A kinematic analysis of the discontinuities based on photogrammetric data (Figure 2) was performed by Singh & Sepúlveda (2024). Four main discontinuity sets were identified, three of which favor a combination of wedge and planar failure mechanisms in the main scarp, predominantly in central and crown regions. Another wedge failure is kinematically feasible at the lower angle slope toe, where failure is suspected to be initiated (Singh & Sepúlveda 2024).

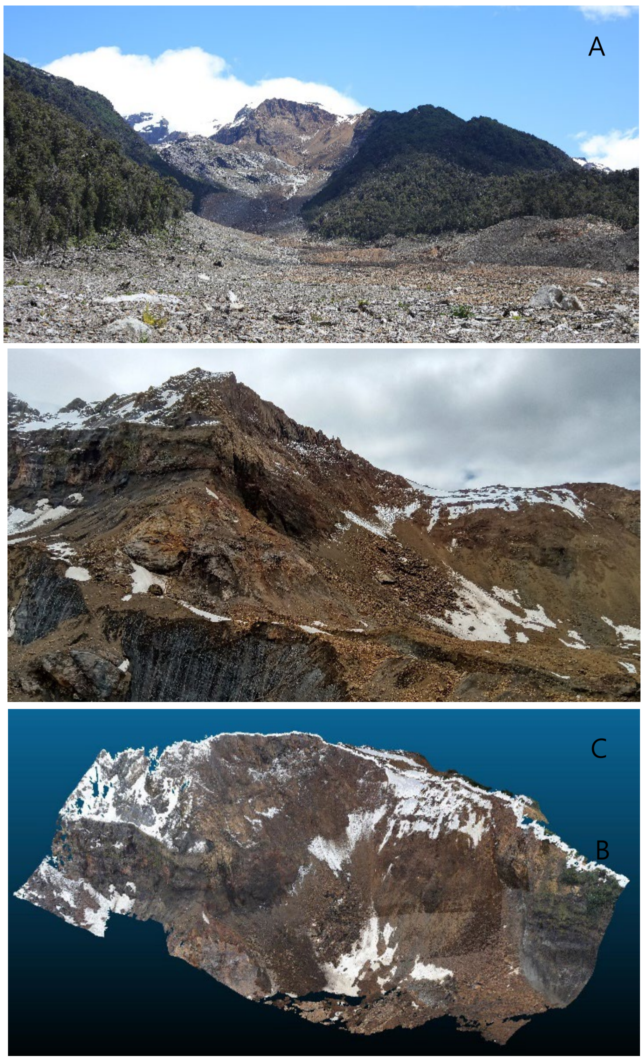

Figure 2. (A) Panoramic view of the Río Burritos valley, Santa Lucía initial rock slide (background), and debris flow deposits (foreground). (B) Close view of the rock slide scarp in hydrothermally altered volcanic rocks. (C) 3D model from airborne SfM photogrammetry used for the kinematic and stability models of the rock slope failure.

2.3 *Deglaciation and rock damage*

The presence of a retreating glacier in the valley suggests a debutressing effect on the slopes. This hypothesis was tested by Burgos (2022), Palma (2022), and Ochoa-Cornejo et al. (2024) using numerical modeling, in which the loading-unloading cycle of the last glaciation was modeled. The results suggest that deglaciation generated significant rock damage, with increasing stress concentration in the joints and rock mass that favored the occurrence of the landslide, although other factors such as kinematic feasibility and a final trigger, in this case, heavy rainfall, were still necessary to induce the slope collapse. In that sense, deglaciation can be considered a preparatory factor for the landslide (McColl 2012).

3 LANDSLIDE FAILURE MECHANISMS

Preliminary 2D modeling in UDEC by Burgos (2022) suggested a progressive failure mechanism from toe to top, aided by rock damage due to deglaciation. Further modeling in 3DEC by Singh & Sepúlveda (2024, Figure 3) included the kinematic effect of jointing, proposing an initial failure at the toe that propagates upward. The release by the main slide allowed a secondary failure on the left flank. A reduced strength was necessary to induce slope collapse, which can be explained by the rock damage induced by deglaciation (Singh & Sepúlveda 2024). Finally, numerical modelling in 3DEC shows increasing displacements with higher saturation, confirming the role of high-rate water infiltration as a main trigger for rock slope failure (Palma 2022, Ochoa-Cornejo et al. 2024).

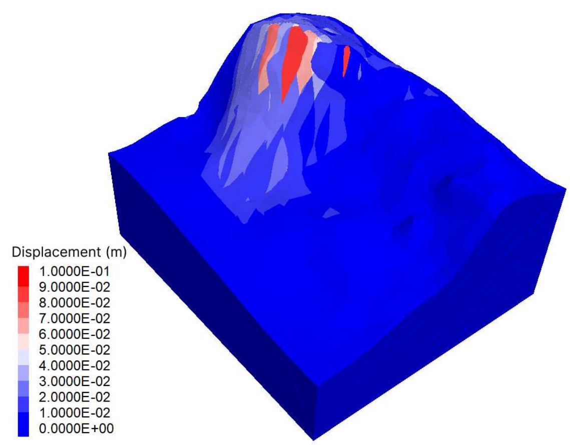

Figure 3. Example of 3D numerical modelling showing displacements and structure control on the slope failure (modified from Singh and Sepúlveda, 2024).

4 CONCLUDING REMARKS

This case study highlights the complexity of large rock slope failures in paraglacial settings. A combined effect of reduced strength due to hydrothermal alteration and rock mass damage induced by glacial retreat, favorable slope morphology with steep slopes and lateral freedom due to glacial erosion and previous landslide activity, kinematically favorable geological structures, and a rainfall trigger related to an atmospheric river, generated long-term and short-term conditions to generate a rock avalanche with catastrophic consequences far downstream. A comprehensive engineering geological approach including fieldwork, laboratory geotechnical testing, remote sensing analysis, and numerical modeling proves to be a good method for better understanding complex rock slides and improving landslide hazard assessment in high mountain regions. More investigations on the mechanics of rock damage induced by deglaciation would benefit more detailed insights into the failure mechanics for this type of slope collapses.

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