Controls over debris flow initiation in glacio-volcanic environments in the Southern Andes

Response of authors

Reviewer #1:

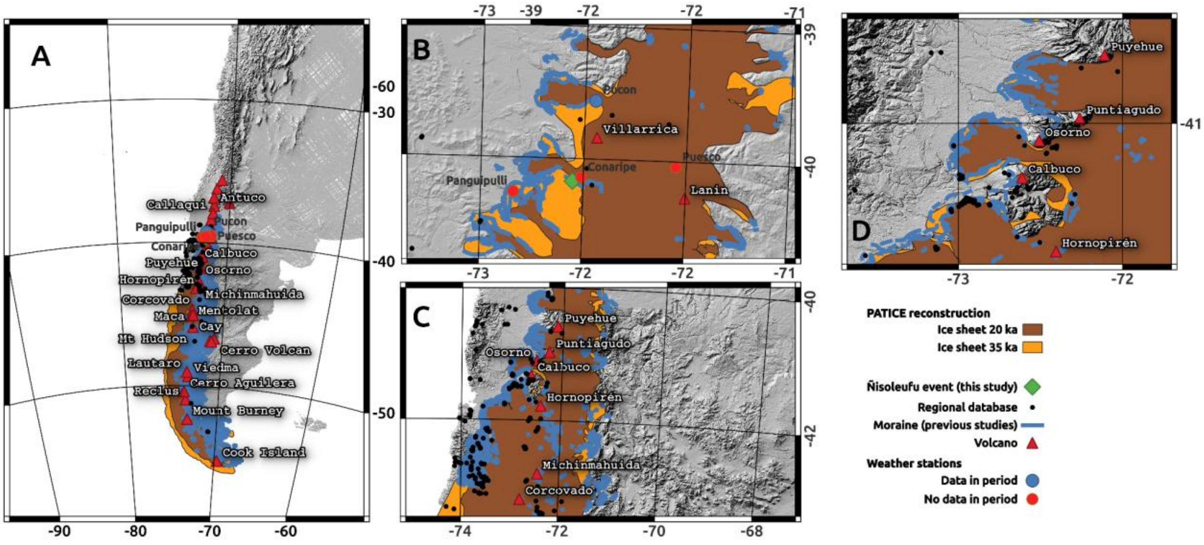
General comments:

This manuscript presents a comprehensive investigation into the initiation mechanisms of debris flows in the Southern Andes, with a focus on the Ñisoleufu event. The authors attribute this event to increasing soil saturation during an extreme rainfall episode under typical glacio-volcanic geological conditions, where a low-permeability basal layer promotes water retention in the overlying soil.

RC1_1: However, the extent to which this case represents common conditions across the Southern Andes, as implied by the title, has not been adequately discussed.

A: We agree. A new Figure 1 showing the emplacement of rainfall-induced landslides and debris flow was introduced. Also, new text was introduced in the Discussion section 5.3, “Regional implications and future scope”.

Figure 1 Rainfall-Induced mass wasting in Southern Andes. A) Regional map of Ice-sheet extension during 35 ka and 20 ka as example and volcanoes emplaced in the area. B) Zoom to study area with Ñisoleufu in Northen Ice sheet sector showing the weather stations. C) Zoom to Northern Patagonian area showing correlation between mass wasting events and moraine lines (blue line). D) Zoom to Osorno volcano area showing high debris flow generation area discussed in Fustos et al., 2022.



These figure was discussed in detail in the subsection 5.3

Additional paragraph:

The Ñisoleufu debris flow showed a characteristic pattern of mass wasting processes in the Southern Andes, becoming analogues to Petrohue event (Fustos-et al., 2021) in Osorno Volcano (Figure 1D). The occurrence of debris flows in the Southern Andes, particularly in the border of the maximum extension of the Patagonian ice sheet suggest that debris flows are typically related to saturated soils that can transform into more fluidic mixtures. Our observations and previous studies (Davies et al., 2020; Fustos et al., 2021) propose a strong correlation between debris flows and glacial landforms, particularly where the last glacial maximum shaped the relief (examples in Figure 1B and Figure 1C). The interaction of past glacial dynamics with contemporary environmental processes related to new precipitation patterns provides a backdrop for increased debris flow activities in Southern Andes based on rainfall-induced mass wasting data from Fustos et al. (2022). Stand out regions at the borders of these past glaciers tend to exhibit increased susceptibility to debris flow generation due to the combination of steep slopes and the prevalence of loose moraine deposits (Figure 1B and C), which can be mobilized during significant precipitation events (Sepúlveda et al., 2014).

RC1_2 Additionally, the overall structure and clarity of the manuscript require improvement, which currently undermines the value of the research. Further comments are detailed below.

A: We appreciate and agree with the reviewer's comments, focusing on his specific comments and making the suggested changes with the goal of improving the manuscript.

Specific comments:

1. **SC1_1 L32:** The opening sentence suggests that debris flows may result in extreme rainfall, which is likely a typographical error. Please carefully review the manuscript for similar errors.
    - **A:**We agree with R1 about the inconsistency of this idea. It was changed to: "*Episodes of extreme rainfall have increased due to climate change, resulting in a greater frequency of debris flows*..."
2. **SC1_2 Introduction:** The introduction requires restructuring. A clearer overview of the Southern Andes in terms of debris flow features and glacio-volcanic environments is needed. The current structure lacks coherence; for instance, the paragraph starting at Line 41 introduces the importance of understanding debris flows in inhabited regions but abruptly shifts to discussing the impact of climate change. At the same time, please reduce repetitive content about the research's significance.
    - **A:** We agree with reviewer 1 and 2. We have addressed all the requested modifications in our response to comment RC2_2. Now, we rewrite the introduction, introducing a paragraph 3 where we discuss the state of art in Southern Andes under glacio-volcanic point of view.

      New paragraph:

      > Nowadays, understanding the impact of debris flows in glacial environments become critical in the Chilean southern Andes, particularly due to the most part of the inhabitants lives there. Changes of precipitation patterns related to climate change, particularly fast and intense rainfall events, could amplify the frequency and magnitude of debris flows (Fustos et al., 2022). An increase of extreme hydrometeorological events affecting slopes in glacial settings is observed, whose mechanical properties and geomorphology have evolved since the Last Glacial Maximum (Fustos-Toribio et al., 2021b; Somos-Valenzuela et al., 2020; Ochoa-Cornejo et al. 2025). Considerable uncertainty remains about how the interaction between volcanic-derived soils over glaciar landforms will respond to extreme hydrometeorological events. One of the current model initiation of debris flow are related to slow deforming surface in hillslopes stand out, mainly due to gravity and surface erosion during high precipitation events (Xie et al, 2020; Yi et al, 2021). Slow surface deformation could lead to extensional failures that could expand and deepen, generating landslides and evolving into debris flows, especially under water-saturated conditions or heavy rainfall (Gregoretti, 2000; Fustos et al., 2017; Wang et al., 2024). The capacity to oversee these extensional failures in remote areas close to roads is an open question yet, mainly in Southern Andes.

3. **SC1_3 L104:** The authors mention that three complementary methodologies were used, yet only two are listed in the introductory paragraph of the methodology section.
    - **A:** Our apologies, is an error. Now we improved the redaction.

      Original text:

      > To achieve this, we employed three complementary methodologies.

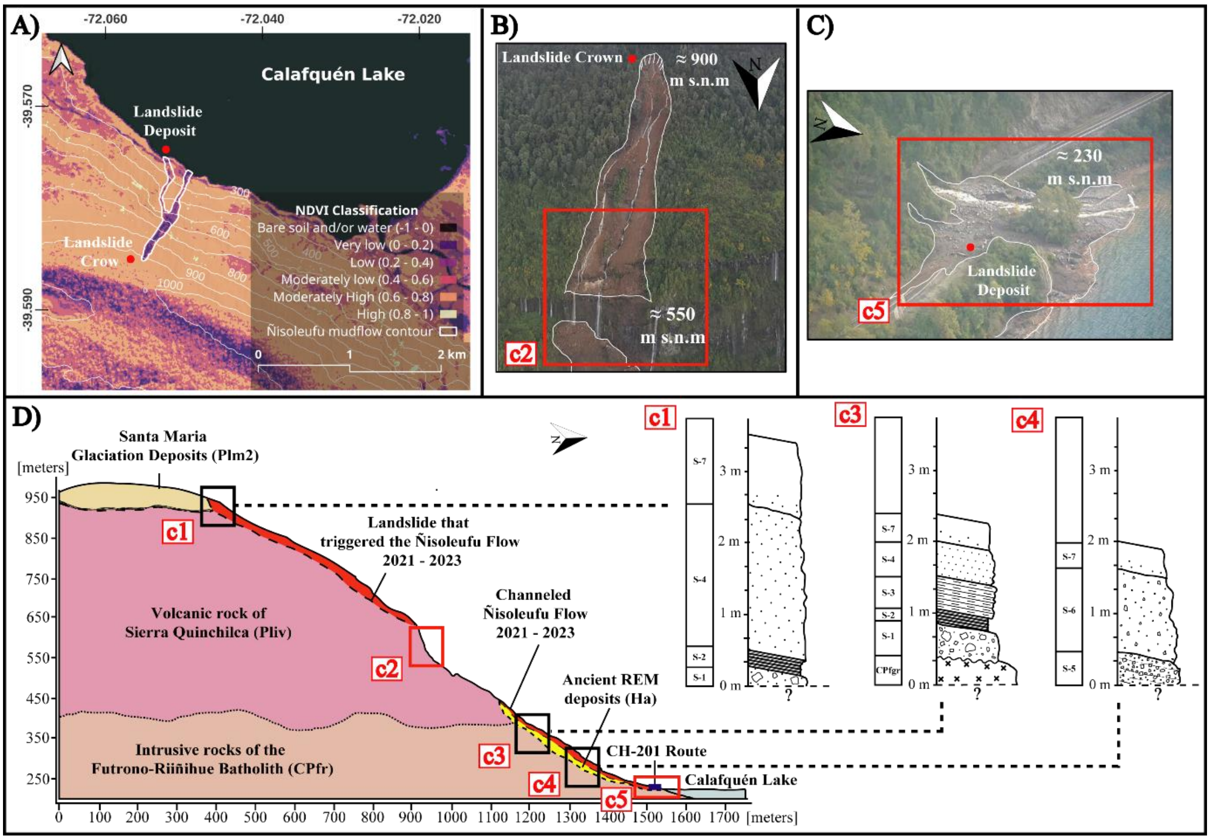
      Modified text:

      > To achieve this, we employed two complementary methodologies.

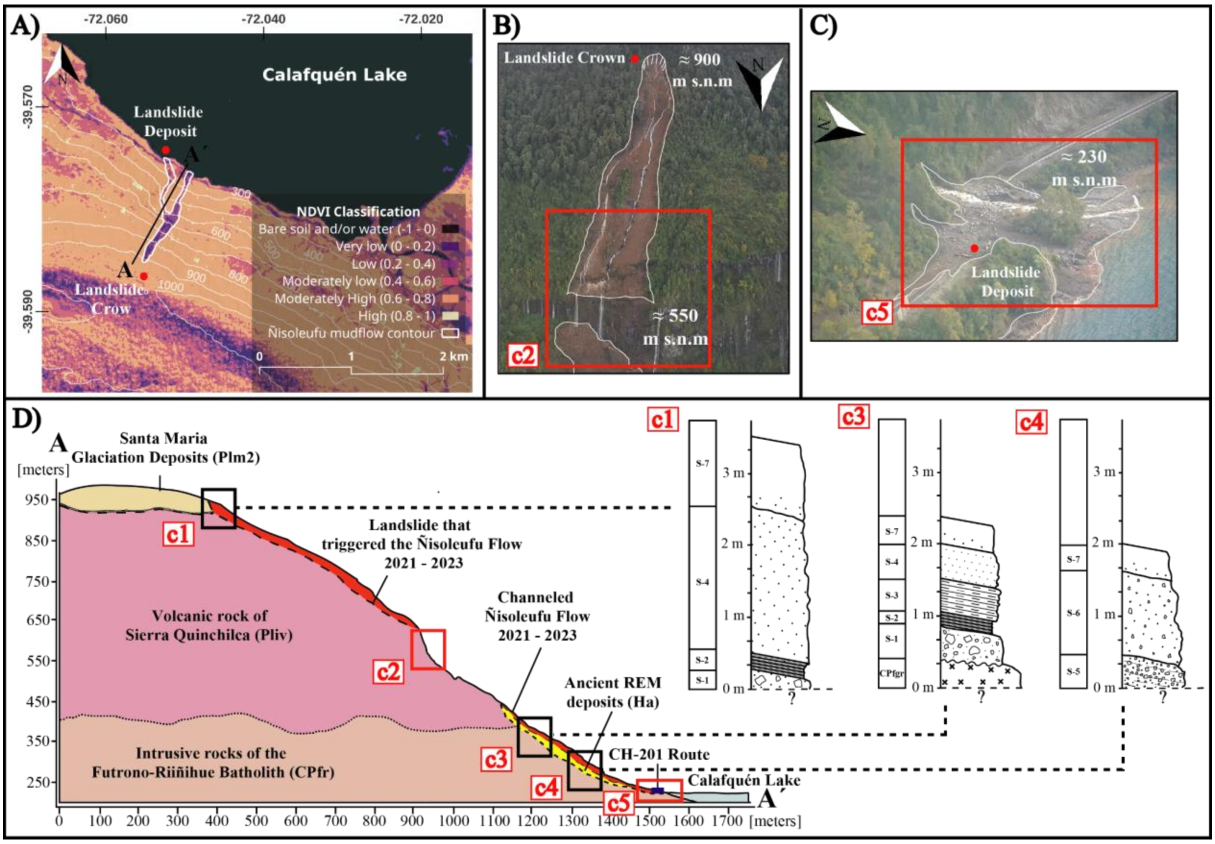
4. **SC1_4 Figure 4D:** It is recommended to display the position of the profile line in a plan view (e.g., in Figure 4A). Additionally, please consider replacing the north arrow with one indicating the slope direction angle, which would aid reader comprehension.

    A: We agree with the reviewer's comment. To improve the presentation of Figure 5A (previously Figure 4A), we have modified it to include the position of the profile line, labelled as AA′. This identifier also appears in Figures 2D and 2A (previous Figures 1D and 1A) to ensure consistency and facilitate interpretation. Additionally, we have removed the north arrow from Figure 5D and replaced it with an indication of the slope direction, aligned with the AA′ profile. This change is intended to enhance the reader's understanding of the topographic context.

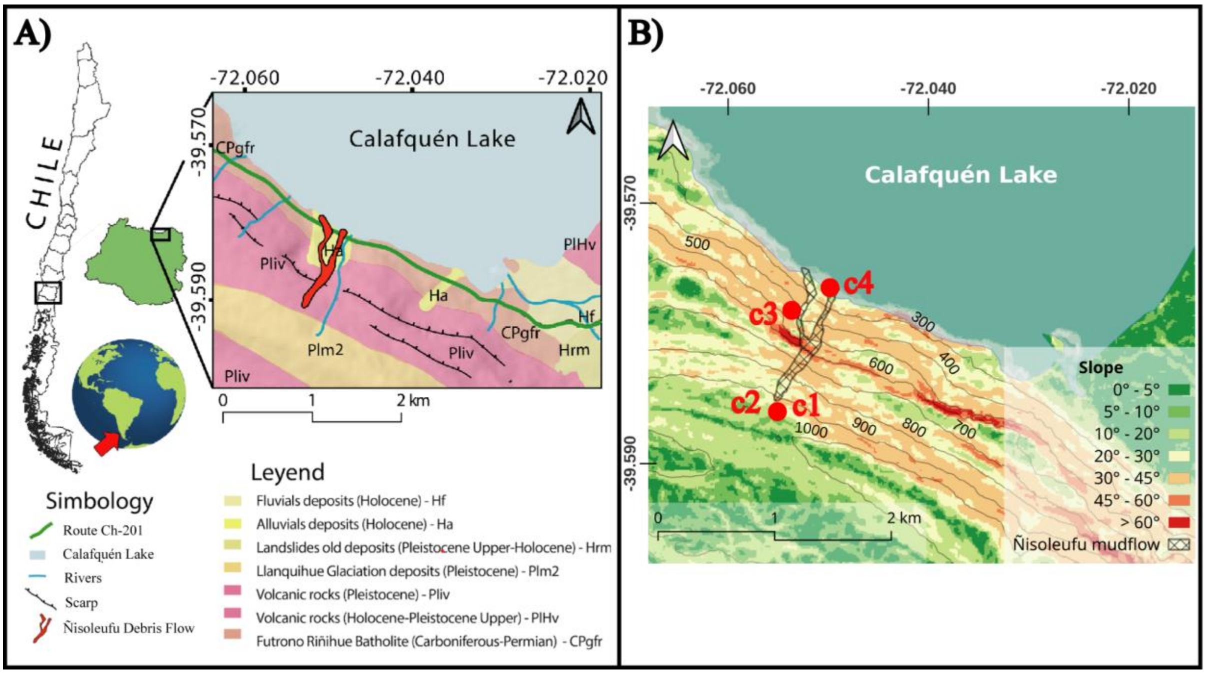
    Original Figure 5



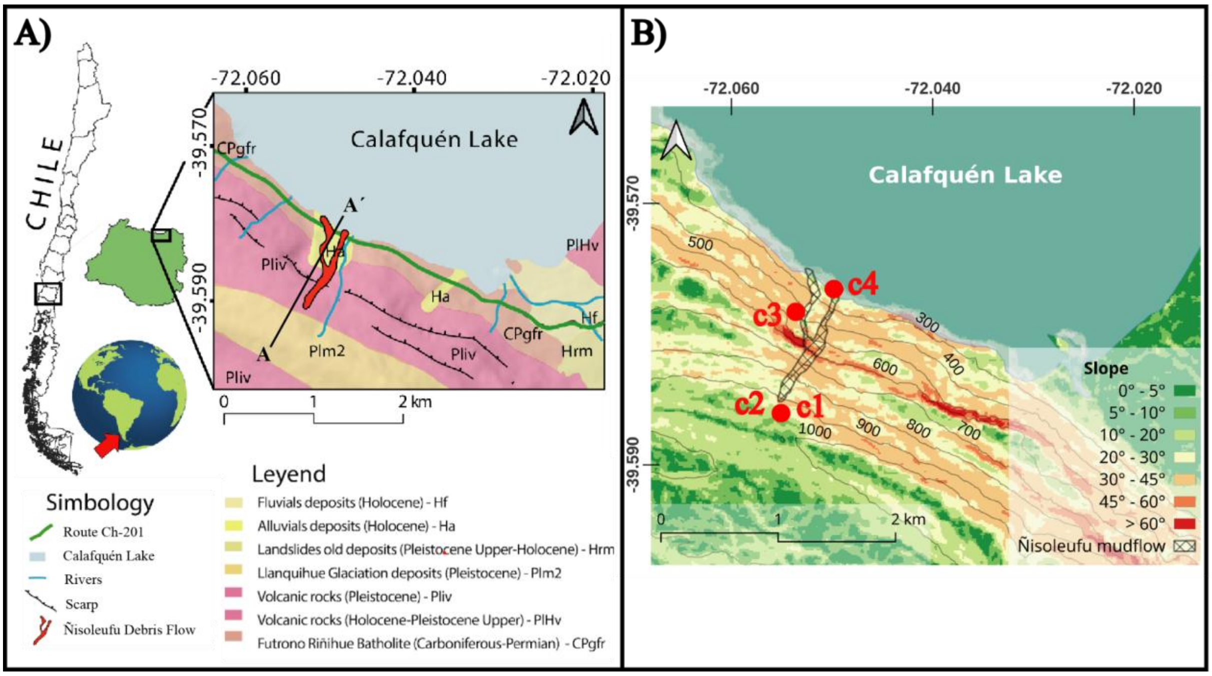
Modified Figure 5



Original Figure 2:



Modified Figure 2:

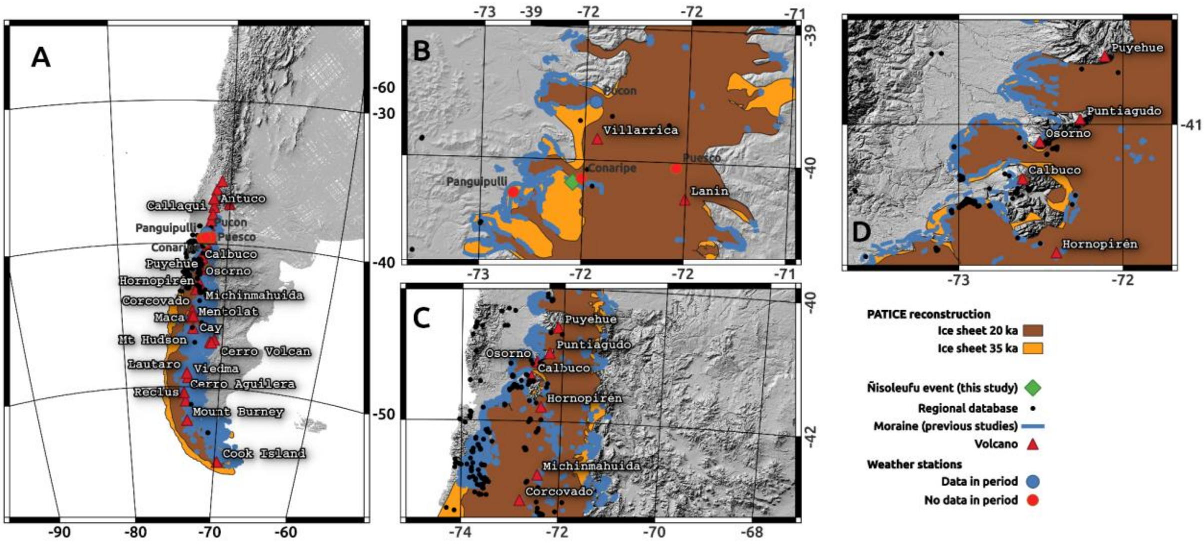


5. **SC1_5** L146: Data from four weather stations were used, but only the Pucon station is plotted in the figure. Where is this station located and why do you select it as representative?
   - **A:** For the analysis of the event that occurred in the Ñisoleufu area, we exhaustively reviewed the meteorological stations located nearby. A total of four stations were identified within a reasonable radius for potential use as sources of meteorological data. However, upon examining the temporal

coverage and continuity of their records, it was found that only the Pucón station had complete and operational data for the study period. Panguipulli, Conaripe and Puesco had records ending in 2019, while others exhibited data gaps during the Nisoleufu months, probably due to telemetry failures. These interruptions compromised the use of the data required for the analysis, and thus, these stations were excluded. Therefore, the use of the Pucón station is fully justified as the most reliable and representative source of meteorological data for this study. Now, we included in a new figure the location of the weather stations as Figure 1.

New Figure:

Figure 1 Rainfall-Induced mass wasting in Southern Andes. A) Regional map of Ice-sheet extension during 35 ka and 20 ka as example and volcanoes emplaced in the area. B) Zoom to study area with Ñisoleufu in Northen Ice sheet sector showing the weather stations. C) Zoom to Northern Patagonian area showing correlation between mass wasting events and moraine lines (blue line). D) Zoom to Osorno volcano area showing high debris flow generation area discussed in Fustos et al., 2022.



The same information was introduced in the text:

Original text in section 3.3:

We specifically selected data from the Pucón station and CHIRPS dataset for comparison with the time series of deformation to examine the relationship between precipitation and deformation.

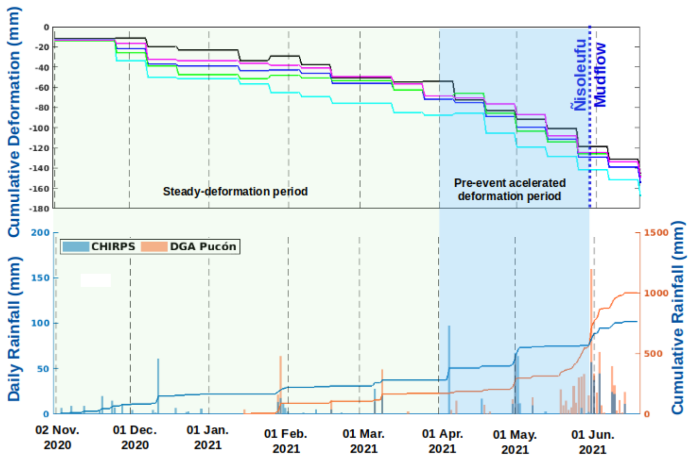
Modified text in section 3.3:

The four weather stations were identified within a reasonable radius for potential use as sources of meteorological data. However, upon examining the temporal coverage and continuity of their records, it was found that only the Pucón station had complete and operational data for the study period.

Moreover, we merged this data with CHIRPS dataset for comparison with the time series of deformation to examine the relationship between precipitation and deformation.

6. **SC1_6** Furthermore, based on this data, the debris flow appears linked to intense rainfall approximately 15 days prior to the event. Why is the pre-event described as occurring two months earlier?

A: We appreciate the reviewer’s insightful comment. We agree that the final triggering phase of the event appears to have occurred approximately 15 days prior to the main manifestation. However, based on our analysis of InSAR time series (Figure below), we identified changes in surface deformation beginning in late January. This timing coincides with a significant precipitation event during the same period.



We therefore propose that the summer rainfall may have acted as an initial trigger, initiating a lateral spreading process that evolved progressively over time. In this context, we consider the event to be the outcome of a process that began during the austral summer precipitation, even though its most evident expression occurred later.

Original text:

Our results suggest a precursory deformation signal based on two distinct periods (Figure 7). The first period displayed a high-deformation pattern starting from January 2021 until April 2021 marked by consistent precipitation (Figure 6C) that infiltrated into the soil increasing the soil moisture (Figure 6B). A second period characterized by pre-event deformation patterns following a high precipitation event in May 2021. Our results suggest that the variation in surface deformation rates could be a response to a significant precipitation event that occurred at the end of January, being related to the high-intensity rainfall throughout the second half of May (Figure 7).

Modified text:

> Our analysis reveals a precursory deformation signal that comprised two distinct phases (Figure 9). The first phase, beginning in late January 2021 and extending through April, exhibited a high-deformation pattern associated with consistent precipitation (Figure 8C), which infiltrated the soil and increased soil moisture levels (Figure 8B). This timing coincides with a significant precipitation event in late January, suggesting that summer rainfall may have acted as an initial trigger, initiating a surface deformation that evolved progressively over time. A second deformation phase following a high-intensity rainfall event in mid-to-late May 2021, characterized by pre-event deformation patterns. Despite that most evident precipitation event occurred in late May (15-day before), our surface deformation estimations could suggest that the triggering process likely began approximately in summer period.

7. **SC1_7** Table 2: Both plastic and liquid limits of samples S-3 and S-7 are exceptionally high, approaching or exceeding 100%, which is unusual in geotechnical testing. Have these results been validated? If so, the unique nature of these soil layers should be highlighted and discussed in detail.

A: We agree with the reviewer's observations and have thoroughly reviewed both the methodologies employed and the results obtained, reaffirming the high Atterberg limits presented in Table 2. These values were carefully measured using standard procedures (AS 1289.3.9.1 and NCh 1517/2), validating the results as being consistent with previous results obtained from the same soils (Vasquez et al., 2025). Following the reviewer's suggestion, we have now included a more detailed discussion in the revised manuscript (Section 5.2), highlighting the distinctive geotechnical behaviour of these soils. The exceptionally high plastic and liquid limits observed in samples S-3 and S-7 likely reflect the volcanic soil genesis, weathering, and extreme climate processes around the Mocho-Choshuenco volcanic complex. This singular pedogenetic pathway—characteristic of glacio-volcanic terrains in the Southern Andes—produces fine-grained, organic-rich soils with high water retention and deformability, which in turn play a critical role in slope stability and debris flow initiation in the region.

Original text in section 5.2:

> Moreover, field evidence suggests that the Ñisoleufu event is not an isolated case as seen in the remobilised events (Figure 1, geological map - alluvial deposit: Ha). The geotechnical properties of the material to be remobilised are crucial for establishing stability conditions. The granulometric characteristics of the deposits, primarily granular types associated with S-4, are identified as frictional soils overlying fine-grained, cohesive soils like varves (S-2).

Other soils in Southern Andes, such as S-3 and S-7, could be originated from the decomposition of volcanic glass from ashes and glacial clays (Sanhueza et al., 2011), resulting in particles smaller than 0.1 mm (Figure 5). The distribution of the soil layers varies abruptly downslope, as observed in columns c1 and c3 for S-1, S-2, and S-4, indicating intense mass wasting and erosion productivity in areas close to glacial lakes (Figure 4D). The frictional soils, related to S-4, exhibit high shear resistance (Chen et al, 2021), combined with steep slopes, can contribute to stability control of post-glacial volcanic deposits (Walding et al, 2023; Ontiveros-Ortega et al, 2023). However, while frictional soils are generally more resistant to sliding (Chen et al, 2021), soil saturation can significantly decrease their strength, thus increasing the risk of failure under extreme precipitation events detected in recent years in the Southern Andes (Fustos et al., 2017; Somos-Valenzuela et al., 2020; Fustos et al., 2021). This is consistent with the presence of extensional failure observed before flow initiation and subsequent reactivations in June 2023 and 2024 (Figure 3C; Figure 8).

Modified text in section 5.2:

Moreover, field evidence suggests that the Ñisoleufu event is not an isolated case, as indicated by other remobilised events in the area (Figure 2, geological map – alluvial deposit: Ha). The geotechnical properties of the remobilised materials are critical for defining slope stability conditions. Granulometric analyses indicate that the deposits are primarily granular soils, such as those associated with S-4, which are classified as frictional and are found overlying finer-grained cohesive soils, such as varves (S-2). Other soils found in the Southern Andes, including S-3 and S-7, originate from the decomposition of volcanic glass and glacial clays (Sanhueza et al., 2011; Vasquez et al., 2025), producing particles smaller than 0.1 mm (Figure 6).

Specifically, S-3 soils, derived from explosive eruptions of the Mocho-Choshuenco volcano, consist of non-cohesive volcanic ash mixed with fine-grained sediments, forming a matrix with elevated plasticity and a high liquid limit (Vasquez et al., 2025). These properties result from the introduction of fine material during the deposition. Moreover, S-7 soils, classified as organic soils derived from volcanic deposits, exhibit notably high liquid limits due to the accumulation of organic matter. The organic matter enhances the soil's water retention and promotes the formation of organic colloids, which may increase the liquid limit (Deng et al., 2017; Fiantis et al., 2019). Our results are consistent with independent laboratory testing in the zone (Vásquez et al., 2025), which shows that organic-rich paleosols were buried after the Last Glacial Maximum, approximately

5 km south of the study area, and exhibit similar liquid limit values to those observed in S-7.

The spatial distribution of soil layers varies abruptly along the slope, as observed in columns C1 and C3 for S-1, S-2, and S-4, indicating significant mass wasting and erosion processes near glacial lakes (Figure 5D). The frictional soils, such as those related to S-4, generally exhibit high shear strength (Chen et al., 2021), and when combined with steep topography, may contribute to the relative stability of post-glacial volcanic deposits (Walding et al., 2023; Ontiveros-Ortega et al., 2023). However, under extreme precipitation events—such as those recorded in recent years in the Southern Andes—soil saturation can substantially reduce the strength of even frictional soils, increasing the likelihood of failure (Fustos et al., 2017; Somos-Valenzuela et al., 2020; Fustos et al., 2021). This mechanism aligns with the observed extensional failures that preceded the initiation and reactivation of flows in June 2023 and 2024 (Figure 4C; Figure 10).

- **References:**

Deng, Y., Cai, C., Xia, D., Shuwen, D., Chen, J., & Wang, T. (2017). Soil atterberg limits of different weathering profiles of the collapsing gullies in the hilly granitic region of southern china. Solid Earth, 8(2), 499-513. https://doi.org/10.5194/se-8-499-2017

Fiantis, D., Ginting, F., Gusnidar, G., Nelson, M., & Minasny, B. (2019). Volcanic ash, insecurity for the people but securing fertile soil for the future. Sustainability, 11(11), 3072. https://doi.org/10.3390/su11113072

Ustiatik, R., Ariska, A., Hakim, Q., Wicaksono, K., & Utami, S. (2023). Volcanic deposits thickness and distance from mt semeru crater strongly affected phosphate solubilizing bacteria population and soil organic carbon. Journal of Ecological Engineering, 24(10), 360-368. https://doi.org/10.12911/22998993/170860

8. **SC1_8** Figure 6: The ERA5-based analysis reveals a clear annual cycle in soil moisture content. However, similar levels of high soil moisture appear to have occurred in previous years, such as around 5 February 2015. What additional factors, beyond soil moisture, may explain the occurrence of the 2023 event compared to those previous intervals?

   A: We appreciate the reviewer's comment regarding the need to explore additional factors beyond soil moisture that may explain the occurrence of the 2023 debris flow event, particularly when similar soil moisture levels were observed in previous years (e.g., February 2015) without resulting in such events. We agree with this observation and now we have elaborated a more comprehensive explanation in the revised manuscript. Now, we added in 5.2 two new paragraphs:

> Climate change is intensifying debris flow hazards by increasing the frequency and severity of extreme precipitation events and disrupting soil moisture regimes (Talebi et al., 2007). In the Southern Andes, these changes interact with stratified volcanic terrain to produce heightened slope instability. Our study shows that the 2023 debris flow event was triggered by an episode of extreme precipitation (Figure 8), which delivered intense rainfall over a short period, rapidly saturating the surface and subsurface soil layers. This event highlights how short-duration storms, increasingly associated with climate change, can overwhelm the buffering capacity of mountainous terrain. The soil media S-7 and S-4, both composed of organic-rich and granular volcanic materials, played a critical role in this response. During the 2023 event, infiltrating rainwater rapidly percolated through these coarse upper layers until reaching the underlying varved glacial sediments (S-2), which have significantly lower permeability. This layering caused a perched water table, increasing the pore pressure and reducing shear strength, ultimately contributing to slope failure. These effects were captured in our remote sensing observations, which showed expanded saturated zones and local instability near the contact between volcanic and glacial deposits.

> Our results suggest strong stratigraphic controls and extreme precipitation events in the soils derived from volcanic materials overlying denser glacial layers, acting as failure planes under saturated conditions (Figure 7B; Figure 8B). Our conceptual model promotes water retention and localized pressurization, especially during extreme rainfall events such as 2021 (not observed previously). The conditioning factors are further exacerbated by mid-term climate trends, including the ongoing megadrought in the Southern Andes (Garreaud et al., 2019), which increased desiccation cracking, and weakened root cohesion. Such drought-induced degradation lowers slope resistance, making even moderate precipitation more hazardous. Therefore, our observations suggest that the Ñisoleufu debris flow event, may exemplify the climate-induced changes in both hydrological extremes and landscape memory (drought legacy) act in concert to reduce slope stability. As extreme precipitation becomes more frequent under future climate scenarios, similar failures are

expected to occur across a broader area than observed in past events (Figure 2A). Our findings stress the urgent need for debris flow forecasting models to incorporate stratified soil behaviour, seasonal soil moisture dynamics, and drought-related weakening—factors essential to anticipating the growing hazard posed by climate change (Iverson et al., 2010; Gariano and Guzzetti, 2016).

References:

Garreaud, R. D., Boisier, J. P., Rondanelli, R., Montecinos, A., Sepúlveda, H. H., and Veloso-Aguila, D.: The Central Chile Mega Drought (2010–2018): A climate dynamics perspective, Intl Journal of Climatology, 40, 421–439, https://doi.org/10.1002/joc.6219, 2019.

Technical corrections:

1. **TC1_1 L19:** The phrase "influencing by" is unclear. Consider rephrasing as "influenced by" or revising the sentence for clarity.
    - **A:** Thanks, we modified the text.
2. **TC1_2 L20:** Does ‘an active area’ refer to ‘The southern Andes’?
    - **A:** We modify the text to emphasize the area.

    Original text:

    > This study investigates the generation of the Ñisoleufu debris flow, an active area of debris flow generation, reviewing the interplay between geomorphological, geotechnical and hydrometeorological controls in debris flow dynamics, focusing on the effects of soil properties, slope characteristics and precipitation events.

    Modified text:

    > This study investigates the generation of the Ñisoleufu debris flow, an active area of debris flow generation in Southern Andes, reviewing the interplay between geomorphological, geotechnical and hydrometeorological controls in debris flow dynamics, focusing on the effects of soil properties, slope characteristics and precipitation events.
3. **TC1_3 L83:** The sentence "Recent events become a significant geological hazard" is unclear.

    A:Thanks for this observation, now we have modified the text.

Original text:

Recent events become a significant geological hazard especially in steep zones near alluvial plains where human settlements are often established (Fustos et al., 2017; Fustos-Toribio et al., 2021).

Modified text:

Recent extreme precipitation events have produced mass wasting hazard, especially in steep zones near alluvial plains where human settlements are often established (Fustos et al., 2017; Fustos-Toribio et al., 2021).

4. **TC1_4** L115: The subheading appears incomplete.

   A: We agree, now modify the subheading.

   Original text:

   Geomorphological and geotechnical

   Modified text:

   Geomorphological and geotechnical conditions

5. **TC1_5 L134-136:** The sentence "Finally, the changes …" is incomplete and ambiguous.

   A: We agree. Now, we reduced extension and rewrite to be more assertive.

   Original text:

   Finally, the changes in vegetation that occurred as a consequence of the event (Figure 1B), allowing for the inference of the evolution of the post-event landscape and its influence on local eco-geomorphological processes.

   Modified text:

   Finally, we assessed changes in vegetation that occurred as a result of the May 31st event and its subsequent reactivations (Figure 2B), allowing the estimation of the evolution of the landscape.

6. **TC1_6 Table 2:** Please ensure consistency in the formatting of units. For example, "moisture [*w*](%)" and "density[*ρ*](g/cm3)".

Original text:

Soil type/Property	Normative	S-2	S-3	S-4	S-7
Moisture [w%]	NCh-1515	17.8	56.2	119.3	111.6
Density [ρ] (gr/cm3)	UNE-103-301-94	2.07	1.52	<1	1.06
Specific Gravity [Gs]	ASTM-D854-14	2.76	2.49	2.5	2.34
Liquid Limit [WL] (%)	AS 1289.3.9.1	27.48	123.93	-	149.83
Plastic Limit [WP] (%)	Nch 1517/2	16.07	91.3	-	114.13
Plasticity Index [PL]	NCh1517/2	11	33	-	36

Hydraulic Conductivity [ku] (m/s)	Porchet and Laferrere (1935)	-	-	-	3.13E-4

Modified text:

Soil type/Property	Normative	S-2	S-3	S-4	S-7
Moisture [w] (%)	NCh-1515	17.8	56.2	119.3	111.6
Density [ρ] (g/cm^3)	UNE-103-301-94	2.07	1.52	<1	1.06
Specific Gravity [G_s]	ASTM-D854-14	2.76	2.49	2.5	2.34
Liquid Limit [W_L] (%)	AS 1289.3.9.1	27.48	123.93	-	149.83
Plastic Limit [W_P] (%)	Nch 1517/2	16.07	91.3	-	114.13
Plasticity Index [PL]	NCh1517/2	11	33	-	36
Hydraulic Conductivity [k_u] (m/s)	Porchet and Laferrere (1935)	-	-	-	3.13E-4

7. **TC1_7 L439:** 'to' should be removed from 'can to deliver'.

Original text:

All the codes used in this manuscript are reproducible from the main text. We can to deliver the main script under any request.

Modified text:

All the codes used in this manuscript are reproducible from the main text. We can deliver the main script under any request.