RC2: 'Comment on egusphere-2025-962', Anonymous Referee #2, 12 Jun 2025

This paper presents a multi-method geophysical campaign utilizing Electrical Resistivity Tomography (ERT), Seismic Refraction Tomography (SRT), and Multichannel Analysis of Surface Waves (MASW) to characterize the subsurface of the Flüela rock glacier. The study effectively demonstrates the complementary strengths of MASW in permafrost environments, particularly in overcoming some limitations of conventional SRT, such as issues with velocity inversions. The comparison of synthetic seismic models with field data is a valuable aspect of the work, corroborating the authors' interpretations.

The manuscript is generally well-structured and clear. The methodology is adequately described, and the figures are informative. The application of MASW in this challenging high-mountain environment is a significant contribution to permafrost research.

Main Comment:

My primary concern revolves around the interpretation of the ERT results concerning the hypothesized thin, water-saturated layer. While it is acknowledged that ERT sensitivity decreases with depth, it is generally expected that a **1-meter thick layer near the surface** should be resolvable with a **3-meter electrode spacing**. Furthermore, since you are considering a **more conductive layer** (interpreted as water-saturated sediment), the ERT method should exhibit **heightened sensitivity** to its presence.

It would be highly valuable to include **synthetic ERT modeling** to illustrate the expected response to such a thin, low-resistivity layer at the proposed depth (around 4m, based on Figure 4). A synthetic model would help clarify whether the observed field ERT data aligns with the theoretical detectability of such a feature, given the acquisition parameters and the assumed resistivity contrast. This would strengthen the argument for why the ERT model does not clearly resolve this layer despite its potential conductivity.

We thank Reviewer2 for his/her comment, that gave us the opportunity to further investigate the sensitivity of our system (electrode array and acquisition configuration) to the hypothesized structures, in particular to the thin supra-permafrost water-saturated sediment layer. To do so, we performed a forward modelling of ERT using the open-source software ResIPy (Blanchy et al., 2020). The forward model was based on the subsurface structure shown in Figure 4 of the manuscript, with electrical resistivity values assigned to each layer according to the inverted resistivity model derived from field data (Figure 2a of the manuscript). Specifically, resistivities of 20 kΩ·m, 10 kΩ·m, 5 kΩ·m, and 100 kΩ·m were assigned to the surface debris layer, compact sediment layer, bedrock, and frozen layer, respectively (Figure S1 of the Supplementary Material). A representative value of 1 kΩ·m was assigned to the water-saturated sediment layer; as usual in rock glacier environments for such layer (depending on factors such as material composition, water chemistry, and temperature). This value is plausible particularly when the substrate consists of coarse, blocky debris with large pore spaces and low clay content, which reduces electrical conductivity even under saturated conditions (see Hauck & Vonder Mühll, 2003; Hilbich et al., 2021). Additionally, if the pore water has low ionic content—as is typical of meltwater—the resulting electrical conductivity remains low, yielding higher resistivity values (Hauck, 2002). Cold yet unfrozen conditions, or partially saturated porous media, may also lead to resistivities within this range.

The synthetic dataset was generated using a dipole–dipole multi-skip acquisition scheme identical to that employed in the field survey, with an array of 48 electrodes spaced 3 meters apart. A 5% noise level was added to the synthetic measurements, consistent with the estimated noise in the real dataset. The synthetic data were then inverted using the same parameters applied to the inversion of the real dataset, resulting in the resistivity model shown in Figure S2 (Supplementary Material).

The result does not clearly reveal the presence of the thin water-saturated sediment layer overlying the frozen layer, confirming that the ERT survey conducted at the Flüelapass rock glacier lacked the resolution and configuration necessary to resolve such a feature. This limitation is likely due to the relatively large electrode spacing.

Compared to the real electrical resistivity model (Figure 2a of the manuscript), slight deviations can be observed, which can be attributed to the simplifications adopted in the conceptual model (Figure 4 of the manuscript and Figure S1 of the Supplementary Material). The conceptual model used for the synthetic simulation does not account for the natural heterogeneity typically encountered in the field, including lateral and vertical variations in layer thickness, composition, and continuity. As in the seismic forward modeling, we assumed laterally homogeneous, planar layers and excluded surface topography, resulting in an idealized representation intended to enhance the theoretical detectability of the target layer.

Overall, this is a well-executed study that provides important insights into the internal characteristics of rock glaciers. Addressing the main comment with additional synthetic modeling would significantly enhance the clarity and robustness of the ERT interpretation.

We thank Reviewer 2 for his/her clear and insightful review. We hope that our additional analyses with synthetic data were thorough and addressed all concerns regarding our interpretation.

References

Blanchy, G., Loke, M. H., Ogilvy, R., & Meldrum, P. (2020). ResIPy: A Python-based GUI for 2D/3D resistivity modeling and inversion. Journal of Open Source Software, 5(54), 2432. https://doi.org/10.21105/joss.02432.

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Hilbich, C., Fuss, C., Mollaret, C., Hauck, C., & Hoelzle, M. (2021). Multi-decadal geophysical monitoring of permafrost evolution in mountain terrain – The PACE legacy. The Cryosphere, 15(11), 5121–5145. https://doi.org/10.5194/tc-15-5121-2021.

Supplementary Material

ERT Synthetic (Forward) Modeling

Forward modeling in Electrical Resistivity Tomography (ERT) involves the numerical simulation of the electrical potential distribution in the subsurface based on a known resistivity model. This process requires solving Poisson's equation, which describes the behavior of the electric field generated by current injection through electrodes placed on the surface or in boreholes (Binley & Slater, 2020). Forward modeling is a crucial step in the ERT workflow, as it allows for the prediction of the theoretical response of the subsurface for a given resistivity distribution and electrode configuration. It is commonly used to test the effectiveness of specific electrode arrays, assess the system's sensitivity to subsurface resistivity variations, and validate the quality of inversion results (Loke et al., 2003; Binley & Kemna, 2005).

In this study, forward modeling of ERT was performed using the open-source software ResIPy (Blanchy et al., 2020). The objective was to evaluate whether the electrode array and acquisition configuration used during the measurement campaign at the Flüelapass rock glacier provided sufficient resolution to detect a thin layer of water-saturated sediment overlying the permafrost. We hypothesize that this layer may have contributed to the attenuation of P-wave propagation at depth.

The forward model was based on the subsurface structure shown in Figure 4 of the manuscript, with electrical resistivity values assigned to each layer according to the inverted resistivity model derived from field data (Figure 2a of the manuscript). Specifically, resistivities of 20 kΩ·m, 10 kΩ·m, 5 kΩ·m, and 100 kΩ·m were assigned to the surface debris layer, compact sediment layer, bedrock, and frozen layer, respectively (Figure S1). A representative value of 1 kΩ·m was assigned to the water-saturated sediment layer. In rock glacier environments, such layers can exhibit resistivities on the order of 1000 Ω·m, depending on factors such as material composition, water chemistry, and temperature. This value is plausible particularly when the substrate consists of coarse, blocky debris with large pore spaces and low clay content, which reduces electrical conductivity even under saturated conditions (Hauck & Vonder Mühll, 2003; Hilbich et al., 2021). Additionally, if the pore water has low ionic content—as is typical of glacial meltwater—the resulting electrical conductivity remains low, yielding higher resistivity values (Hauck, 2002). Cold yet unfrozen conditions, or partially saturated porous media, may also lead to resistivities within this range.

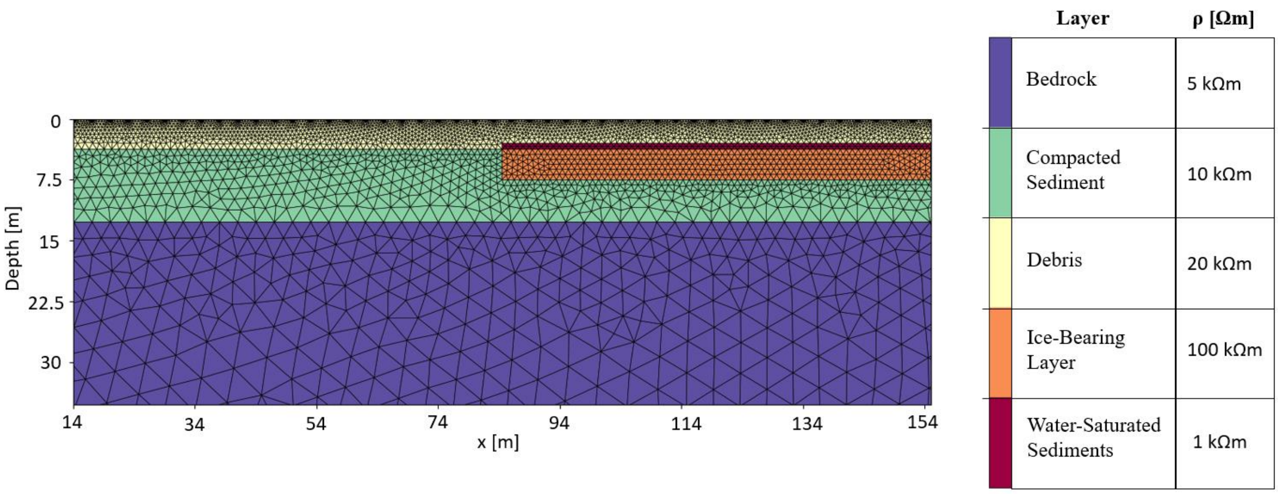

Figure S1: Conceptual model used for the synthetic ERT modelling.

The synthetic dataset was generated using a dipole–dipole multi-skip acquisition scheme identical to that employed in the field survey, with an array of 48 electrodes spaced 3 meters apart. A 5% noise level was added to the synthetic measurements, consistent with the estimated noise in the real dataset. The synthetic data were then inverted using the same parameters applied to the inversion of the real dataset, resulting in the resistivity model shown in Figure S2. The color scale used corresponds to that of the electrical resistivity model obtained from the real data, presented in Figure 2a of the manuscript.

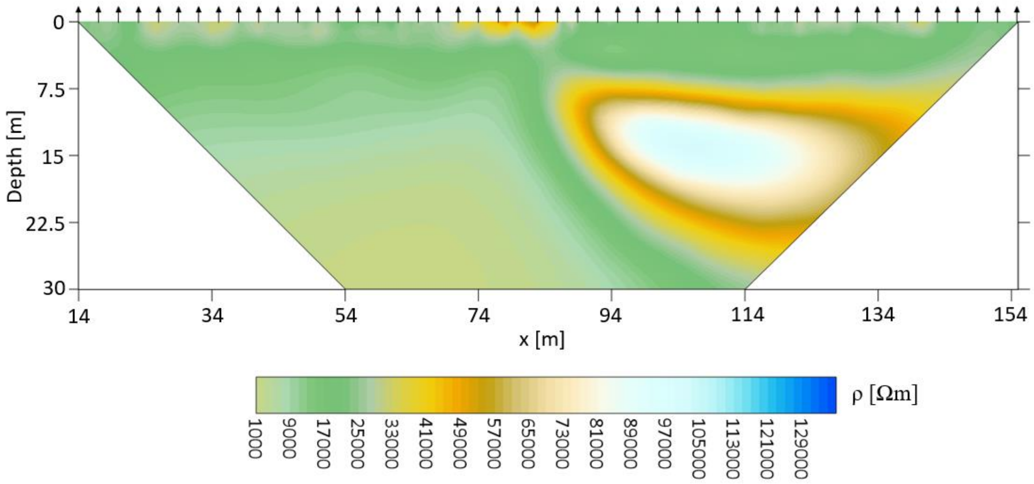

Figure S2: Synthetic electrical resistivity model derived from forward modeling applied to the conceptual model presented in Figure S1.

As shown in Figure S2), the result does not clearly reveal the presence of the thin water-saturated sediment layer overlying the frozen layer, confirming that the ERT survey conducted at the Flüelapass rock glacier site lacked the resolution and configuration necessary to resolve such a feature. This limitation is likely due to the relatively large electrode spacing.

Compared to the real electrical resistivity model (Figure 2a of the manuscript), slight deviations can be observed, which can be attributed to the simplifications adopted in the conceptual model (Figure 4 of the manuscript and Figure S1). The conceptual model used for the synthetic simulation does not account for the natural heterogeneity typically encountered in the field, including lateral and vertical variations in layer thickness, composition, and continuity. As in the seismic forward modeling, we assumed laterally homogeneous, planar layers and excluded surface topography, resulting in an idealized representation intended to enhance the theoretical detectability of the target layer.

Ray density in Seismic Refraction Tomography (SRT)

Figure S3 shows the Vp model obtained through Seismic Refraction Tomography (SRT) together with the computed ray paths. In the first half of the model domain ($0 < x < 60$ m, where we assume the absence of the thin water-saturated layer), ray coverage is well distributed both at the shallow and intermediate depths. Conversely, in the second half of the section ($x > 60$ m, where we hypothesize the presence of the saturated layer above the permafrost), the majority of rays are concentrated within the near-surface portion of the model, with only a limited number of rays penetrating to deeper levels.

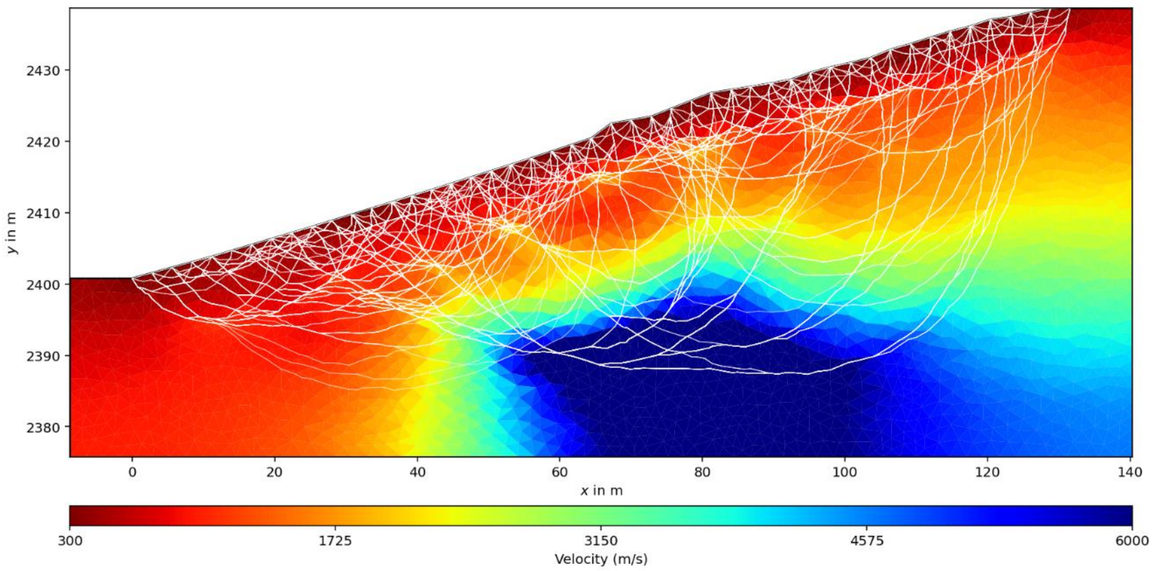

Figure S3: Vp model obtained through seismic refraction tomography (SRT), together with the computed ray paths.

References

Blanchy, G., Loke, M. H., Ogilvy, R., & Meldrum, P. (2020). ResIPy: A Python-based GUI for 2D/3D resistivity modeling and inversion. Journal of Open Source Software, 5(54), 2432. https://doi.org/10.21105/joss.02432.

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