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The Santa Lucia disaster: rockslide and landslide in the Chilean Patagonia

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ABSTRACT: As climate change accelerates deglaciation, its effects on slope stability in glacial valleys become increasingly prominent, influencing the frequency of large landslides and cascading geohazards. On December 16, 2017, a major rockslide near a retreating glacier in Chilean Patagonia transformed into a debris-mud flow that struck Villa Santa Lucía, resulting in 22 fatalities and significant damage to infrastructure, connectivity, and the economy. This incident occurred in a volcanic-dominated valley experiencing recent deglaciation within a paraglacial setting, triggered by heavy rainfall. The study employs a three-dimensional numerical model and analysis to examine how glacial processes contributed to the gradual paraglacial failure, with rainwater infiltration acting as the immediate trigger. Geological and geotechnical characterization involved field reconnaissance, sample collection, and laboratory testing. The geological context was reconstructed through 3D modeling of glacial stages, incorporating the valley's glacial history. Simulating the historic hydrometeorological event helped identify key failure factors, which originated at the slope's toe. Results show that deglaciation weakened the rock slope by increasing stress concentrations, forming critically stressed joints, and predisposing it to failure. Ice retreat caused ongoing deterioration, while rapid water infiltration during extreme rainfall led to quick saturation and ultimately triggered the slide. The study emphasizes that paraglacial rock slopes may undergo progressive deterioration during glacier retreat, with hydrological events acting as final triggers. This underscores the importance of including realistic glacial histories in hazard assessments. A comprehensive understanding of these processes is essential for the development of monitoring systems and decision-making strategies, particularly in regions where glacier retreat increases the risk of catastrophic slope failures.

KEYWORDS: Rock slides, Progressive failure, Paraglacial environment, Deglaciation, Climate change.

1 INTRODUCTION

Landslides represent one of the natural hazards with significant repercussions for human life, infrastructure, and the economy (e.g., Tan et al., 2020; Sepúlveda and Petley, 2015; Froude and Petley, 2018). Their impacts are especially critical in mountainous regions characterized by steep slopes, complex geology, and dynamic geomorphic processes.

The Andes exemplify this vulnerability through their steep relief, elevated erosion rates, and structurally complex rock formations that make them unstable (e.g., Schuster et al., 2002; Antinao and Gosse, 2009; Moreiras and Sepúlveda, 2015; Serey et al., 2020). In Chile, where mountains occupy 80% of the land, large-volume rock slides and avalanches occur alongside hazards such as significant earthquakes and volcanic eruptions. Although landslides are frequently associated with climatic or seismic triggers (e.g., Welkner et al., 2010; Sepúlveda et al., 2010; Oppikofer et al., 2012; Moreiras and Sepúlveda, 2015; Serey et al., 2019), the impact of long-term processes such as progressive slope weakening or deglaciation has only recently been investigated within the Andes region (e.g., Sepúlveda et al., 2021, 2023; Ochoa-Cornejo et al, 2025).

Glacial cycles significantly impact slope stability. The loading of ice during glaciations can serve to stabilize slopes, while also eroding and steepening valley walls. Upon the melting of glaciers, the stabilizing load is removed, which redistributes stresses, increases fracture growth, and gradually weakens rock masses over time, making slopes more susceptible to failure following glacier retreat.

Numerical modelling has extensively documented these processes in the Alps, analyzing mechanical effects in paraglacial environments (Eberhardt et al., 2004; Leshchinsky et al., 2015; Grämiger et al., 2017). Eberhardt et al. (2004) demonstrated that deglaciation gradually leads to rock mass degradation, which can trigger large landslides. Recent studies by Grämiger et al. (2017, 2018, 2020) have incorporated thermo-hydro-mechanical factors to broaden the understanding of glacier-associated slope failures.

In the Andes, such analyses are rarely conducted, even though rapid glacier retreat is evident in Patagonia and other mountain areas. This gap in understanding is essential because ice loss preconditioning, combined with hydrometeorological or seismic triggers, could lead to devastating landslides in populated valleys.

One of the most serious recent incidents occurred on December 16, 2017, near Santa Lucía in Chilean Patagonia. A large rockslide fell from a steep slope and struck the debris-covered end of a retreating glacier. The impact turned the slide into a fast-moving debris–mud flow that traveled for several miles, causing the deaths of 22 people and destroying a significant part of Villa Santa Lucía.

This study uses three-dimensional numerical modeling to analyze stress variations induced by the last glacial cycle. The simulations cover both loading and unloading phases, facilitating the assessment of rock mass damage over time and the identification of critically stressed regions. Furthermore, the models replicate hydrological conditions associated with the extreme rainfall event preceding the landslide, integrating long-term preconditioning with short-term triggers. The results support the hypothesis that glacier retreat contributed to slope destabilization. The retreat of ice likely redistributed stresses within the rock mass, resulting in joint and fracture opening and propagation. This continuous damage diminished the mechanical strength of the rock, leading to instability. The intense rainfall probably caused rapid water infiltration and elevated pore pressures, particularly in the fractured toe zone, thereby acting as the final triggering mechanism.

These insights are crucial for comprehending this particular event and for broader hazard assessments in the deglaciating mountainous regions of South America. As glaciers continue to melt rapidly due to ongoing climate change, analogous events might be likely to occur more frequently, resulting in significant landslides. It is essential to integrate glacial history into hazard models to enhance monitoring and early-warning systems within susceptible communities.

Finally, the findings contribute to the worldwide evidence linking climate change with an increase in landslide events (Crozier, 2010; Gariano and Guzzetti, 2016), emphasizing the significance of multidisciplinary approaches that integrate geological, climatic, and mechanical perspectives.

2 MAIN ASPECTS AND CONTEXT OF THE EVENT

Villa Santa Lucía (43.413° S, 72.367° W) is located within a tectonic valley at an approximate elevation of 200 meters above sea level, southwest of Yelcho Lake, and is situated 77 kilometers south of Chaitén in Palena Province, Los Lagos Region, Chile (Duhart et al., 2018). The village covers an area of approximately 1.68 square kilometers and has a population of fewer than 300 residents (INE, 2019).

The regional drainage network includes the Burritos and Frío rivers, which originate from the western slopes and traverse toward the central valley, continuing southward. The Burritos River flows through Villa Santa Lucía's alluvial deposits for a distance of 3 km before conjoining with the Frío River (Duhart et al., 2018, 2019; Fig. 1).

The village is bordered by the Cordón Yelcho Volcanic Complex, a 15 km glacier-covered mountain range extending northwest to southeast between latitudes 43.26° and 43.37° S and longitudes 72.33° and 72.55° W. The peaks rise to 2,100 meters above sea level, featuring steep, radial valleys and nearly vertical cliffs (Duhart et al., 2018). Structurally, the Liquiñe-Ofqui Fault Zone (LOFZ), an active dextral strike-slip fault running north-south, crosses Villa Santa Lucía, making the region susceptible to seismic activity and potential landslides (Cembrano et al., 1996).

Figure 1 illustrates the local geology, including metamorphic, granitic, volcanic, and some sedimentary rocks (Sernageomin-BRGM, 1995; Duhart et al., 2019). The oldest units consist of Paleozoic amphibolitic schists, ultramafic rocks, gabbros, and amphibolites of the Main Range Metamorphic Complex. Jurassic-Cretaceous volcano-sedimentary rocks, while Miocene and Cretaceous tonalites and granites form the intrusive basement of the North-Patagonian Batholith. The Oligocene–Miocene La Silla Formation, a lacustrine sedimentary unit, is covered by andesitic-dacitic volcanic rocks from the Cordón Yelcho Volcanic Complex (~1.2 Ma). The landslide zone contains middle to upper Pleistocene volcanic rocks of the Cordón Yelcho Volcanic Complex, including lapilli tuffs and andesitic-dacitic blocks with widespread hydrothermal alteration (Duhart et al., 2018, 2019). Sub-horizontal volcanic layers exhibit prominent sub-vertical fractures. Tonalitic amphibole-biotite intrusions occur beneath, intersected by metric-width, sub-vertical basaltic dikes with an east-west orientation (Duhart et al., 2018, 2019).

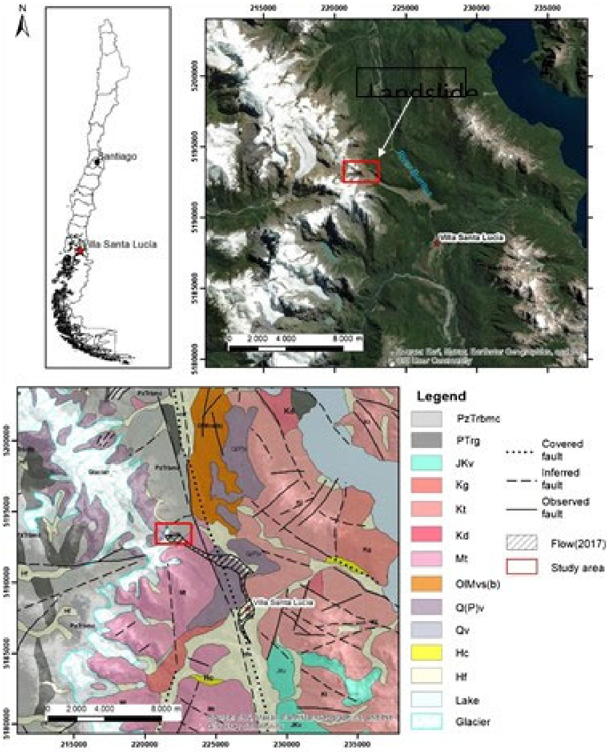

Figure 1. Location and geology of Villa Santa Lucía (modified from Duhart et al. 2019.

Villa Santa Lucía's glacial-tectonic valley shows signs of intense Pleistocene glaciation, such as polished rock surfaces, U-shaped valleys, subglacial lakes and rivers, and debris-covered glaciers with substantial ice-rich sediments (Duhart et al., 2019). Additionally, the valley experienced volcanic activity during the Upper Tertiary–Lower Quaternary period, leading to a complex mix of volcanic, glacial, fluvial, and alluvial deposits.

Holocene Patagonian glaciers have experienced multiple advances and retreats (Mardones et al., 2011). Two significant Holocene advances are recognized: Early Holocene (10,000–8,000 ^{14}C years BP) and Neoglacial (5,000 ^{14}C years BP to early 18th century). Recent studies show accelerated glacier retreat in the region (Barcaza et al., 2017; Carrasco et al., 2008; Rivera et al., 2000, 2008). Between 1985 and 2011, glaciers lost about 25% of their area (~293 km²), including in Cordón Yelcho (Paul and Mölg, 2014). Ugalde et al. (2022) report a 650 m retreat at Cordón Yelcho from 1987 to 2020, with rates reaching up to 30 m/year in the last decade.

Figure 2 presents a reconstruction of the Patagonian Ice Sheet in Palena province at 13, 10, 5, and 0.2 ka using the PATICE database (Davies et al., 2020), highlighting historical glacial extents relative to the Villa Santa Lucía area. This visualization complements Figure 1 by linking the geological setting with glacial history and retreat patterns relevant to landslide susceptibility.

3 SANTA LUCIA LANDSLIDE EVENT

On December 16, 2017, Villa Santa Lucía was struck by a devastating landslide that profoundly affected the village. At 9:03 a.m., a rockslide started at the headwaters of the Burritos River valley. This mass of loose rock and debris hit the toe of a receding covered glacier (CL111023182), causing a subsequent debris-mud flow that rushed down the valley. The flow reached Villa Santa Lucía, resulting in 22 deaths and destroying much of the town.

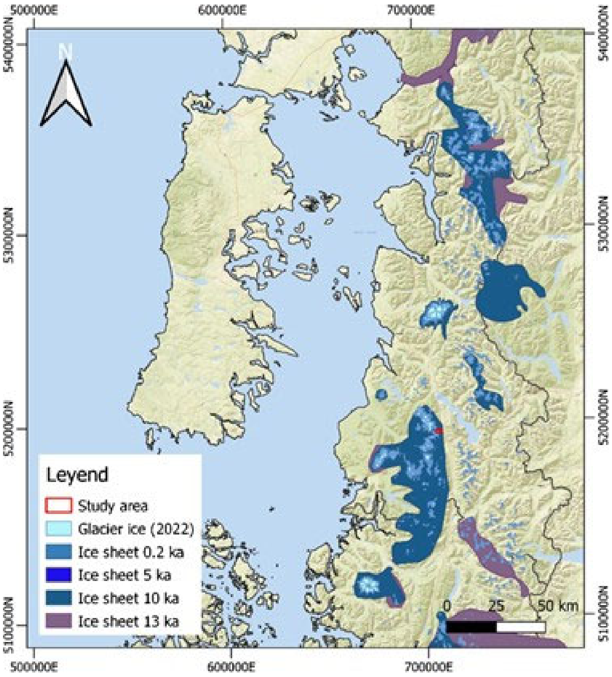

Figure 2. Ice sheet reconstruction (13, 10, 5, and 0.2 ka) for Palena province according to the PATICE database (Davies et al. 2020). Glacial ice data from DGA (2022). The study area is marked in a red rectangle (Ochoa-Cornejo et al, 2025)

Transportation infrastructure was severely impacted. Parts of Route 7 and Route 235 became unusable, cutting off the towns of Palena and Futaleufú from Chaitén for nearly three months (Duhart et al., 2018, 2019).

The volume of material mobilized in the event has been estimated in multiple studies. Duhart et al. (2018) estimated a total volume of 7.2 Mm³, including sediments, ice, water, and vegetation. Singh and Sepúlveda (2024) later revised this to 12.5 Mm³. Approximately 2 Mm³ of this material was deposited on Villa Santa Lucía itself, covering a fan area of 900,000 m². The upper portion of the flowing mass reached an average velocity of 72 km/h (Fernandez et al., 2018). However, the initial blast was likely faster due to uprooted trees and the tearing of vegetation along the valley walls (Duhart et al., 2019).

The landslide began in the headwaters of the Burritos River, at altitudes between 1,000 and 1,400 meters above sea level. The prominent escarpment, located on a northwest-facing, nearly vertical slope, has an elevation difference of about 350 meters. The semicircular crown measures around 800 meters long and 500 meters wide, covering an estimated area of 0.44 square kilometers (Fig. 4; Duhart et al., 2019; Sepúlveda et al., 2018). The northern slopes are the steepest, with angles between 77° and 81°. The rock slide scar remains potentially unstable, showing vertical fractures, open cracks, and a prominent hanging block (Duhart et al., 2019).

Figure 3 offers a detailed visualization of the landslide scar, showing the semicircular shapes, steep escarpment, and the orientation of fractured volcanic rocks. This figure depicts the geomorphological features of the failure zone, including the sub-vertical slopes, the overall size of the scar, and the shape of the source area, which are essential for understanding both the mechanics of slope failure and the behavior of debris flow afterward.

After the rock slide impacted the glacier, the debris-mud flow traveled about 8.6 km to the base of the fan at Villa Santa Lucía, significantly eroding the walls of the Burritos River valley (Duhart et al., 2018, 2019). The entire flow path, from its origin to where the Burritos and Frío rivers meet, was 12 km long.

Several factors conditioned the slopes and contributed to the landslide's occurrence:

- Steep slopes: Slopes in the Cordón Yelcho mountains within the source area reach 70–80°.
- Rock mass weaknesses: Volcanic rocks in the area show argillaceous hydrothermal alteration, intense sub-vertical fracturing, and open cracks.
- Glacial retreat: Receding glaciers in the Cordón Yelcho range reduced lateral support and increased debris accumulation.
- Volcanic ash deposits: The 2008 eruption of Chaitén Volcano left ash in nearby areas, obstructing riverbeds and estuaries.
- Abundant transport material: Loose sediments, water, and ice were readily available to feed the debris flow.
- High soil porosity: Porous volcanic soils facilitated rapid infiltration, contributing to material mobilization (Somos-Valenzuela et al., 2020).

Two principal triggers directly induced the mass movement. First, a high 0 °C isotherm at 2,771 m a.s.l., combined with liquid precipitation on the Cordón Yelcho glaciers in the days before the event, increased water availability (Duhart et al., 2018). Second, an intense hydrometeorological event on December 15–16, 2017, delivered 122.8 mm of precipitation in 24 hours—exceeding 99% of historical rainfall in the area. This event occurred in the context of unusually warm temperatures and followed two weeks of elevated heat (Rivera, 2017; Duhart et al., 2018).

The combination of steep, hydrothermally altered slopes, saturated soils, and glacier-ice interaction created optimal conditions for slope failure. The debris-mud flow that ensued was amplified by the loose volcanic material and the glacier impact, resulting in a high-mobility mass movement that traveled over 12 km to Villa Santa Lucía.

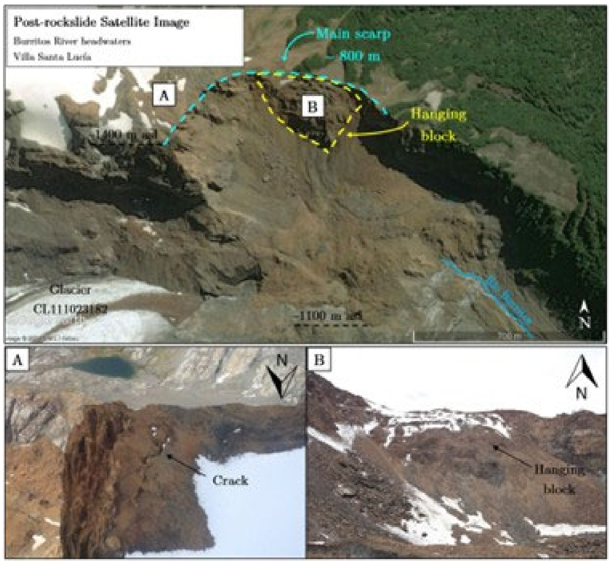

Figure 3. Post-rockslide configuration of the slope; (A) open crack on the prominent scarp and (B) current (2021) condition of the hanging block (Ochoa-Cornejo et al, 2025)

4 SANTA LUCIA LANDSLIDE MODELLING

The numerical analysis uses a three-dimensional discontinuous deformation approach with 3DEC, which has been effective in examining rock slope failures involving complex jointed media (e.g., Brideau et al., 2008; Longoni et al., 2016).

The pre-landslide topography was reconstructed from a 30 m-resolution ALOS PALSAR DEM (2011) and supplemented with a 1 m LiDAR DEM from MAPTEK (Duhart et al., 2018). This enabled the creation of a triangulated irregular network (TIN) and the delineation of surface geometries before and after failure. The slope consists of subhorizontal volcanic layers overlying tonalitic intrusions, with widespread subvertical fracturing. Four joint sets were included in the model, with orientations measured from satellite images and field surveys.

Rock mass parameters for tuff and tonalite were obtained from laboratory testing, with Hoek–Brown parameters adjusted to ensure model stability before applying external loads. Joints were modeled with Mohr–Coulomb parameters based on experimental data for rhyolite and tuff (Daemen et al., 2004; Read & Stacey, 2009).

Roller constraints were applied to the lateral boundaries, while the base was fixed in all directions. A gravitational load was applied with a hydrostatic initial stress state (k = 1). Elastic and plastic phases were run to reach equilibrium before simulating glacial and hydraulic effects.

The effect of glacier loading and unloading was evaluated in two scenarios: Case 1 (uniform unloading) and Case 2 (unloading according to glacial history).

Case 1 – Uniform Unloading. The glacier was modeled as a hydrostatic pressure acting on a horizontal ice surface, initially at 1500 m a.s.l., gradually reduced to ice-free conditions over 58 stages. The stress from the ice load was proportional to ice thickness and density.

Figure 4 illustrates the maximum shear strain increase across four glacial stages (I–IV). In Stage I (full ice cover), high strain levels (up to 1×10^{-4}) were focused from mid-slope to toe. As unloading progressed, strain decreased but stayed significant in certain areas. In Stage IV (ice-free), the strain amplitude dropped to 0–2.5×10^{-5}, yet much of the slope still exhibited elevated strain, corresponding to the eventual landslide zone. This ongoing deformation demonstrates the long-term destabilizing impact of deglaciation, even after the ice disappeared. Profiles across the slope revealed that during early loading, deformation was concentrated in the lower slope, but by the final stage, strain was more evident upslope. Displacement vectors also changed from ice-pressure-driven movement in Stage I to downslope-oriented instability in Stage IV.

Case 2 – Unloading Based on Glacial History. This scenario modeled glacial retreat from the Last Holocene Glacial Maximum (LGMh) to the Little Ice Age (LIA), then to the glacier extent in 1986, and finally to an ice-free state, following Rivera (2017). Shear strain patterns were generally similar to Case 1 but showed localized differences due to the inclined glacier surface. Maximum strain decreased from 1×10^{-4} to 2.5×10^{-5}, with zones of concentration moving upslope in later stages.

Given that intense rainfall preceded the landslide, hydrological modeling was performed after simulating complete deglaciation. The model introduced pore-water pressures by varying the Ru coefficient (ratio of pore pressure to overburden stress), with values of 0.10, 0.20, 0.30, 0.40, and full saturation.

Figure 5 illustrates the maximum shear strain increments under different saturation scenarios. At low Ru values (0.10), strain (~1×10^{-3}) was diffuse, but with Ru = 0.20, deformation concentrated in the upper scarp (~2×10^{-3}). At Ru = 0.30–0.40, strain intensified (~2.5×10^{-3}) and localized in the scarp area. The complete saturation scenario produced an extreme response, with critical deformation extending to currently intact sectors northwest of the main slide.

Profiles showed that higher Ru values increased both the depth and extent of shear strain. The longitudinal profile indicated instability across all scenarios, with maximum displacements rising from 0.15 m (Ru = 0.10) to 1.17 m (full saturation). The transversal profile showed smaller magnitudes but the same upward trend, peaking at 0.36 m under full saturation.

The modeling results reveal a two-phase destabilization mechanism:

- Deglaciation-driven progressive damage – As shown in Figure 4, the gradual unloading from glacier retreat induced persistent zones of shear strain that remained even after ice disappearance, preconditioning the slope for failure.
- Rainfall-triggered instability – As shown in Figure 5, high pore pressures from intense rainfall critically increased strain and displacement, particularly in the scarp zone. Full saturation produced deformation patterns extending beyond the current failure limits, indicating potential for future instability in adjacent slopes.

Deglaciation, even in the absence of other triggers, left the slope in a mechanically weakened state, with strain patterns aligning with the eventual landslide geometry. The role of rainfall was decisive in crossing the stability threshold, with pore pressure increases strongly amplifying deformation in pre-weakened zones. The combined effect suggests that other slopes in the Patagonian Andes with similar deglacial histories may be prone to rainfall-induced failures.

6 DISCUSSION

The numerical simulations of the Santa Lucía landslide relied on a reconstructed 2011 pre-slide topography. Although some DEMs contained glacier ice, its limited surface coverage likely had minimal impact on results. Landslide volume estimates from DEM comparisons exceed field estimates (7–10 m^3). Future work should further examine erosive and sedimentary processes influencing pre-slide morphology.

Glacial process modeling considered two unloading regimes—uniform and based on local Holocene glacial history (Rivera, 2017)—with hydrostatic stress used to represent ductile glacier loading. Both methods produced valid results, but historical stages offered a more realistic slope response. Progressive unloading reduced shear strain magnitude, yet residual strain remained concentrated in the eventual slide zone, indicating damage from deglaciation. This damage, combined with the loss of ice buttressing, increased slope susceptibility to triggers such as rainfall or earthquakes. Profiles showed strain propagation to approximately 150 m depth and critical joint states aligning with the landslide fault trace.

Deglaciation was found to progressively increase critically stressed discontinuities, especially in shallow areas exposed by glacier retreat, supporting a progressive failure mechanism. Two-dimensional CWFS modeling also indicated retrogressive failure surfaces similar to the 2017 event, consistent with Singh and Sepúlveda (2024).

The influence of rainfall was analyzed using a water table or Ru coefficient (0.10–0.40), including full saturation. At the same time, complete saturation caused extreme instability—even in areas not affected in 2017—the Ru = 0.40 scenario best matched observed failure conditions. Increasing saturation raised shear strain and displacement levels, with full saturation resulting in more than 1 meter of displacement in profiles.

Overall, results show that glacial cycles gradually weakened the slope, creating conditions for failure. Heavy rainfall and high saturation acted as immediate triggers, while the long-term damage from deglaciation contributed to the instability that caused the 2017 Santa Lucía landslide.

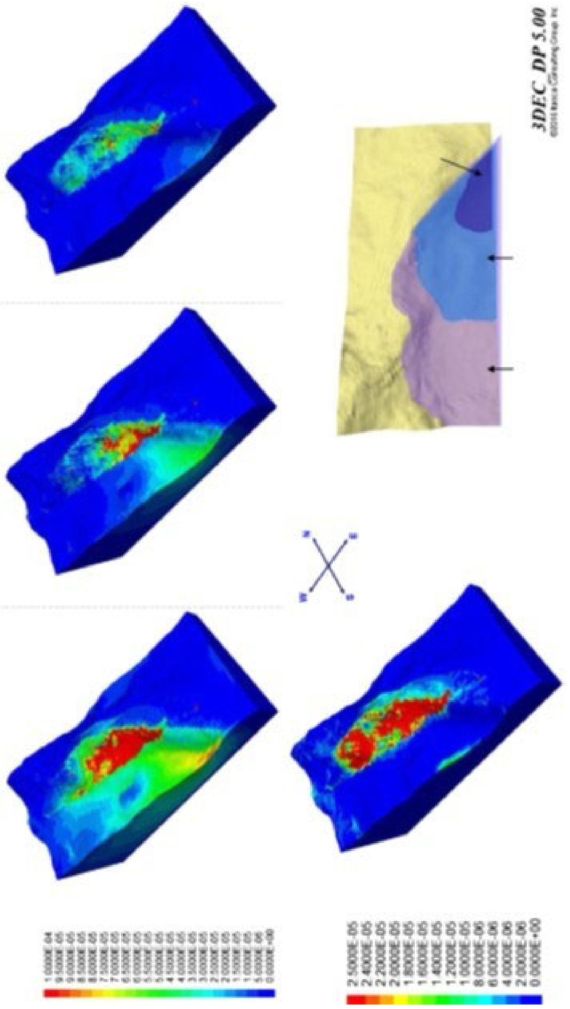

Figure 4. Maximum shear strain increment of each glacial stage (I, II, III, and IV). Case N°1, uniform unloading (Ochoa-Cornejo et al, 2025)

7 CONCLUSION

The 2017 Santa Lucía landslide was examined through 3D numerical modeling and analysis of the area's glacial history, showing that glaciation–deglaciation cycles can significantly weaken nearby slopes, making them more susceptible to paraglacial failures. This may be one of the earliest documented cases of its kind in South America. Modeling of Holocene glacial stages confirmed that glacial loading and unloading acted as preparatory forces, with an extreme rainfall event just hours before serving as the final trigger. Two glacier-loading approaches were tested: a simplified uniform unloading and a reconstruction of the actual glacial history, with the latter recommended for similar retreating glacier environments. Hydrometeorological triggers were assessed under both full and partial saturation conditions, indicating that even moderate saturation (Ru = 0.40) could initiate failure. Results show that deglaciation caused shear damage, gradually weakening slope structures and enlarging joints, consistent with a progressive failure mechanism. Although glacial processes significantly reduced stability, they alone did not cause the collapse; the extreme rainfall was essential in triggering the landslide. The study emphasizes that progressive degradation from glacier cycles, combined with extreme hydrological events, controls the timing of slope failure. The findings support incorporating realistic glacial histories into hazard assessments and suggest considering additional factors—such as ice meltwater infiltration, rainfall triggers, thermal effects, and hydrological parameters—when sufficient site-specific data are available. Given climate change's role in accelerating glacier retreat and increasing landslide risks, especially in geomorphologically vulnerable regions like the Andes, understanding slope behavior in paraglacial settings is crucial for risk mitigation and management in South America.

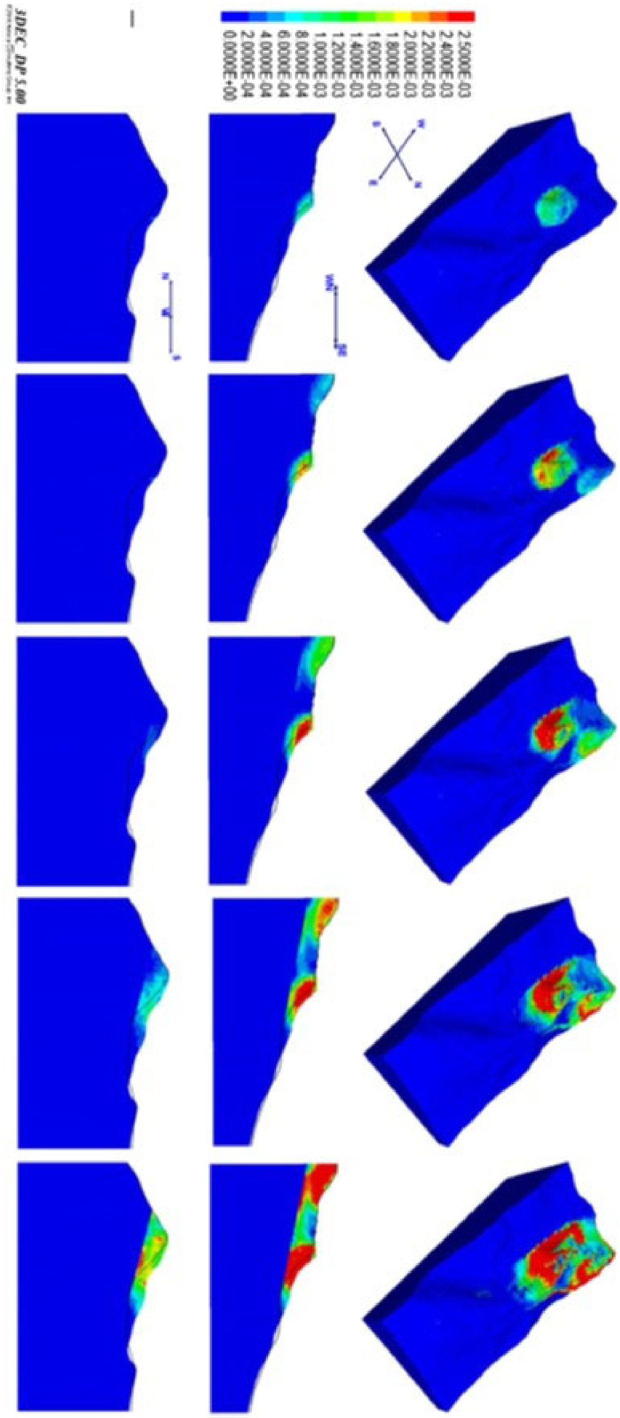

Figure 5. Maximum shear strain increment of each hydric scenario. General results and longitudinal and transversal profile results are shown in the top, middle, and bottom rows, respectively. (Ochoa-Cornejo et al, 2025)

8 ACKNOWLEDGEMENTS

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