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EDYTEM

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To: Cryosphere

Dear Editor,

Please find enclosed a revised version of our manuscript for submission to Cryosphere. All the comments made by the referees have been accounted for as discussed below. A manuscript with the changes overlaid is also provided.

Thanks for the opportunity to resubmit and we deeply thank the referees for their time and comments.

Best regards,

Dr. Feras Abdulsamad  
Corresponding Author

### Referee 3

1. The Referee wrote *“Review of the manuscript entitled: “Rockwall permafrost dynamics evidenced by Repeated and Automated Electrical Resistivity Tomography at Aiguille du Midi (3842 m a.s.l., French Alps)”*. This manuscript reports the use of an automated system capable of recording periodic electrical resistivity tomography profiles over a permafrost dominated high altitude site in the French Alps. As much as I admire the authors for being able to instrument such a challenging site, and despite slight improvements from the previous iteration, the manuscript requires a thorough revision and potential reorganisation of scope and narrative. A few major issues prohibit me from recommending it for publication: There is a certain ambiguity around the methods used in this work. Authors need to be clearer and add more details about methods around field water sampling, laboratory complex impedance measurements, electrical resistivity data processing pre and post geophysical inversion.” **Response:** We have revised the manuscript to improve the clarity of the methodology and we have added further details regarding field water sampling (a reference to Ben-Asher et al., 2026 has been included). Furthermore, the laboratory complex impedance measurements, and electrical resistivity data processing before and after inversion, are now better described. In addition, we now cite previous studies that describe the laboratory complex resistivity measurements in detail; therefore, we consider that reproducing the full methodology here would be redundant.

1b. The Referee wrote *“There is a serious lack of detail regarding the cross-peak tomograms (produced using two electrode cables). As these are not repeat measurements they need to be presented separately from the A-ERT measurements.”* **Response:** The cross-peak tomograms provide a general overview of the internal structure of the site (i.e., the full image) prior to focusing on the single-sided measurements. The repeated datasets represent the temporal continuity of the A-ERT dataset. We consider these datasets are important for contextualizing and supporting the interpretation of the A-ERT time-lapse dataset presented subsequently. In the revised version we made sure that the reader doesn’t consider it as a result from A-ERT measurements but rather as a punctual measurement used for site characterization.

In the revised version, we added the text shown here:

Line 380: Data acquired Wenner electrode arrays with 64 electrodes.

Line 399: A total of 320 data points used for the inversion (475 data points constitute the complete pseudo-section), about 30% of dataset was filtered).

Line 414: A total of 310 data points were used for the inversion (475 data points constitute the complete pseudo-section), about 35% of dataset was filtered).

2. The Referee wrote *“As was mentioned by the authors, data acquisition was plagued by issues along the way. Whereas this is somewhat to be expected in such a challenging site, I cannot refrain from doubting the quality of the data and suspect the overinterpretation of the results. As mentioned in Table C1, each individual timestep does not contain that many datapoints, post filtering, which it is worrying with regards to the tomogram’s sensitivity and ability to resolve thin layers (such as the active layer) and other features within the profile. There is also quite a lot of inferences regarding the near subsurface but the distance between electrodes within a quadrupole would indicate there are little or no measurements in the near subsurface (top 5m).”* **Response:** We acknowledge the reviewer’s concern regarding the data quality and near-surface resolution, for this reason, a rigorous quality control of the presented

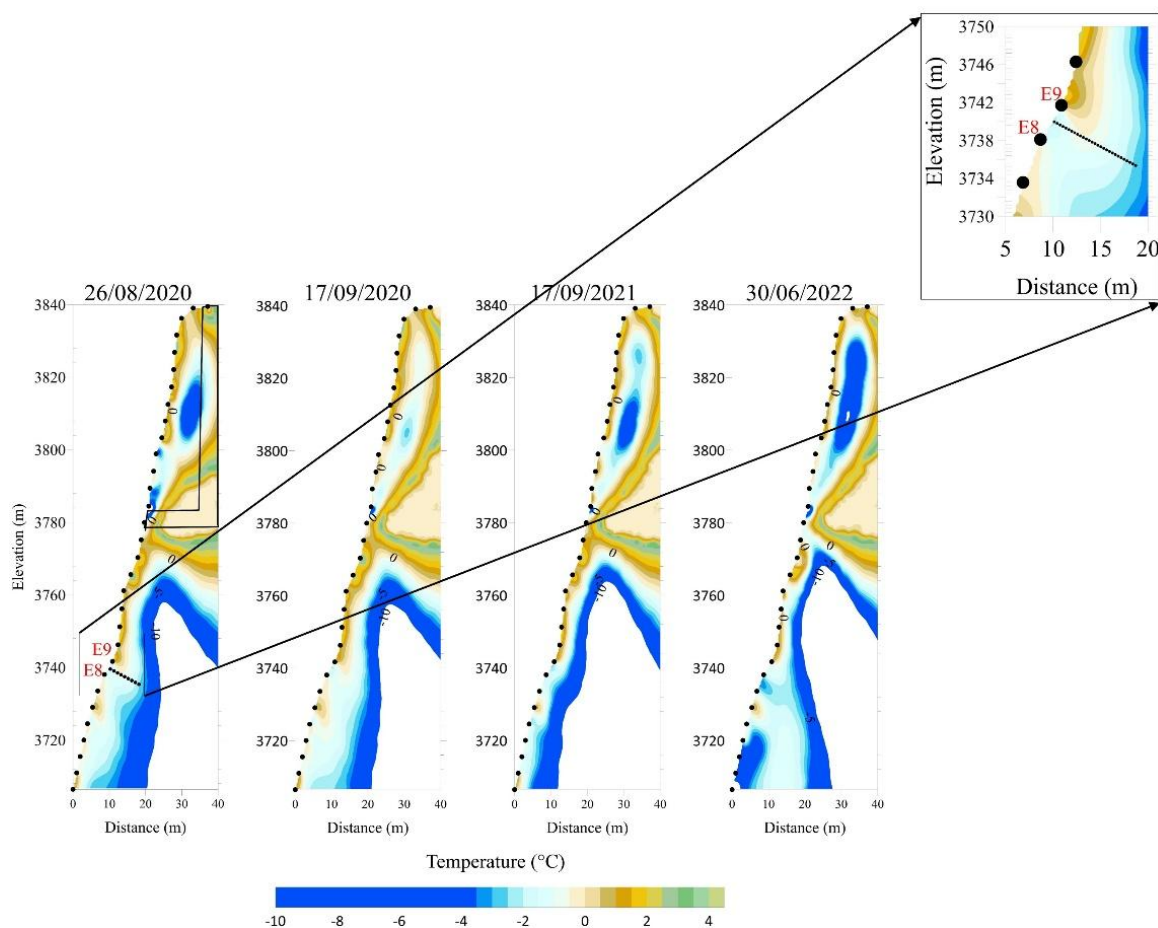
datasets was performed as explained in the manuscript (section 4.3). The smallest quadrupole length used in this study is 15 m, which corresponds to an approximate depth of investigation of about 2.5–3 m. Therefore, these measurements do contain information about shallow subsurface conditions. However, we agree that the sensitivity within the very near surface (approximately the upper 2 m) is limited due to the quadrupole length. This limitation and its implications for resolving very shallow features are clearly discussed in the revised manuscript.

3. The Referee wrote “*My suggestion to the authors is to reorganize the manuscript and put forward only the datasets which can : 1) be backed up by a clear and appropriate methodology and 2) have data processing metrics that clearly attest to its validity.*”

**Responses:** The data presented here have been chosen according to the quality of the Pseudosection of the apparent resistivity (number of data points). Now we clearly explain these choices in the new version of the paper.

4. The Referee wrote “*On a previous round of revisions, the novelty of this manuscript was put under scrutiny. And I would agree, A-ERT alone is not novel for the study of permafrost stability. However, I see a lot of value and potential fruitful discussions in aligning temperature datasets derived from geophysical measurements with temperature datasets measured in boreholes (as was done for Figure 10). I also like the idea of having pseudo boreholes to compare temperature variability with depth at different locations along the profiles. If you have a good resistivity-temperature conversion model, why not present a series of 2D temperature profiles corresponding to the different timesteps?*”

**Response:** We agree and the change has been done accordingly. We thank the reviewer for this insightful and constructive suggestion. We agree that aligning temperature datasets derived from geophysical measurements with borehole observations provides valuable insights, and we appreciate the positive feedback regarding Figure 10 and the pseudo-borehole approach. While it is technically feasible to generate a full series of 2D temperature sections from the resistivity–temperature conversion, we included in the revised version of the manuscript. Nevertheless, in response to the reviewer’s suggestion, we now provide a representative 2D temperature section corresponding to the dataset presented in the Temperature–Resistivity conversion section.



**Figure 1:** Distribution of temperature ( $^{\circ}\text{C}$ ) at the AdM site. Temperature was derived from geophysical resistivity measurements using Equation (2) and the parameters obtained from the laboratory measurements reported in this manuscript. The dotted line indicates the location of borehole BH-NW. The datasets correspond to the same datasets as shown in Figure 10.

5. The Referee wrote “*I will also list line specific comments below, some of which refer to the aforementioned issues (red headings) and help put them into context. Line 28: To give the narrative a better flow you should first say something like “Borehole temperature measurements are often used to monitor such geohazard susceptible areas, but they lack sufficient ...”*” **Response:** We agree and the change has been done accordingly. 6. The Referee wrote “*Line 33: 3.5 years*”. **Response:** We agree and the change has been done accordingly. 7. The Referee wrote “*Line 33: It would be better if you said what instrumentation you installed along the profiles.*” **Response:** We agree and the change has been done accordingly.

8. The Referee wrote “*Line 34: Autonomous is not synonym to automated. Do you mean automated here as in A-ERT?*” **Response:** We agree and we mean “automated”. The text has been updated accordingly. Thanks for the comment.

9. The Referee wrote “*Line 79-89: I don't really understand the need of this section here. Apart from ERT you are not using any of these other techniques. Why not save it for the discussion arguing how can an ERT survey be enriched by other geophysical information.*” **Response:** This is the introduction and we like to broaden first the methods used in this type of setting. In other words, we included this section to provide an overview of the geophysical

methods commonly used in this field and to highlight what could be achieved through the combination of different methods. Although only ERT was applied in this study, presenting these complementary methods helps to place our work within a broader methodological context. We agree that this is a valuable suggestion, and in the revised manuscript we have also added a paragraph in Discussion to briefly address how geophysical surveys could be further strengthened through the integration of complementary geophysical methods in addition to ERT.

10. The Referee wrote “*Line 110: “from a fixed”.*” **Response:** We agree and the change has been done accordingly.

11. The Referee wrote “*Line 114: Might want to add Cimpoiasu et al., (2025). It talks about capturing freeze-thaw transitions in the active layer with an automated ERT system. Cimpoiasu, M.O., Kuras, O., Harrison, H., Wilkinson, P. B., Meldrum, P., Chambers, J. E., Liljestr nd, D., Oroza, C., Schmidt, S. K., Sommers, P., Vimercati, L., Irons, T. P., Lyu, Z., Solon, A., and Bradley, J. A. (2025). High-resolution 4D electrical resistivity tomography and below-ground point sensor monitoring of High Arctic deglaciated sediments capture zero-curtain effects, freeze–thaw transitions, and mid-winter thawing. The Cryosphere, 19, 401–421, <https://doi.org/10.5194/tc-19-401-2025>.”*” **Response:** We agree and the change has been done accordingly.

12. The Referee wrote “*Line 127: Do you mean “of the same site”?*” **Response:** We agree and the text has been updated.

13. The Referee wrote “*Line 128: “pluriannual permafrost dynamics”.*” **Response:** We agree and the text has been updated.

14. The Referee wrote “*Line 135-137: Suggest rephrasing to: “temperature estimated using geophysical measurements of electrical resistivity is quantitatively evaluated by comparison with borehole temperature measurements.”*” **Response:** We agree and we have rephrased this sentence.

15. The Referee wrote “*Line 142: Explain the acronym AdM before using it in text.*” **Response:** The acronym AdM was already defined at line 123 (in the previous version of the manuscript).

16. The Referee wrote “*Line 142: “by around 5000 visitors...”. What is the point of this information? I think you want to say that it is an important landmark that deserves to be protected and monitored.*” **Response:** we rephrased and developed this section.

17. The Referee wrote “*Line 166: I’d save this for the discussion.*” **Response:** We agree and the change has been done accordingly.

18. The Referee wrote “*Line 169: “different dates”.*” **Response:** We agree and the change has been done accordingly.

19. The Referee wrote “*Line 219: How was this collected? Please be clearer and more specific when you are explaining your methods.*” **Response:** In the galleries at the Aiguille du Midi site, infiltrating water is routinely collected using fixed containers installed beneath active seepage zones. These containers allow the continuous accumulation of drip water

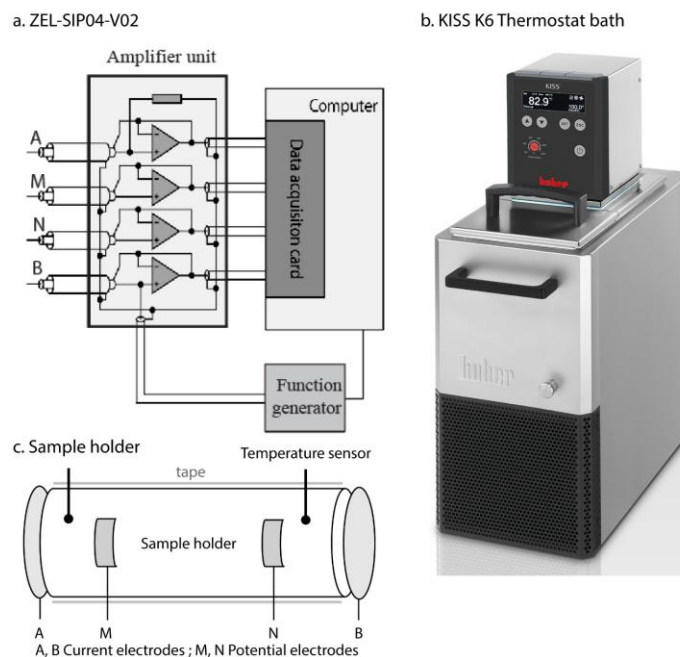
originating from fracture-controlled infiltration within the rock mass. The electrical conductivity of the collected water is measured in situ using a calibrated conductivity probe. This water is then used in the laboratory to saturate the granite sample. Reference describing the monitoring and characterization of infiltrating water at the site has been added to the manuscript. Line 230: This value is representative of the conductivity of infiltrating water collected and measured in galleries at the AdM site (approximately  $150 \mu\text{S}/\text{cm}$  or  $0.015 \text{ S m}^{-1}$ , see Ben-Asher et al. (2026).

20. The Referee wrote “*Line 221: Small s in “sample”.*” **Response:** We agree and the change has been done accordingly.

21. The Referee wrote “*Line 227: Have you steadily increased the temperature of the bath within that range? It is not clear at all what the temperature increments were used and when you have collected resistivity measurements.*” **Response:** The experimental procedure, including the temperature increments and the timing of resistivity measurements, has been described in detail in our previous studies (Abdulsamad et al., 2019; Coperey et al., 2019; Duvillard et al., 2021; Duvillard et al., 2018). In brief, the temperature of the bath was controlled and stabilized at each target value before performing resistivity measurements to ensure equilibrium conditions. These references provide a full description of the methodology, and we believe that including all the details again would go beyond the scope of the present paper.

22. The Referee wrote “*Line 227: How was the impedance meter attached to the rock sample? It really isn't clear.*” **Response:** We used thin carbon film electrodes, which were placed in contact with the rock sample for the ABMN configuration. These electrodes were stacked against the sample surface and connected to the impedance meter using shielded cables to ensure stable electrical contact during the measurements.

23. The Referee wrote “*Figure 3: Do you happen to have a photo/schematic of the lab setup? It would help a lot to understand your experiment.*” **Response:** Here is a photo of the experimental setup (from our previous work, Coperey et al., 2019). The sample was placed in the bath, and the electrodes were connected to the impedance meter for the measurements. To avoid increasing the number of figures which is already high this figure will not be included in the manuscript.



**Figure 2:** schematic of the sample holder, the bath, and the impedance meter used for the laboratory electrical resistivity measurements.

24. The Referee wrote “Line 237: No need to mention both electrical conductivity and electrical resistivity.” **Response:** We agree and the change has been done accordingly.

25. The Referee wrote “Line 242: How do you work out  $T_f$ ? Is it the inflection point of these model fit lines?” **Response:** yes,  $T_f$  corresponds to the inflection point between both models or equations (1 and 2 in text). It is determined directly from the laboratory measurements by fitting them with the model.

26. The Referee wrote “Line 244: How is  $\theta_r$  calculated?” **Response:** The residual water content is determined by fitting the laboratory resistivity vs temperature data using equation 2 (at  $T < T_f$  °C).

27. Line 258: Again, it would be very valuable if you had a photo. Do you mean “jumper cable”?” **Response:** Yes, we used a jumper cable to fix the cable at each take-out. A photo of the specially designed stainless-steel jumper used to attach the cable takeout to the climbing bolt is available (a duplicated electrode is shown in the photo to ensure improved electrical contact). However, in order to keep the number of figures in the manuscript reasonable, we have chosen not to include this image.

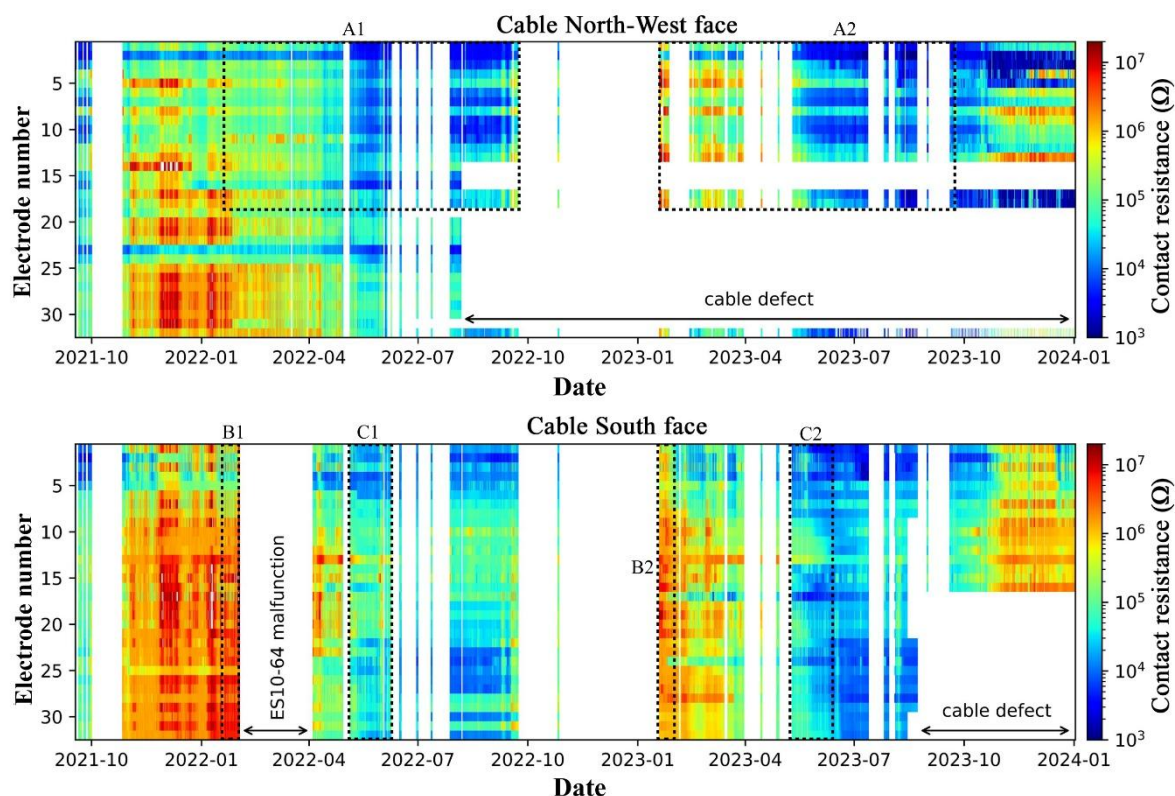


**Figure 3:** Photo of the jumper used to attached electrodes and take-out.

28. The Referee wrote “Line 270: “number”” **Response:** We agree and the change has been done accordingly. 29. The Referee wrote “Line 271: Between June 2020 and ...” **Response:** We agree and the change has been done accordingly. 30. The Referee wrote “Line 272: Does “occasionally” mean not automated and periodical? What were the dates?” **Response:** The measurements were not fully automated in the first year, so we launched the measurements manually at regular time intervals. During the first year, measurements were mostly conducted monthly, at least when the field conditions were acceptable. This is now explained in the revised version of the manuscript.

31. The Referee wrote “Line 278: What is the CR threshold?” **Response:** The device has 600 k $\Omega$  as CR threshold. In our treatment we filtered electrodes with CR > 200 k $\Omega$ . This is now explained in the revised version of the manuscript.

32. The Referee wrote “Line 283: Figure B1 doesn't indicate when the improvements were made to the cables, and it doesn't discuss the improvements. I personally can't see the improvements reflected in the datasets; the authors need to explain them a bit better by pointing at features in the plot shown.” **Response:** In Figure B1, we highlighted the specific time periods that allow comparison before and after the CR improvement by doubling the electrodes. These comparison intervals are indicated in the figure and described in the corresponding section of the text and the caption to explicitly point out the relevant features in the plot and better illustrate the effect of the modifications.



**Figure B1.** Temporal evolution of contact resistance at the North-West side and South side. Data partly missing is due to cable defects. The panels highlighted by dotted lines (A1, B1 and C1) are compared with their corresponding periods (A2, B2, and C2) to evaluate the change in contact resistance after doubling the electrodes.

33. The Referee wrote “*Line 298: Do you mean three orders of magnitude instead of “decades”?*” **Response:** Yes, we meant three orders of magnitude, the manuscript has been changed accordingly.

34. The Referee wrote “*Figure 4: Different colours should be appropriately explained. What were the quadrupoles used?*” **Response:** The quadrupole configurations (ABMN) corresponding to each colored time series have been explicitly added to the legend of figure 4.

35. The Referee wrote “*Line 308: Do you mean CR?*” **Response:** We agree and the change has been done accordingly.

36. The Referee wrote “*Line 310: How do you define an outlier here?*” **Response:** For the analysis and outlier filtering, we individually examined several pseudosections acquired at different times of the year (summer, spring, etc.). Based on this assessment, we defined outliers as data points falling outside specific resistivity ranges. For datasets acquired in summer and autumn, values outside the range of 300  $\Omega \cdot m$  to 20  $k\Omega \cdot m$  were filtered out. For datasets acquired in spring and winter, the filtering range was extended to 300  $\Omega \cdot m$  to 200  $k\Omega \cdot m$ . (see Figure 4 in the revised manuscript).

37. The Referee wrote “*Line 311: “analysed individually a subset of the pseudosections recorded”* Done. 38. The Referee wrote “*Line 311: “(at different times of year (spring, summer))”* Done. 39. The Referee wrote “*Line 311: “. As a result...”* **Response:** We agree and the change has been done accordingly. 40. The Referee wrote “*Line 311: It is not very clear what the analysis procedure was.*” **Response:** The processing steps applied to the datasets prior to inversion are described in the manuscript (Lines 306–314). We have clarified this section to make the analysis procedure more explicit.

41. The Referee wrote “*Line 312: “we decided to filter outliers out of the range”* **Done.** 42. The Referee wrote “*Line 314: Do you mean “more high resistivity data was filtered...”*” **Done.** 43. The Referee wrote “*Line 315: I thought you collected a dataset daily. What was the criteria used to subselect these datasets for analysis?*” **Response:** we have two criteria to select dataset: 1- the measurement has enough data in the Pseudosection (almost completed Pseudo-section), 2- data that could serve the objective of the study. In some cases, we have data of 15 days with no considerable change, so we select one representative Pseudosection.

44. The Referee wrote “*The Referee wrote “Line 317: It is not very clear what kind of inversion it is. Is it a timelapse inversion or have you inverted timesteps individually? Is it a timelapse inversion where all timesteps use only one timestep as reference or a timelapse inversion which uses the preceding timestep as reference.”* **Response:** Line 317 we just introduced the inversion code that we used to perform the tomograms. Later, in lines 394 to 395, we explained the time lapse inversion that we use: 394 [In order to track the seasonal and interannual variations in the permafrost, a time-lapse inversion approach was employed to invert datasets for each profile (NW, S). The reference model was moved along with the inversion so that the difference to the preceding step is constrained.]. The related content has been reorganized and consolidated in the processing and inversion section.

45. The Referee wrote “*Line 320: “in the absence of a”*” **Response:** We agree and the change has been done accordingly.

46. The Referee wrote “*Line 321: “reciprocal errors” - explain what they are.*” **Response:** Reciprocal errors are calculated from the difference between reciprocal measurements, which are obtained by exchanging the current bipole (A–B) with the potential electrode bipole (M–N). According to the principle of reciprocity, the measured resistance of a four-electrode array should remain unchanged. In practice, however, differences are observed, and these are used to estimate the measurement error. However, this procedure is not generalized in ERT data acquisition and could not provide a good estimation of all errors on ERT data. As this procedure is well known, and was not used in this study, we did not initially provide a detailed explanation.

47. The Referee wrote “*Line 326: Which one is the reference dataset?*” **Response:** The reference dataset is the dataset of 30/06/2020, which is the first and completed Pseudosection.

48. The Referee wrote “*Figure 5: change X-axis label to “distance between electrodes”.*” **Response:** We agree and the change has been done accordingly.

49. The Referee wrote “*Figure 5: “at different distances between electrodes within a quadrupole”*” **Response:** We agree and the change has been done accordingly.

50. The Referee wrote “*Line 348-350: remove from caption, keep for discussion.*” **Response:** We prefer to retain this information in the caption so that the figure can stand alone and remain fully understandable without requiring reference to the main text.

51. The Referee wrote “*Line 365: between the sun exposed ... strong isolation) and the shaded ...*” **Response:** We agree and the change has been done accordingly.

52. The Referee wrote “*Figure 6: Your rms is quite high. In your methods you only discuss the daily profiles and their processing, you don't mention anything about data quality corresponding to this tomogram. How many measurements do you have? Were they filtered? What is the resulting sensitivity?*” **Response:** We agree that the RMS value is relatively high. However, a low RMS is not always the most appropriate criterion for assessing inversion quality, particularly in complex geological environments. Moreover, under permafrost conditions, such high rms is usual because of the data quality which affect the inversion convergence. In Figure 6, we present data from a long profile acquired using a Wenner electrode array, comprising 475 data points in the complete pseudo-section. After applying the filtering procedure described above, 320 data points were retained for the inversion (approximately 30% of the total dataset was removed), which may partly explain the relatively high RMS value. Additional information has been added to the figure caption to explicitly provide these details.

53. The Referee wrote “*Line 395-396: It is not very clear which one is the reference model? Is the preceding timestep the reference model?*” **Response:** Yes, the reference model is the preceding timestep response (as was mentioned in the manuscript: “the reference model was moved along with the inversion). We added this information to the “**data processing and inversion section**”.

54. The Referee wrote “*Line 398: “acquired along the NW profile”*” **Response:** We agree and the change has been done accordingly. 55. The Referee wrote “*Line 399: “can be observed”*” **Response:** We agree and the change has been done accordingly. 56. The Referee wrote “*Line 400: “The permafrost layer associated with high...”*” **Response:** We agree and the

change has been done accordingly. 57. The Referee wrote “*Line 402: “was cooler than both...”. A colder year? On average? You need to rephrase this sentence.”* **Response:** We meant that 2021 was colder on average than both 2020 and 2022. The sentence has been rephrased accordingly for clarity.

58. The Referee wrote “*Line 412: I think it is pretty obvious you are above the water table.”* **Response:** This is not necessarily obvious because of the possible existence of transient perched aquifers. The reference is there to confirm this point.

59. The Referee wrote “*Line 413: I generally prefer it to be presented as percentage difference rather than ratio. My main concern is that I was expecting a distinct region with values around 1 (white) for where the gallery is and I can't see that in your figure.”* **Response:** The values are indeed very close to 1 in the gallery, which we consider realistic. In this context, the gallery is not completely homogeneous, there is water infiltration from surrounding rocks, slight variations in conductivity due to temperature changes at the gallery walls because of air flow inside the gallery. And the inversion process cannot produce perfectly uniform values within the gallery itself. Therefore, the observed deviation is likely related to multiple factors influencing both the measured data and the inverted model around the gallery.

60. The Referee wrote “*Figure 8: Label where the gallery is on these figures as you did for figures 6 and 7.”* Done

61. The Referee wrote “*Figure 8: You don't have to repeat the X-axis label for all subplots.”* **Response:** We believe it is preferable to retain the X-axis labels as they are, because there is an offset between the five subplots in the upper panel and the four subplots in the lower panel.

62. The Referee wrote “*Line 443: Why would that be? More fractures in that area? More water retention?”* **Response:** At point P2, the observed differences in electrical conductivity can be attributed to higher temperatures compared to P1. P2 is located closer to the sun-exposed surface, it is reasonable to hypothesize that this proximity results in higher temperature. Under these conditions, a greater volume of unfrozen water is likely to be present and contribute to electrical conductivity.

63. The Referee wrote “*Line 449: Are you expecting porosity to be very different in P2?”* **Response:** No significant difference in porosity between P1 and P2 is expected. The zone corresponding to P2 does not exhibit structural characteristics (e.g., fracturing or heterogeneous lithology) that would suggest a marked variation in porosity. Our analysis assumes that the observed differences in electrical resistivity are primarily driven by temperature variations leading to variation in water content, rather than by variations in the intrinsic porous structure.

64. The Referee wrote “*Line 451: Are you basically saying there are no electrical resistivity measurements in the active layer? You do make quite a lot of inferences about the active layer though.”* **Response:** The maximum depth of the active layer is about 2.7 m on the NW face and reaches up to 7.6 m on the S face (see Fig. A1). We estimate that the first data point corresponds to an apparent depth of approximately 2 – 2.5 m. Although the measurements include the contribution of the active layer but lacks resolution to delineate it precisely. Inferences about the active layer are thus based on direct and indirect evidence.

65. The Referee wrote “*Line 466: Explain the acronym before using it.*” Done

66. The Referee wrote “*Line 484: Which one is the dominant factor then? Water content?*”  
**Response:** Both water salinity and water content influence the resistivity of a rock. However, in the context of the ADM, water salinity is not expected to vary significantly; therefore, water content is likely the dominant factor.

67. The Referee wrote “*Line 487: Please rephrase, I don't know what you are trying to say here.*” Done

68. The Referee wrote “*Line 496: How did you extract resistivity at P1? This is yet another thing not well explained. Are you selecting the mesh element with the closest coordinates to a specific depth along P1 and report its resistivity?*”  
**Response:** To extract resistivity at P1, we created a list of positions (at the needed depth), we used a forward operator that selects the resistivity value from the model vector corresponding to the mesh cell containing the P1 coordinates. This approach ensures that the reported resistivity is representative of the specific depth and location along P1.

69. The Referee wrote “*Line 505: “part of datasets”? This is vague.*”  
**Response:** By “part of the datasets,” we refer specifically to the datasets acquired on 26/08/2020 and 17/09/2020. This clarification has been added to the manuscript.

70. The Referee wrote “*Line 507: Do you mean “whereas”?*” Yes, change has been made.

71. The Referee wrote “*Figure 11: There is a lot to unpack here. I don't think the field and lab agree very well so the strategy needs to be revised for future work. Perhaps a list of suggestions on how to improve this would help the readers. It is possible that the sample's resistivity evolution with temperature is not representative of the area extracted from the inversion result.*”  
**Response:** We do not believe that the discrepancy originates from the laboratory results. We conducted numerous tests on different types of rocks and consistently observed similar trends, with variations from one sample to another depending on lithology, porosity, and water saturation. In this study, the site is particularly complex case. The combination of lithology, topography, climatic conditions, and infrastructure containing metallic elements likely contributed to the discrepancy observed in Figure 11. We therefore do not consider the laboratory results to be the primary source of this discrepancy.

72. The Referee wrote “*Figure 12: As before, superimposing the approximate location of the gallery would help interpret these results. Please explain the red arrow.*”  
**Response:** The red arrows show the position of possible water infiltration in this fractured zone. Changes have been made to both the figure and text.

73. The Referee wrote “*Line 551: “high altitude mountainous site*”  
**Response:** We agree and the change has been done accordingly.

74. The Referee wrote “*Line 551-554: This is phrased as if high CR is an A-ERT problem, but it is not, it is a problem that appears when collecting ERT data in frozen environments.*”  
**Response:** Our intention was to say that high CR is a real issue in A-ERT (more than in manual ERT) in frozen environments, and it is important to reduce CR as much as possible to ensure good ERT data quality.

75. The Referee wrote “*Line 563: Decide between using words like "two" or numbers "4" to describe numerals. I think for numerals <10 you should use words and for numerals >=10 use numbers.*” **Response:** We agree and the change has been done accordingly.

76. The Referee wrote “*Line 574: “of the used electrode array”. Remove other instances of “dispositive”.*” **Response:** We agree and the change has been done accordingly.

77. The Referee wrote “*Line 579 and equation 2: Around 0C it is known that the supercooling effect takes place and Wu et al., (2017) showed it is reflected in geoelectrical data too. Your model doesn't seem to be able to reproduce that. Why is that? I think it is worth a talking point. Wu, Y., Nakagawa, S., Kneafsey, T. J., Dafflon, B., & Hubbard, S. (2017). Electrical and seismic response of saline permafrost soil during freeze - Thaw transition. Journal of Applied Geophysics, 146, 16–26. <https://doi.org/10.1016/j.jappgeo.2017.08.008>.”* **Response:** We believe that it is not a problem in the model itself. This behavior depends on the direction of the temperature transition. When the temperature decreases (from 2 °C to –5 °C), the increase of salt concentration in saturated solution at the freezing point reduces electrical resistivity, which shifts the inflection point to around –2 °C. In contrast, when the temperature increases (from –5 °C to 2 °C), this effect is not observed, and the inflection point can be identified near 0 °C.

78. The Referee wrote “*Line 585: “some datasets” is a vague statement. Please be specific.*” **Response:** By “some datasets,” we refer specifically to the datasets acquired on 12/08/2021 and 17/09/2021. This clarification has been added to the manuscript.

79. The Referee wrote “*Line 588: Gradual? Is it not a linear increase on a log plot which makes it an exponential increase in resistivity below 0C.*” **Response:** Gradual does not mean linear. That said, we fully agree with the Referee that gradual was inappropriate. We replace “gradual” by “progressive”.

80. The Referee wrote “*Line 591: Didn't you say electrodes are not close enough so you cannot reliably infer what is happening in the near-surface? Please clarify.*” **Response:** Although we could not determine the precise boundary of the active layer, the measurements provide a general understanding of the conditions in the near-surface zone, as the information is integrated within the measurement of the smallest electrode quadrupoles. In addition, comparisons between data from different zones offer qualitative insights into the active layer spatial extent.

81. The Referee wrote “*Figure B1: Electrode “number” for the Y-axis label; “Date” for the X-axis label.*” **Response:** We agree and the change has been done accordingly. 82. The Referee wrote “*Figures D1-3: Please label the approximate position of the gallery.*” **Response:** We agree and the change has been done accordingly.

## Referee 4

1. The Referee wrote “*Time-lapse ERT monitoring of permafrost is a challenging topic, and experimental studies in extreme environments are characterized by complex operational procedures. Therefore, papers on this topic are welcome and should be encouraged. I would only suggest removing paragraph 5.5, 'Hydrogeological dynamics', as some of the information about the water flux could easily be included in the previous paragraphs.*”

**Response:** We agree with and thank Dr. Lapenna for highlighting the difficulties and challenges associated with A-ERT monitoring in high-mountain environments, and we appreciate his constructive suggestion. While we acknowledge that part of the discussion on water flux relates to the previous sections, we believe that retaining Section 5.5, entitled “*Hydrogeological dynamics,*” improves the readability of the manuscript by providing a dedicated synthesis of the hydrogeological processes and of the limitations of ERT in this type of extreme environment. Nevertheless, we have revised this section to streamline the text and to better link it to the preceding paragraphs.

## Referee 5

1. The Referee wrote *“I have evaluated the revised manuscript together with the authors’ response letter and the previous review round. The revised version shows some improvement: the writing is clearer, data availability is more transparently documented, the laboratory calibration is described in more detail, and several figures have been moved to the appendices. The authors have therefore made an effort to address the reviewers’ concerns. However, there is still a noticeable mismatch between the scope of the stated objectives, particularly regarding hydrogeological characterization and temperature quantification, and what the available data can actually support. A tighter alignment between aims, results, discussion, and conclusions is still required to strengthen the manuscript. In addition, further restructuring of the paper is needed to improve readability, scientific clarity, and to better articulate the novelty of the study, which remains limited in the current version. For these reasons, I recommend major revision and provide the following comments.”*

**Response:** we thank the Referee for his constructive comments that help to improve this manuscript. We have done our best to accommodate the referee comments in the previous round and we continue to do so in this round. Regarding the structure of the manuscript, we pass our revised manuscript to 4 of our colleagues specialized in the field and their unanimous feedbacks was that the current structure was very clear.

2. The Referee wrote *“1. Paper structure: one of my main concerns remains the structure of the manuscript, which is still difficult to follow even after revision. The paper reads more like a technical report than a scientific article. The separation between Materials and Methods, Results, and Discussion is unclear, and these sections are strongly mixed. Many results are already presented and interpreted within the Materials and Methods section, while some methodological aspects are introduced later in the Results. For example, the time-lapse inversion approach is described in Section 5.3 rather than in the data processing section. In addition, several figures are not sufficiently described, and in multiple cases it is unclear why specific dates or results were selected and how they are representative of subsurface dynamics at the site. A clearer and more rigorous restructuring of the manuscript would significantly improve readability and scientific clarity.”*

**Response:** We thank the Referee for this detailed comment regarding the structure of the manuscript. We acknowledge that the initial organization may have made it difficult to clearly distinguish between the Materials and Methods, Results, and Discussion sections. In response to this comment, we have revised the manuscript to improve its clarity and readability. In particular, we have clarified the description of the data processing and inversion workflow and consolidated all methodological aspects related to processing and inversion (including the time-lapse inversion approach) into the appropriate section. We have also strengthened the interpretation of the results and added new figures showing 2D sections of temperature estimated from the geophysical measurements, which illustrate realistic temperature gradients and distributions consistent with typical permafrost conditions. Finally, the hydrogeological section has been revised and expanded with additional information about the site in order to better support the interpretation of subsurface dynamics.

3. The Referee wrote “2. *Hydrological interpretation based solely on ERT data. The revised manuscript still lists hydrogeological characterization (e.g., water infiltration and drainage in fractures) as one of its main objectives, but the discussion and interpretation remain weak. The hydrological interpretation is based solely on resistivity changes, without independent hydrological constraints or a clear presentation of the existing conceptual understanding of the site. Without complementary information, resistivity variations remain non-unique and cannot be interpreted unambiguously. This limitation is further amplified by the absence of an uncertainty analysis for the resistivity models and the observed changes. As a result, the hydrological conclusions remain speculative and should be more clearly framed as hypotheses rather than objective of paper.*” **Response:** Hydrogeological processes is a key challenge to address to better assess non-linear permafrost degradation processes and rock slope destabilisations (e.g. Krautblatter et al., 2012 ; 2013 ; Magnin and Josnin, 2021 ; Cathala et al., 2024; Walter et al., 2020; Fischer et al., 2010). Ponctual and repeated ERT measurements have been the only used approach to assess potential hydrogeological processes in-situ in steep alpine frozen bedrock (Keuschnig et al., 2017; Krautblatter and Hauck, 2007), because of the field constrain in such a harsh environment. Only very recently other approaches have been deployed to apprehend water flow in steep alpine frozen bedrock, such as coupled thermal and hydrogeological models (Magnin and Josnin, 2021; Ben-Asher et al., 2023), or direct observations (Ben-Asher et al., 2025; Scandroglio et al., 2025). All the methods have been developed independently and their coupling remains highly challenged by the harshness of the field work: some methods can be deployed at some areas but not in others because of access or security issues. As an example, at the Aiguille du Midi, we developped several approaches (numerical modeling, direct observation and A-ERT → in this paper) but at different locations or based on different hypotheses (due to the youngness of the research fields), such as their explicit comparison or coupling is yet impossible. The only study that couples direct observation (with piezometer) and A-ERT is the one from Offer et al., 2025, that is really recent. Therefore, based on the past studies that have built up existing knowledge and conceptual models based on ERT only, and the uniqueness of our site, whose settings are different from other settings in steep bedrock slopes (single rock faces embedded in glaciers and resulting proximity of the possible piezometric level) we claim that our observations are as valuable as any other observations reported and interpreted before, despite uncertainty analyses are inherently not feasible, and that they have the main asset to bring a different perspective than the one discussed so far. Furthermore, in our revised version, we rather insisted on the novelty **related to quantitative temperature interpretation**, that is for the **very first time evaluated against in-situ temperature measurements**. The hydrogeological investigation remains a side-quest that has demonstrated some contrasting patterns compared to previous studies that deserve to be shared and discuss in light of existing data and knowledge.

4. The Referee wrote “3. *Temperature - resistivity relationship: Another major objective of the paper “assessing the accuracy of temperature estimates derived from resistivity data” is still not convincingly addressed. In agreement with the other reviewers, I do not consider a single rock sample, and a limited laboratory experiment sufficient to infer a representative petrophysical model for the site. Furthermore, the statement that “temperature estimation based on ERT data leads to good agreement with observed temperatures, with differences of less than  $\pm 1$  °C at depths of 4 to 10 m” is based on a single borehole comparison and appears*

*limited to specific periods, likely when the active layer is unfrozen. In contrast, Figure 11 shows discrepancies of up to approximately 5 °C between laboratory-based and field-derived temperature estimates, which should be considered in the final discussion. I wonder also why not the authors applied the methodology to another borehole available, in proximity of ERT profile. As with hydrological interpretation, no uncertainty analysis is presented. A significant part of the observed discrepancy seen in figure 11 may originate from data quality issues and inversion artefacts. Given that a key motivation for using A-ERT is its potential as a proxy for temperature over larger spatial and temporal scales, a more explicit discussion of its ability to capture spatiotemporal temperature variability would be very useful.”*

**Response:** Below, we address each point individually: First, the study site consists of granite and fractured granite. Laboratory measurements performed on one or several samples are expected to yield very similar results, as the samples originate from the same lithology. However, at the field scale, the presence of fractures— which cannot be adequately represented in laboratory samples— strongly influences the measurements and the resulting interpretations. Furthermore, we have already discussed the points raised concerning the temperature–resistivity relationship and the estimation of temperature from resistivity data. We also introduced the assumptions required to apply this model, the results obtained under these assumptions, and the limitations encountered in this study. We developed the section about Temperature - resistivity relationship with 2D section of temperatures evaluated from geophysical measurements at different times which provides reasonable temperature distribution and gradient with depth. The discrepancy observed in Figure 11 may result from field-scale heterogeneity as well as from the influence of metallic structures and the tunnel, which can affect the distribution of the electrical field in uncontrolled manner. We used data from the borehole located along the geophysical profile. The other borehole (BH-S) is located far from the geophysical profile and was therefore not considered in our interpretation. However, the geophysical measurements along the North-East profile (coincident with borehole BH-E) encountered some cable issues, as was mentioned in the manuscript. Therefore, in the aim to avoid any speculative conclusions, we refrained from using data from these boreholes whose data cannot be compared to ERT data.

5. The Referee wrote “4. *Novelty beyond the use of A-ERT in extreme environments. In line with the two other reviewers, I still find the novelty of the work insufficient or at least insufficiently articulated. The authors describe the main novelty as a “multi-year high-resolution A-ERT dataset obtained at the Aiguille du Midi site providing new insights into temporal permafrost dynamics,” but this contribution is not clearly demonstrated in the manuscript. While I acknowledge the uniqueness of the multi-profile setup in such a challenging environment, it remains unclear, even in the revised version, what specific new understanding is gained from the A-ERT data. In particular, the added value of continuous A-ERT monitoring compared to repeated ERT surveys is not clearly demonstrated, especially given the data gaps, missing periods, and substantial maintenance challenges. A more explicit discussion of what these challenges reveal, what can and cannot be improved, and how this experience advances current practice would significantly increase the relevance of the study for the permafrost and geophysical monitoring communities. In addition, further discussion of*

*data processing choices (e.g., how filtering criteria and thresholds were defined) and the inclusion of uncertainty/sensitivity/resolution analyses would substantially strengthen the paper and improve the interpretation of both hydrological and temperature-related results.”*

**Response:** First, the temperature field is modeled modelling based on the joint petrophysical models and A-ERT surveys validated and the result is validated against borehole temperature measurements. This work provides insights for future studies about the uncertainty associated with using the petrophysical model to estimate temperature from geoelectrical measurements. This is particularly valuable because it allows the construction of 2D or 3D model about the thermal state of a permafrost site, rather than relying on local borehole measurements, which are not always feasible due to the high cost and logistical constraints of accessing such sites. (i) Novelty: This study advances permafrost monitoring from a purely point-based quantitative approach toward a quantitative and spatially distributed monitoring framework, allowing improved imaging of the subsurface and better identification of permafrost zones and fracture networks. (ii) New insights into the capability and limitations of A-ERT monitoring for detecting water flow pathways and identifying potential infiltration zones that warrant further investigation in future studies. (iii) Key research directions for monitoring at such high altitude that still deserves lot of work.

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