# Responses to reviewers

## Reviewer 1:

We thank the reviewer for his valuable and insightful comments, which have helped improve this manuscript. Below, we provide our responses and explanations to the points raised and we have incorporated all minor comments into the revised text.

1- The manuscript titled "Rockwall permafrost dynamics evidenced by Automated Electrical Resistivity Tomography at Aiguille du Midi (3842 m asl, French Alps)" presents repeated ERT measurements in a high-alpine environment, complemented by laboratory experiments and a comparison of measured borehole temperatures with ERT-derived temperature estimates. The dataset is not entirely unique in terms of elevation, as it represents only a partially higher-altitude setting with conditions comparable to other study sites and publications. While we acknowledge the effort involved in obtaining and processing this dataset, we recommend major revisions.
Specifically, the manuscript would benefit from a clearer articulation of its novelty and research objectives. At present, the focus and unique contribution of the study remain somewhat unclear. The identified research gap – namely, that A-ERT at high altitudes has not yet been tested for long-term permafrost monitoring – is relatively weak. As a result, the study's aim appears vague, and the added value or benefit of the findings remains insufficiently presented and discussed. Furthermore, we encourage a more transparent presentation of the dataset, particularly regarding its temporal and spatial coverage (see specific comments below).

**Answer**: we want to highlight that the novelty of our work lies in the multi-year high-resolution A-ERT dataset obtained at the Aiguille du Midi site that provides new detailed insights into temporal permafrost dynamics. The Aiguille du Midi presents a unique setting due to its complex structure steep rock faces with varying aspects (massif and fractured rocks), human made infrastructure, and challenging accessibility. Furthermore, we highlight the challenges to get such dataset at that harsh climate conditions that could be very useful for future works. However, we tried to clarify our main objectives and advances in the new version:

- Testing potential of A-ERT to assess permafrost dynamics ➔ all previous studies are over < 1 year and therefore do not address permafrost dynamics, in Offer et al., 2025, several years but not comparable dataset over several years. Repeated measurements that are different from automated measurements do not assess the infra-seasonal changes, so our approach aims at assessing permafrost evolution over various time scales. Furthermore, our study also covers different rock faces with very different thermal and hydrological regime and it highlights the variability of these processes as well as the variability of some practical issues from one face to another
- Test potential of A-ERT to detect short term changes that could be due to water flows ➔ previous studies report such findings but in different lithologies, over different time scales. These methods are emerging and this study contributes to exploring its potential in different settings
- Test the possibility to calibrate the temperature-resistivity relationship *in-situ* to overcome some limitations inherent to laboratory experiments ➔ our study brings the very first *in-situ* calibration and provide some perspectives on the limitations of lab measurements. It also shows the difficulty of accurate/precise calibration in the

shallowest layers (~0-4 m) that are layers that are also the most difficult to accurately simulate with heat transfer models due to the complexity of heat transfer processes that involves air circulation, water infiltration, icing, latent heat exchanges and heat conduction (Magnin et al., 2017 ; Legay et al., 2021).

We will clearly articulate our research questions, emphasizing the value of long-term continuous A-ERT monitoring in a complex high-alpine environment. We will highlight the unique characteristics of the Aiguille du Midi and explain how our study addresses the specific challenges of monitoring permafrost dynamics in this setting.

Main concerns

2- Novelty **and previous studies:** The methods applied in the A-ERT monitoring (e.g., Keuschnig et al., 2017; Mollaret et al., 2019), the inversion routines, and the laboratory calibration approaches (Krautblatter et al., 2010; Magnin et al., 2015; Scandroglio et al., 2021; Etzelmüller et al., 2022, Offer et al., 2025) are well-established. Several parts of the lab analysis and interpretation closely resemble those of previous studies. We recommend reconsidering the novelty of your study – possibly by applying new or more advanced analyses – and restructuring the manuscript accordingly. The stated goals (1–3) at the end of the introduction have been substantially addressed in prior work (e.g., Keuschnig et al., 2017; Mollaret et al., 2019, Scandroglio et al., 2024, Offer et al., 2025). Clarify what differentiates your approach or findings from those.

**Answer**: Keuschnig et al., 2017 ➔ 1 year of measurements, therefore no infomration on the permafrost evolution that is a pluriannual evolution. Mollaret et al., 2019 ➔ repeated measures that are not A-ERT (see further comments below where it is stated that « which raises the question of whether A-ERT truly offers advantages over occasional repeated campaigns » One objective of this paper is to address this question to determine what we can gain from both pluriannual measurements and infra-seasonal measurements.

3- Abstract (Lines 44–47): The abstract should clearly state the main goal of the study. As currently written, it reiterates that ERT is effective in permafrost studies – something that is already well-known (Herring et al., 2023). The methodological innovations or scientific contributions are not emphasized enough. Please revise this to highlight what is new or different in your approach or findings.

**Answer**: the introduction was revised in the main text to clarify the main goals and findings of this work.

4- Time period and spatial coverage of A-ERT monitoring: The abstract states that monitoring occurred from 2020–2023. However, there are no measurements before June 2020, and between June 2020 and September 2021, ERT acquisitions were only conducted occasionally. Furthermore, significant data gaps occurred from summer 2022 onward on the NW-facing profile, and from summer 2023 on, due to cable failures. These sparse measurements (occasional repetition and cable defects) do not constitute continuous monitoring. Please clarify the actual continuous data availability in the entire manuscript (maximum of 2 years instead of 4 years).
Moreover, the east profile, although included in the inversion models, is not adequately analyzed, particularly in terms of contact resistance, average apparent resistivity, and its

temporal evolution. Why not analyze this profile more comprehensively? You mentioned problems with data gaps, however, data sets of the E profile are included in the inversions. Furthermore, the interpretation relies on a limited number of selected tomographies, which raises the question of whether A-ERT truly offers advantages over occasional repeated campaigns – given this, the conclusions appear overstated.

With reference to the selected data presented in Table 1, it remains unclear how representative these data are. We recommend clarifying the criteria for their selection and discussing to what extent this choice may influence the overall findings and interpretations.

**Answer**: the East face cable was damaged by a lightning strike days after installation. That is why no longer analyses were done on this side. The data presented go back to the installation day and at this day some electrodes were not connected because of high contact resistance as mentioned in the text and in the caption of the figure. The period of A-ERT is about 2.5 years. However, measuring in winter (e.g., from October to march) looks very difficult to realize. Even if we could measure in winter the data are unexploitable (most of electrodes are disconnected). Offer et al (2025), showed the same problem a gap in the dataset of A-ERT in winter because of high contact resistance.

Offer, M., Weber, S., Hartmeyer, I., Keuschnig, M., Rau, M., and Krautblatter, M.: From ice-filled fractures to pressurised water flow in permafrost bedrock: seasonal changes in rockwall hydrology, EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-15585, https://doi.org/10.5194/egusphere-egu25-15585, 2025.

Other points are discussed in the new version of the manuscript.

5- Laboratory calibrations: We disagree with the statement that the temperature–resistivity dependency is less pronounced in field conditions. Rather, the temperature–resistivity relation remains consistent, but it is often influenced by discontinuities, not captured in lab samples.
The manuscript presents calibration data from only one sample (and one electrode array!) taken directly from the study site, while the second sample originates from the lower Cosmiques ridge and may not be fully representative. We strongly recommend additional tests using multiple samples and/or multiple array configurations on each sample to characterize variability and quantify uncertainty. Prior studies (Krautblatter et al., 2010; Magnin et al., 2015; Scandroglio et al., 2021; Offer et al., 2025) have demonstrated the considerable range in temperature–resistivity relationships between different rock samples and even within individual electrode arrays. Your main interest lies between the temperature range from -5 to +5°C, but you only show five observations for each sample with only one point on the freezing path. Please address this in your further laboratory testing.

Furthermore, in Line 540, it is stated that resistivity in frozen conditions is primarily dependent on temperature, while other parameters are assumed to be constant. We would like to clarify that resistivity in freezing rock is primarily controlled by the remaining unfrozen pore water content, which in turn strongly influenced the pore water salinity. Porosity, by contrast, remains constant in both frozen and unfrozen states and should not be considered a temperature-dependent variable in this context. Finally, we question the decision to perform the calibration tests using vacuum saturation with degassed water. Why was this approach chosen over using snowmelt water from the field site and applying atmospheric pressure conditions? The latter would be more realistic for field conditions.

**Answer**: we mentioned that the relationship is “less pronounced” regarding the field results in comparison to laboratory, which could be influenced by the heterogeneity and discontinuities of the medium and could be influenced by the data quality, leading to this observation as you explained and we explained that in the text. We will clarify the idea about resistivity in frozen conditions.

Theoretically, configuration of electrodes should not influence the measured resistivity, as it is an intrinsic property of the sample. We use a standard method to measure the resistivity with current injection at both sides of the cubic sample to ensure homogenous distribution of current density in the sample, and in this case, the calculation of the geometric factor is easier (which reduces uncertainty related to the calculation of the geometric factor). Testing different samples: the site consists of massive granite as found from the boreholes, the heterogeneity and discontinuities at higher scale (fractures) could not be captured by testing other samples. Lower Cosmiques ridge is basically the same site. Furthermore, one of the main advantage and novelty of our paper is that we perform in-situ calibration.

We used vacuum saturation with degassed water to insure 100% saturation of small pores (where capillarity effect is very high) and for faster saturation than in atmospheric pressure conditions. The conductivity of the saturated water is close to the conductivity of water collected in the gallery of the AdM.

6- Data Processing and Inversion Parameters: Please clarify the following points regarding your data processing:

- How are outliers defined (Line 288)?
- Why was a linear error model with 5% chosen? What is the absolute error?
- Which inversion parameters were applied, especially lambda, paraDepth, quality, and z-weighting?
- Include chi² values for all inversion results, as the model mesh appears very fine, with little growing with depth, raising concerns about overfitting of the data.

- Fig. 13 (P1) shows that you already obtain eight resistivity values for a depth<2m, which seems to be inappropriate for an electrode spacing of 5m. We would highly recommend adapting the mesh.

  In addition, we advise against using measured apparent resistivity directly for trend analysis. The instrument may apply incorrect geometric factors, which could distort your results. Reanalyze the data using resistance or properly computed apparent resistivity (e.g., using pyGIMLi) for greater reliability.

**Answer**: the processing made here are more technical process. And we think that they are not important to integrate in the text. I will explain the processing here:

1- We agree with reviewer that the device will not provide the right apparent resistivity, that is why we have already used the measured resistance and then we used pyGimli library to calculate the apparent resistivity (after considering the real positions of electrodes).

2- for the analysis and outliers filtering: we analyzed individually few pseudosections (at different times (summer, spring, etc…), as a result of this analysis we decided to apply filter outliers out of range (300Ωm - 20 kΩm) for data measured in summer and autumn. And out of range (300Ωm - 200 kΩm) for data measured in spring and winter.

More data filtered at higher resistivities, where data quality are usually poor (see figure 5 in the new version).

3- For the inversion of a dataset: the first concern is the high Contact Resistance (CR) which could lead to disconnected electrodes once a CR threshold is exceeded. To address this issue, only pseudosections with a maximum of three disconnected electrodes were retained for inversion.

- As we don't have an accurate estimation of errors, we used a linear error of 5% as usually used in permafrost studies. (Mollaret et al., 2020). We tested different values of absolute error, and it has ne influence on the result, so we used a value of 1e5.
- We presented RMS (%) at each inversion figure and as you can find in the next figure both RMS (%) and $\chi^2$ are close and have the same trend.

For the inversion parameters: we made analyzes of the inversion parameters of a reference model. To reinforce the vertical discontinuities (related to the active layer or the infrastructure) in the AdM, we started by choosing the (zWeight > 1), and later with iterative processes we determined the smoothness parameter (Lambda). And we followedthe recommendation of (pyGIMLI creators) mesh quality =34.4, while paraDepth=10.

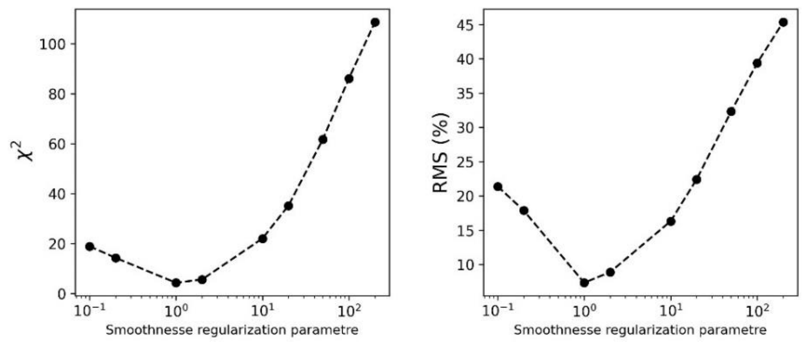


Figure 1: Iterative process to find the smoothness parameters and other parameters of the mesh.

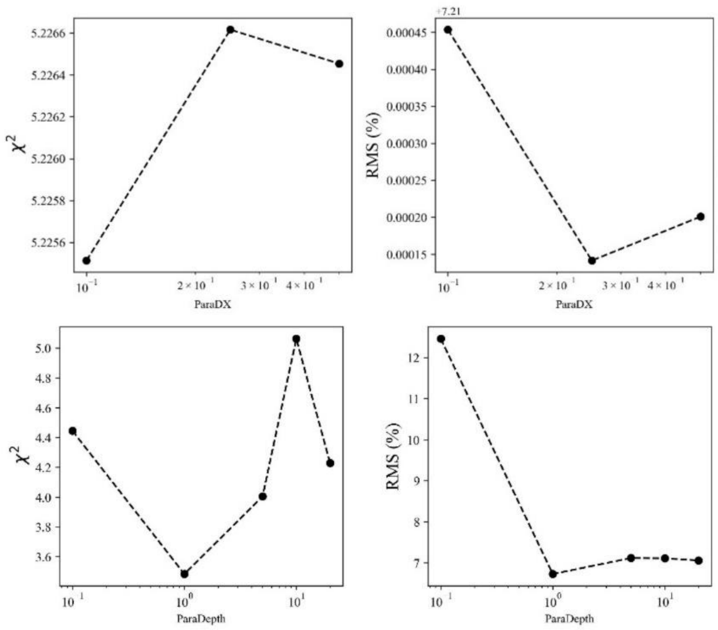


Figure 2: Iterative process to find the parameters of the mesh (paraDx and ParaDepth).

Inversion parameters (zWeight=10, lambda=1, paraDx=0.5, ParaDepth=10, quality=34.4)

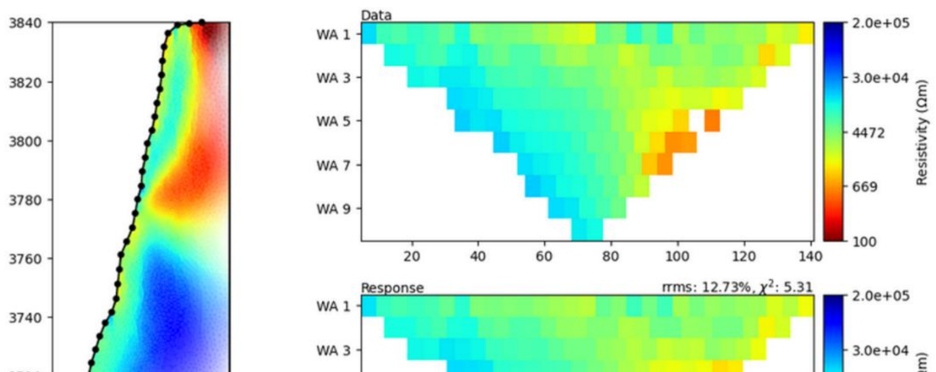


Figure 3: Example of the inversion of the reference dataset used to get the inversion parameters.

7- Figures – numbers, quality and color schemes: The manuscript includes a large number of figures, which makes it difficult to follow the overall narrative. We suggest reducing the number of figures in the main text – moving less essential ones to the appendix or supplementary material – and clearly emphasizing the main findings of each figure, either through improved visual presentation or more informative captions. Nearly all figures are not colorblind-friendly, particularly those using red and green together. Please revise all color schemes accordingly. Additionally, the choice of colors should support the interpretation of the data more effectively. For instance, in Figure 4, consider using clearly distinguishable colors to differentiate between excluded and retained datapoints.

**Answer**: we reduced the number of figures by merging some and moving the less essential figures in the appendix. Concerning the color schemes it is commonly used, we tested many other color schemes, but the one used here represents better results.

In Figure 4 we want to show the general evolution of contact resistance of all electrodes and the gaps in the A-ERT.

8- **Figure 5**: The figure is difficult to interpret. The bars are barely readable, and the intended comparison is unclear. Are you examining interannual changes or comparing specific time periods? The same question arises for Figure 9-12 – what is the focus of the study? In the current layout, it is complicated to distinguish between interannual and pluriannual changes.

**Answer**: Figure 5 was simplified in the new version. We try to show a comparison of seasonal and interannual datasets (three datasets in each subfigure), to get an idea about the seasonal variation and interannual variations at each side of the site.

9- Figure 6: Rather than indicating the number of electrodes, specify the depth of investigation. It would be more appropriate to present inverted resistivity values here. The connecting lines between data points suggest a linear trend, which may misrepresent the actual physical behavior – particularly during the transition between unfrozen and frozen conditions. We therefore suggest removing these trend lines to avoid a misleading interpretation.

**Answer**: The objective is to show the variations in the raw data at different positions of the profile. We added in the legend the theoretical depth of investigation. For the trend line it could mislead the reader but it helps as eye guide (here example of the figure without lines): but we prefer to keep them and to add in the caption that (The dashed lines are just guides for the eyes).

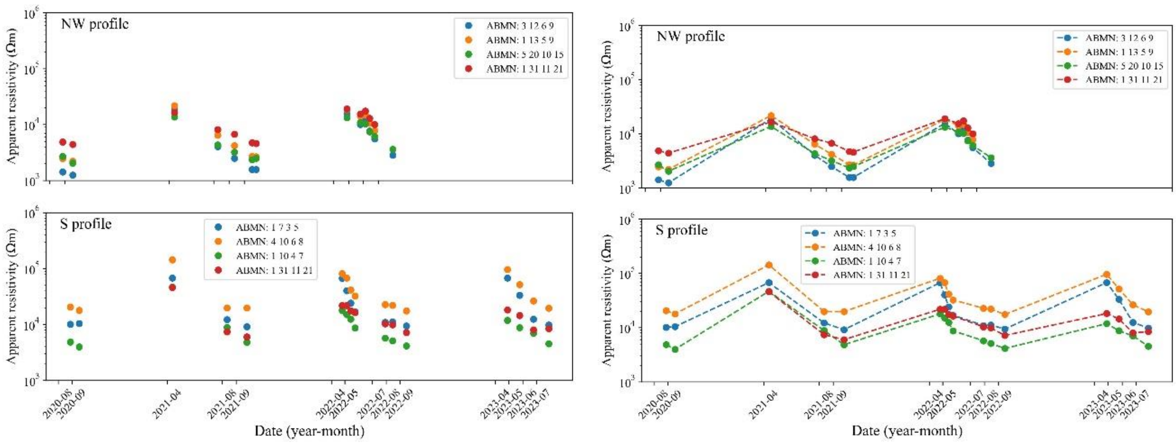


Figure 5: Temporal changes in apparent resistivity for different combinations of quadrupoles (ABMN) 341 reflecting different depths of investigation. (Figure was removed in the new version)

10- **Figure 7**: This figure compares resistivity across multiple profiles. However, a direct comparison is problematic due to differences in profile orientation—P1 is oriented perpendicular to the surface, whereas the others are nearly horizontal. In addition, it would be helpful to indicate the expected permafrost extent and the corresponding threshold resistivity values (subfigure). We also recommend adjusting the color scale: resistivity values as high as 500.000 Ωm are not physically explainable and should be limited. The grey lines representing the infrastructure are barely visible.

**Answer**: P2 and P4 are almost perpendicular to the surface. The extent of active layer varies from one profile to another. We add information in the appendix about the active layer extent from boreholes data. We will improve the quality of the figures.

11- **Figure 9-10**: It appears that different meshes were used for the inversion routines and the subsequent calculation of resistivity change ratios. This inconsistency should be addressed. We also recommend using consistent x- and y-axis limits in both figures.
**Answer**: the same mesh was used for the calculation of resistivity change ratio and the same mesh in both figures 9 and 10; only the x-axis ticks have been changed in display. We have corrected this point in the new figure.

12- **Figure 11**: The red arrows overlaid on the tomograms obscure important details. Additionally, mark the locations of observed drainage paths in Figure 12 for better correlation between figures.
**Answer**: we moved the arrows in figure 11 and added arrows on fig 12.

13- **Borehole validation:** In the discussion, it is stated that borehole temperature data were used to validate both the interpretation and the estimated temperatures (Lines 486–487). The borehole temperature data of the different boreholes are not included; however, the manuscript would greatly benefit from a visual representation of borehole temperatures over time, ideally aligned with the ERT measurement periods and on the north/ south-facing slope. This could include a figure showing active layer thickness evolution over the years.

You presented two calibration curves from the laboratory testing – please clarify which one (and why) was used to estimate temperature. In Figure 14, estimated temperatures below 2 meters are missing, although Figure 13 shows that 13 resistivity values were extracted from profile P1. Why are these data points excluded? Also, consider adjusting the x-axis of Figure 14; the current range (-10°C to +10°C) is unnecessarily broad.
In Line 553, you mention that individually adapted inversion parameters can improve temperature estimation – why does not show a comparison to demonstrate this?

Lastly, when comparing laboratory and field-derived resistivity–temperature relationships, please account for differences in the penetration depth of the current signal.

**Answer**: We mentioned in the text the essential information from boreholes (e.g., maximum depth of active layer at each borehole). And we refer to the study where all data are treated explicitly, and we added in the appendix the following figure to visually represent temperature in borehole over time of ERT at south/north faces as proposed.

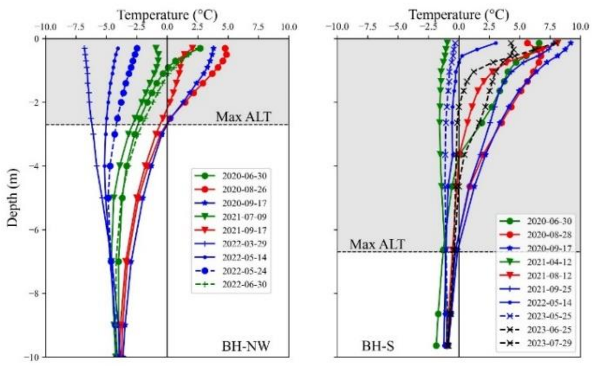


Figure 6: Temperature variation over depth in boreholes BH-NW and BH-S on different date. The colored zones (Max ALT) indicate the maximum extent of the active layer at each borehole.

To estimate temperature, we used the data came from the AdM sample. The other sample came from very close site, was used for comparison just.
We mentioned that the model could not predict temperature at active layer because in active layer many parameters could affect resistivity as mentioned in the text, therefore, we could not estimate temperature in the active layer. We have changed the x-axis in Figure 14, and we added a ±1 shadow zone around measured temperature to show the accuracy in temperature estimation.

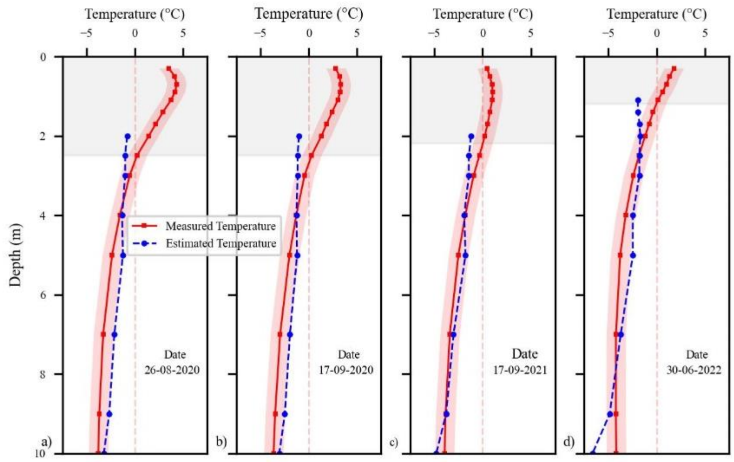


Figure 7: Comparison between measured temperatures in BH-NW and estimated temperatures derived from geophysical measurements (i.e., extracted resistivity values at different dates) using the petrophysical model in Equation 2. The gray-shaded area indicates the extent of the active layer at the time of measurement. The red-shaded zones show the ±1 °C range around the measured temperature.

14- **Hydrological dynamics:** To confidently interpret water pressures, appropriate measurements must be presented, as in Offer et al. (2025) or Scandroglio et al. (2025). Water pressure is influenced not only by the water table elevation but can also result from frozen clefts or permafrost-related constraints. Given that hydrological dynamics are listed among the study's main objectives, their treatment in the manuscript is limited. Either revise the stated objectives or expand the analysis and discussion of these processes.

**Answer**: The goal here is to test the potential of the method as a standalone low-cost approach to characterize the timing and pathways of water flows. Indeed, other approach such as piezometers are expensive and invasive. The ultimate goal of this test is to determine the potential of the method for prompt hazard assessments as water flows are a potential triggering factor of rock falls and rock avalanches (Fisher et al., 2010 ; Cathala et al., 2024). Thus, other instrumentation are not suited for prompt hazards assessment while previous studies have already validated that drops in resistivity over short time periods are due to water pressure (Offer et al., 2025). However, it is important to test the method in other topographical and lithological context and this is what we propose through our study. We know that there is water filtration to galleries. We tried with this dispositive, to detect the fractures used in drainage or the effect of water accumulation. Maybe we should adapte our dispositive to detect small events.

- **Conclusion:** (L630-631) We believe it is important to clarify in the manuscript that the measured resistivity signals on the north- and south-facing sides are similar, and that the main difference lies in your interpretation – namely, attributing high resistivity to surface drying in one case and to the presence of permafrost in the other.

  Additionally, can it truly be claimed that subsurface temperature can be "*accurately"* (L632) derived from ERT measurements using the applied petrophysical models? While the manuscript suggests a potential precision of 1°C, Figure 15 reveals discrepancies of up to ~5°C between laboratory-based and field-derived estimates. Even a precision of 1°C would be substantial in the context of permafrost studies, where internal temperatures often lie just a few degrees below freezing (e.g., Noetzli et al., 2024), and small changes can have major implications for stability and long-term thermal evolution. What about depths from 0-4 m (L634-635) – which are probably most relevant when assessing the progressive deepening of the active layer?

See **answer** above: it is important to know if these methods fail in the shallow layers, this confirm results from previous studies using thermal modelling approach and highlights research gaps for research perspectives: these depths, where many rockfalls occur (Legay et al., 2021) are the most difficult to understand and model.

**Answer**: The accuracy of 1° C came from the estimation made in figure 14. Is this accuracy is enough or not? We think that it is still an open question. It depends on the state of the permafrost. In the active layer, resistivity depends upon different parameters (water content, or saturation, water salinity, and temperature). The temperature effect on resistivity is of second order and could not use resistivity to get temperature in active layer.

Technical corrections:

-Fig 1a: the colors representing the mean annual temperature are not readable in the figure

**Answer**: We believe that these colors have no influence on the paper, reader could go back to original map to see in details.

-L26: permafrost “rocks”. **Done**

-L32: to get “temporal” variations **Done**

-L51: degradation of permafrost(?) **Done**

-L53: affected by (rather use another verb, as it is a repetition with the next sentence) **Done**

-L55: Offer et al. 2025 is not the appropriate study for rockfall monitoring, use Hartmeyer et al. 2020 instead

**Answer**: we maintained the same reference, here we are talking about studies related to effect of permafrost degradation on infrastructure.

-L59: Mamot et al. 2018 would be good to include here **Done**

-L85: the wording "in the last few years" is not in accordance with the used reference of the year 2010. This is now more than 15 years ago and not only a few years…

**Answer**: changed to: "In the last two decades"

- L173: title of the section à "Electrical resistivity-temperature relationship" (in the section you don't show conductivity results)

**Answer**: the section's title is (Electrical conductivity-temperature relationship). We present a model of the thermal dependency of electrical conductivity. And we precise that the electrical conductivity is the invers of electrical resistivity to let unspecialized reader follow our argument.

-L203: what is the snow melt water conductivity of the field site?

**Answer**: Snow melt water conductivity is ~9.2 μS/cm and the conductivity of collected water is about 150 μS/cm (and in lab we prepared solution of conductivity close to that of the site 160 μS/cm). We corrected this information in the text.

-Fig. 4: electrode number: **done**

-L293: three times "data" in a short sentence is a bit overwhelming: **Phrase removed**

-Table 1: no necessary information à consider to put it in the appendix **Answer**: removed to appendix.

-L314-317: please reformulate– it is unclear what you want to express: **Done**

-L356-357: please reformulate – it is unclear what you want to express: **Done**