Additional specific Comments

Upon further consideration I have identified additional points that may require other clarifications:

1. Laboratory Measurements (Table 2): The values reported for liquid limit (WL) and plastic limit (WP) for S-3, as well as WL, WP, and Ku for S-7, appear inconsistent with their geological descriptions. S-3. S-7 represents an active, developing soil, likely rich in organic material, where higher hydraulic conductivity (Ku) would be expected. However, the reported Ku is surprisingly low, potentially indicating compaction, fine-grained content, or measurement errors. Please verify these values and, if accurately, provide additional context to justify these unexpected results.

   A: We verify the results. Our results show similar range of values in comparison to Vasquez-Antipan et al., (2025) and volcanic soils in Southern Andes. Now, we introduced additional information in discussion (section 5.2)

   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 5).

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.

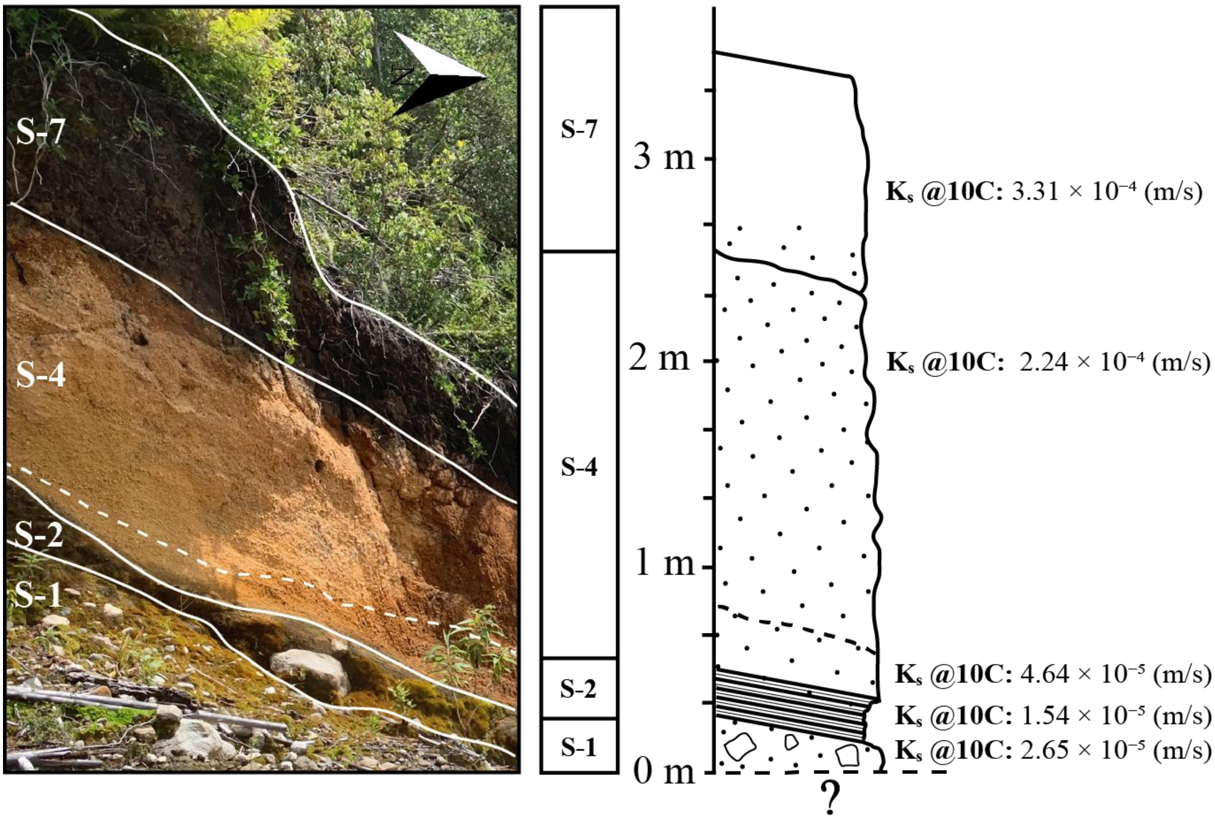
The spatial distribution of soil layers varies abruptly along the slope, as observed in columns C1 and C3 for S-1, S-2, and S-4, indicating significant mass wasting and erosion processes near glacial lakes (Figure 5D). The frictional soils, such as those related to S-4, generally exhibit high shear strength (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



2. Limited Number of PS (Figure 7): The analysis includes only five PS, of which three are located near the boundary and only two within the landslide niche. This sparse dataset may not provide a sufficiently robust basis for reliable precursor identification, especially given that these PS do not appear to exhibit significantly different displacement patterns compared to surrounding points. This raises questions about

the reliability of these PS as early warning indicators. I recommend adjusting the color scale in Figure 7 to better distinguish between PS displacement and elevation, which may improve the interpretability of the figure.

A: We thank the reviewer for the valuable observation regarding the limited number and spatial distribution of Persistent Scatterers (PS) included in our analysis. We acknowledge that the sparse dataset, comprising a reduced number of PS, limits the robustness of our results. As noted by the reviewer, the displacement patterns of these PS do not markedly differ from surrounding points, which indeed constrains their immediate utility as early warning indicators. We consider that this is a preliminary study, and we agree that surface deformation data alone are insufficient for the development of a reliable early warning system. Further investigation is needed, particularly to assess local conditions such as dense vegetation cover, which poses additional challenges for PS detection in the southern Andes.

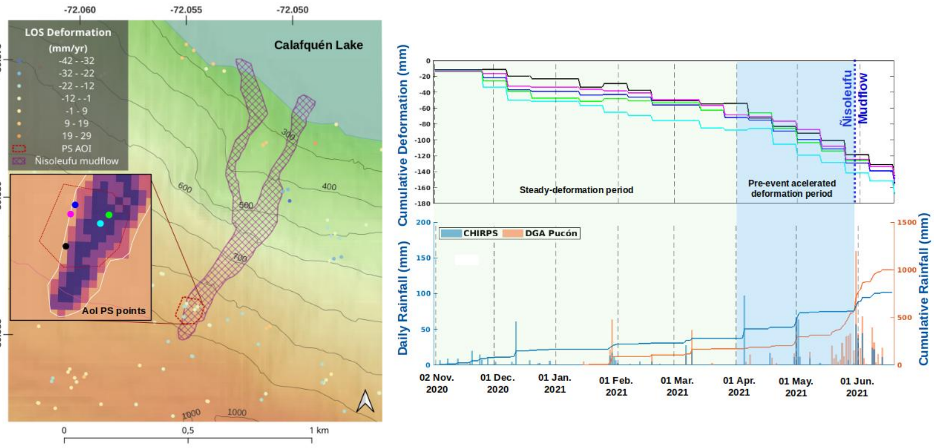
Nonetheless, previous studies in the area have demonstrated the feasibility of using PS data as complementary information to support landslide hazard assessments (Vasquez-Antipan et al., 2025). In our case, although the InSAR-derived displacements are not conclusive on their own, they are consistent with geomorphological indicators observed during fieldwork, which suggest evidence of previous surface deformation in the area. These converging lines of evidence support the hypothesis of progressive slope instability, despite the limitations of the remote sensing dataset. Now, we discuss in detail it in the section 5.2 and 5.3 as limitation of the study and future scope.

Introduced paragraph in section 5.2:

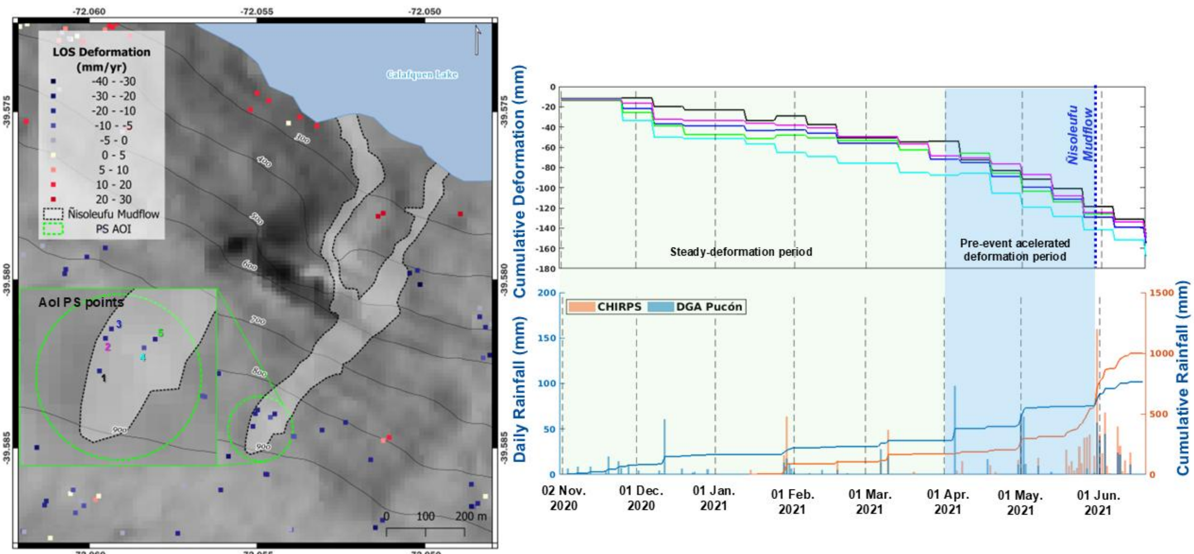
> Our results showed a limited amount of PS in the study area similar to previous studies in the area (Vasquez-Antipan et al., 2025). The Southern Andes, and the Ñisoleufu area, is characterized by complex geomorphological features and varying precipitation patterns that could introduce uncertainty to hte remote sensing measurements. The application of limited persistent scatterer data in assessing slope deformations offers a promising avenue for the development of a landslide early warning system (LEWS) in the Southern Andes. However, the investigation into this method requires a thorough understanding of potential limitations, particularly the extensive vegetation in the Southern Andes, which can obscure satellite signals and affect data accuracy. Vegetation serves as a significant barrier to radar signals, leading to incomplete datasets that might obscure important geological signals indicative of slope movements (Maragaño-Carmona et al., 2023). Therefore, additional efforts must be considered to move forward to an operational scale.

In response to the reviewer’s suggestion, we will revise Figure 7 by adjusting the color scale to enhance the visual distinction between PS displacement and elevation. We believe this improvement will increase the figure’s interpretability and help contextualize the deformation patterns within the topographic setting.

Original Figure:



Modified Figure:



Reference:

Vásquez-Antipán, D., Fustos-Toribio, I., Riffo-López, J., Cortez-Díaz, A., Bravo, Á., and Moreno-Yaeger, P.: Landslide processes related to recurrent explosive eruptions in the Southern Andes of Chile (39° S), Journal of South American Earth Sciences, 157, 105469, https://doi.org/10.1016/j.jsames.2025.105469, 2025.

3. To improve clarity, consider presenting the data in Table 3 as a graph, which may provide a more intuitive visualization of the variation in saturated hydraulic conductivity across different soil types.

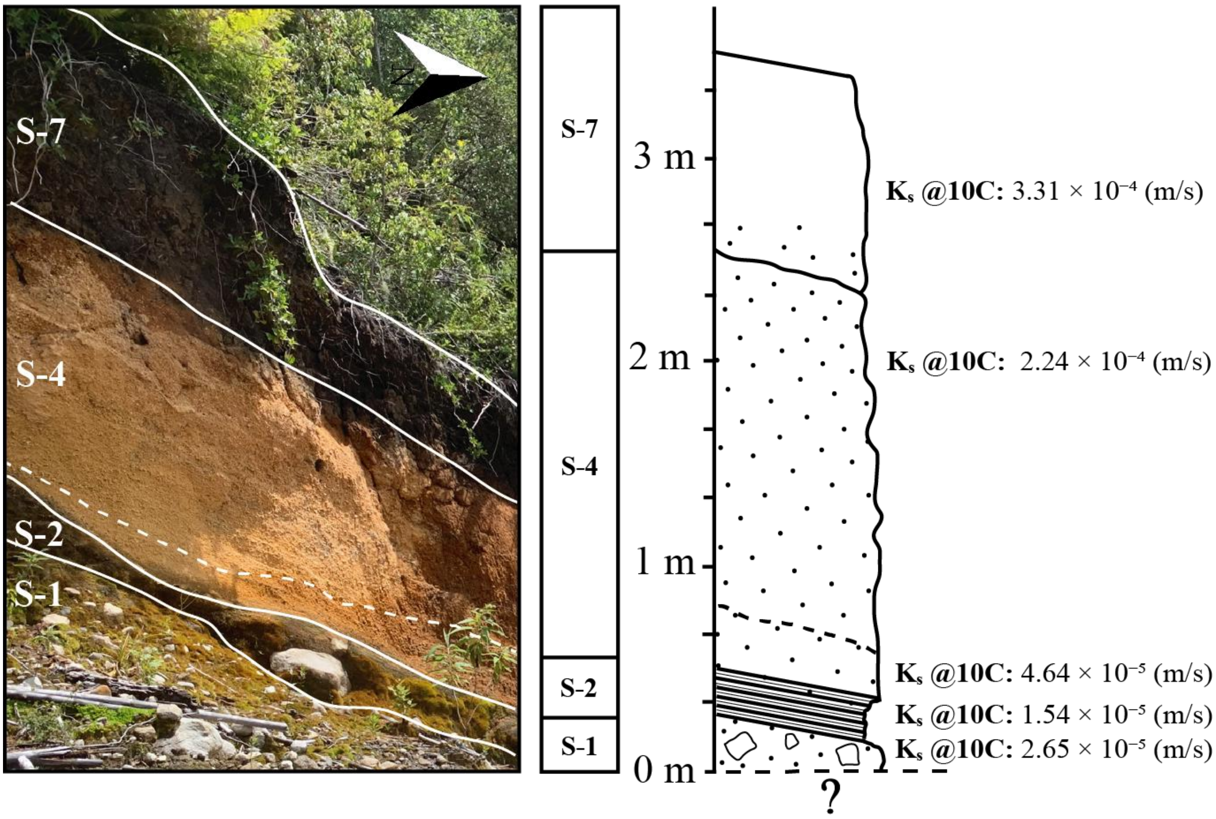
   A: We agree. Now, we modify the table 3

   Original form:

Table 3 Hydraulic properties of release zone in debris flow generation zone (column c1 in Figure 1).

Layer	depth (m)	Ks @10C (m/s)	Description
Superior layer	0-0.5	3.31E-04	Organic (S-7)
Volcanic deposit 1	0.5-2.5	2.24E-04	Neltume ashfall deposit (S-4)
Volcanic deposit 2	2.5-2.7	4.64E-05	base Neltume (S-4)
Varve	2.7-3.0	1.54E-05	Varves (S-2)
Morraine	3.0-??	2.65E-05	Saturated Morraine (S-1)

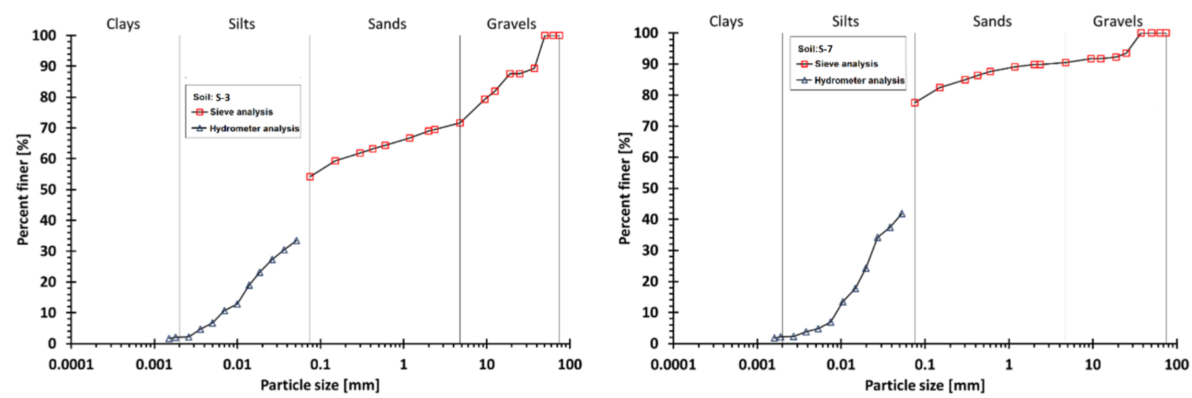
Version in Figure:



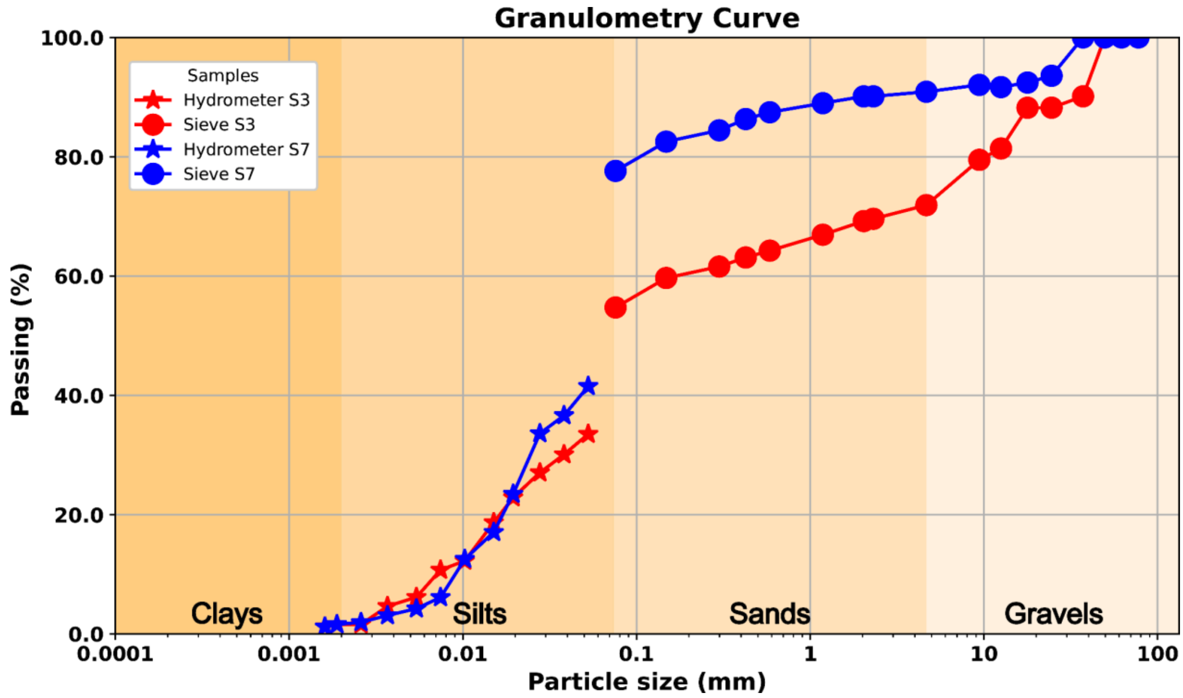
Additional modifications

We modified the granulometric figure (Figure 6).

Original figure:



Modified figure:


Granulometry Curve
Samples
Hydrometer S3
Sieve S3
Hydrometer S7
Sieve S7
Clays
Silts
Sands
Gravels
Passing (%)
Particle size (mm)
100.0
80.0
60.0
40.0
20.0
0.0
0.0001
0.001
0.01
0.1
1
10
100