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To: Cryosphere

Dear Editor,

Please find enclosed a revised version of our manuscript submitted to *The Cryosphere*. All comments you provided during the previous round have been addressed, as detailed below.
Both a clean version of the revised manuscript and a version with the changes highlighted are provided.
We sincerely thank the Editor for the valuable and professional comments that helped improve this work, and we appreciate the opportunity to resubmit our manuscript.

Best regards,

Dr. Feras Abdulsamad
Corresponding Author

Responses to Editor's comment

Line 44: "favorable condition at surface" is a bit vague. You can be more specific here, and note that this method only worked well in summer and fall. **Response:** Changes have been made in the MS by rewriting the sentence as "we estimated the temperature within the frozen zone from the resistivity measurements, under favorable condition at surface in summer and autumn".

Line 45: "accuracy of approximately ±1 °C within the frozen zone". We agree and change **done**

Line 244-251 and figure 3: This would fit better in the results section at line 500 (Referee 5 also suggested more clearly separating methods and results, so this helps address their concern).

Line 267: "The cables installation was gradually" -> "Cables were installed gradually" or "The cable installation was gradual": **Response:** the cables were installed gradually. The Change has been made.

Line 300-301, Figure B1: This seems unnecessarily complex (especially since you do not analyze this further). I suggest removing dotted boxes and simply adding a vertical line on the plot to show the date you installed duplicate electrodes. **Response:** We agree with editor, Figure B1 has been changed as suggested by the Editor. In the revised version of the manuscript, we changed the text as follow: "Figure B1 shows the temporal evolution of CR at profiles S and NW, as well as gaps in the A-ERT measurements caused by cable defects. It also indicates the date of duplicate electrode installation, highlighting a reduction in contact resistance following installation."

Line 302: Here, you only describe hardware issues, so I am curious what the software issues were. **Response:** The software-related issues were mainly associated with compatibility problems between recent software updates on ABEM Terameter LS2 (v2.6.2 and v2.7.1) which was not working with ES10-64 connectors, which affected the acquisition system. In addition, some difficulties were encountered in establishing a stable internet connection and implementing code for remote monitoring of the device from the office.

Line 313-318, Figure 4: Move this to results section 5.1. **Response:** We agree, changes done.

Figure 4: I suggest including directly on the figure the reason(s) for missing data, similar to how you have in Fig. B1. Figure 4: Include data from the north face here too on a separate subplot. **Response**: We thank the editor for this helpful suggestion. In Figure 4, we focus on the repeated and automated measurements from the south-facing profile (with selected time series), where the monitoring period is the longest. For this reason, we chose not to include the causes of missing data directly in this figure (there is long period with repeated measurements). Instead, the reasons for missing data are provided in text and the periods of missing data shown in Figure B1, which presents automated measurements for both the north-west and south profiles, along with the associated data gaps. Regarding the inclusion of data from the north face, we acknowledge the interest of this comparison. However, to maintain clarity and readability of Figure 4, we have opted to keep the focus on the south profile.

Line 341: I assume this is a typo, and the absolute error is 1e-5 not 1e5. **Response:** We thank the editor for pointing out this typographical error. The correct value is 1e-5, corresponding to

an absolute error of indeed 10 μA. This has been corrected in the revised version of the manuscript.

Line 345: You can highlight here that this is a standard methodology by citing the literature. This demonstrates that your methodology is well-chosen and follows best practices. **Response:** We added a reference of this methodology "Following Mollaret et al. (2020), an iterative process was conducted to select the smoothness parameter (lambda) that minimizes the data misfit of individual inversions of a reference dataset (data of 30/06/2020)."

Line 346: Here, say something about how you report the root-mean-square (RMS) error with the tomograms, and explain what this number represents. **Response:** We have added the following clarification: "The root-mean-square (RMS) error is evaluated at the end of each inversion and reported in the figures."

Line 349: Cite literature to show that this cascaded inversion strategy is commonly used for time-lapse inversion. **Response:** We have added two references "In this case, the reference model was moved along with the inversion so that the difference to the preceding step is constrained (Doetsch et al., 2015; Karaoulis et al., 2013).".

Line 382: Explain why you chose to show data collected on this specific date. I guess this is the first dataset? **Response:** yes this is the first dataset at both side, we added this information in the text:" In order to gain an overview of the internal structure of the study site based on the resistivity distribution, we carried out inversions of the first dataset acquired along two long profiles (NW+S and NW+E), using Wenner electrode arrays with 64 electrodes (Figs. 5 and 6). »

Line 390-391: Please provide an explicit interpretation here of what the high and low resistivity zones mean. E.g., sun exposure leads to drier (high resistivity) surface conditions, and warmer wetter (lower resistivity) conditions at deeper depths? **Response:** We explained this part as following : "Although the lower part of the tomogram appears similar on both the NW and S profiles, which is expected since they lie in rockwalls that are alike regarding slope and aspect (where the lowest part of the S profile is deployed on the NW face as well, see Fig 1c), significant differences are evident in the upper part (*i.e.*, above the gallery level). these differences highlight the contrast between the sun-exposed S face, composed of fractured granite (see Fig. 1d) and exposed to strong insolation, leading to drier surface conditions and consequently higher electrical resistivity. In contrast, the shaded NW face mainly consisting of massive granite and less influenced by atmospheric heat flux, remains wetter and thus leads to lower resistivity close to surface."

Figure 6: Explain in the text how the fractured zone was interpreted. Is this just from ERT, or was there evidence on the rock surface too? **Response:** The fractured zone was interpreted based on both field observations at the site (see Fig1. d) and evidence reported in previous studies (e.g., Magnin et al., 2015b), rather than solely from ERT data. This has now been clarified in the revised version of the manuscript.

Line 407: "…NW and E profiles, collected on August 26 2020." Again, explain why you chose to show this date. **Response:** We added this information in the manuscript.

Figure 7: Label interpreted Fz on the figure and add to caption. Also, it appears that the left side of the figure is cropped, cutting od E in elevation. **Response:** The figure has been

carefully revised to ensure that no elements are cropped. Regarding the label “Fz,” it does not appear in Figure 7, and therefore no modification to the caption was necessary.

Line 424: You can re-iterate here that the east profile was excluded from this analysis due to large data gaps from poor connections and rockfalls. **Response:** We thank the reviewer for this suggestion and agree that this is an appropriate section to remind the reader that the east profile was excluded from the analysis due to significant data gaps caused by poor electrical connections and rockfalls. However, this information is already stated twice earlier in the manuscript. To avoid unnecessary repetition, we chose to remove it from the caption of Figure 7. We have ensured that this point remains clearly stated in the main text.

Line 426: As reviewer 5 pointed out, it is not clear why you are showing these specific dates. I guess that these are just representative dates where you had complete datasets – if so, write that explicitly in the text. I suggest marking Figure 4 (maybe with little arrows) which dates you are presenting later in the paper for detailed analysis. That way, your reader can more easily see what dates you’ve selected (and why). Include on Figure 4 also the data from the NW profile, so you can do this for both profiles. **Response:** We thank the editor for this helpful suggestion. We have clarified the rationale for the selection of specific dates by adding the following sentence at the beginning of Section 5 (“Results and interpretation”): “Selected datasets are presented below to address the objectives of this study, including the characterization of the general structure, seasonal variations, and the hydrogeological system.”

The selected dates are representative of key conditions relevant to these objectives, rather than simply reflecting data availability. Although numerous complete and high-quality datasets are available, only a subset is shown here to highlight the most informative situations. Regarding Figure 4, we acknowledge the suggestion to indicate the selected dates directly. However, due to the time axis spanning long periods (with a three-month grid), adding markers such as arrows would reduce the clarity and readability of the figure. For this reason, we have opted not to include these annotations.

Line 428: “remains relatively consistent over time” since it does change a bit. **Response:** We agree. Change has been done.

Line 446: This to me this phrasing is a bit weird, since I wouldn’t expect the geology or topography to change over time. Maybe “reflecting consistent thermal/hydrological conditions”? **Response:** We thank editor for this comment that we agree with this comment. Change has been made accordingly.

Line 460-461: I would move this info to line 426, something like ‘Figure 8 shows the tomograms… along the NW profile at representative time intervals. A more complete time series is presented in appendix D.” **Response:** We agree and changes have been made.

Line 472: I suggest making this a new section, something like 5.4 Virtual borehole analysis. **Response:** We agree change has been made.

Line 473: “P” -> “P1”: **Response:** Done.

Line 484: Why would snow cause lower water content in the active layer? If anything, would I assume that snow increases water content due to spring thaw? **Response**: We agree. We removed this part related to water content.

Line 489: “the whole” -> “detailed”. **Response**: Changed to: “which is insufficient to fully capture the resistivity variations near the surface.”

Line 490: “coherent” -> “consistent” **Response**: Done.

Figure 9: It would be more logical to show P1 on the left subplot. **Response**: We agree and the text has been changed accordingly.

Line 497: “resistivities extracted” -> “resistivities are extracted”. **Response**: We agree and the text has been changed accordingly.

Line 501: “are superimposed on borehole BH-NW” -> “are superimposed on co-located borehole BH-NW”: **Response**: **Response**: We agree and the text has been changed accordingly by writing. “Extracted resistivities at P1 are superimposed on the co-located borehole BH-NW”

Line 505: No capitalization needed in temperature – resistivity relationship Section 5.4: I like that you have now included a temperature model! I do wonder about the inconsistency between what you’ve done in Fig 10 and Fig 11 though. For Fig 10, you say that you can’t estimate temperature in the active layer – but then you do this anyway in Fig 11. Maybe you could plot the full estimated temperature profile in Fig 10, explaining why it is inaccurate in the near surface (as you have already in the text), and then also explaining which areas of the temperature model (Fig 11) you expect to be more or less accurate. As it is, I feel the uncertainty in your full temperature model is not really discussed. **Response**: We thank the editor for these valuable suggestions. We acknowledge that the uncertainty associated with the temperature estimates needs a statistical metric to be mentioned or calculated. We used the MAE to get the information, but we did not include it before, we added it on figure 10. In the manuscript (Lines 506–509), we discuss the limitations of our temperature estimates, which are primarily related to the resolution of the resistivity measurements (near the surface) and their limited depth coverage. We emphasize that reliable temperature estimates cannot be obtained within the active layer due to these constraints. The primary objective of Figure 10 is to demonstrate the consistency between estimated and measured temperatures within the frozen zone. In response to the reviewer’s suggestion, we now provide an updated version of Figure 10 that includes the full estimated temperature profile between 1 m and 10 m depth. However, for depths shallower than 1 m, the resistivity data are not sufficiently reliable to provide accurate temperature estimates, and this limitation is now clearly stated. In addition, we have included the mean absolute error (MAE) in the figure to provide a quantitative assessment of the model accuracy. We have also improved the discussion of the spatial variability of uncertainty in the temperature model (Figure 11), highlighting which regions are considered reliable.

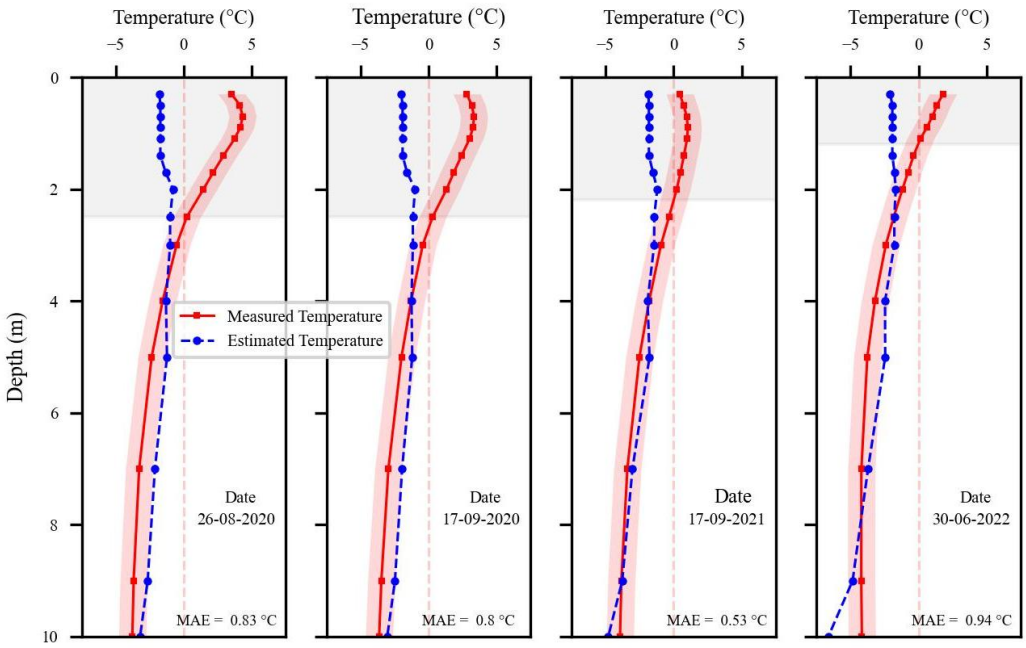

Figure 10. Comparison between measured temperatures in BH-NW and estimated temperatures derived from geophysical measurements (*i.e.*, extracted resistivity values at different dates) using the petrophysical model in Equation 2. The gray-shaded area indicates the extent of the active layer at the time of measurement. The red-shaded zones show the ±1 °C range around the measured temperature. The mean absolute error (MAE, in °C) quantifies the average error within the frozen zone for each date.

Line 517: This seems inconsistent – it's accurate only at depths between 4-10 m, but you can then estimate temperature across the whole model? **Response:** A good agreement between estimated and measured temperatures is observed in the depth range of approximately 2.5 to 10 m. At shallow depths, the resolution of the ERT data is reduced and the presence of the active layer influences the resistivity distribution, which is no longer controlled solely by temperature. At greater depths, 10 m corresponds to the maximum depth of the borehole temperature measurements.

Line 517: Well, it's not always less than 1 degree error. Be more quantitative here. A mean absolute error would be a great metric to include. Then you can also be more precise in the abstract and conclusions as well. **Response:** We integrated the MAE into figure 10. Yes, very few points with difference > 1°C, but the MAE < 1°C.

Line 526: "It can be observed a coherent temperature gradient through depth and positive temperatures around and in the infrastructure." This is not clear, please rephrase**. Response:** A clear temperature gradient with depth is observed on the 2D temperature sections, with positive temperatures around and in the infrastructure.

Line 528: Are you saying that the temperatures below -5 are not reliable? **Response:** Based on borehole temperature measurements (Fig. A1), temperatures at depth are typically around −5 °C. Values lower than this threshold are therefore likely to be influenced by numerical artefacts related to the inversion process (e.g., low sensitivity zone, interpolation out of sensitivity zone). To avoid misinterpretation, we limited the color scale accordingly, which also helps preserve meaningful variations within the physically relevant temperature range.

Line 506-531: This paragraph is a bit clunky, please revise for flow and clarity. **Response**: we revised this part as following: " It is well established that when temperature > 0 °C (i.e., the case in the active layer), electrical resistivity depends on multiple factors, including porosity, water content, water salinity, Cation Exchange Capacity (CEC) and temperature (Revil et al., 2018). This multiple parameter dependance makes it difficult to accurately model or predict electrical resistivity, or to use it as a proxy for temperature estimation in the active layer. In contrast, under frozen conditions, resistivity of the medium is primarily controlled by the remaining unfrozen pore water, which is largely Temperature dependent, while other parameters can be assumed relatively constant. Based on this assumption, the resistivity values extracted from inverted model of resistivity were converted to temperature using the petrophysical model in Equation 2 (Duvillard et al., 2021; 2018; Coperey et al., 2019). Figure 10 shows the measured temperature alongside the estimated temperature from ERT data, plotted against depth at different dates (in summer and autumn). A good agreement is observed between the measured and estimated temperature in frozen zone, with mean absolute error (MAE) less than 1 °C within the frozen zone (approximately from 2-2.5 m to 10 m, depending on the date). These results suggest that the temperature distribution across the site can be reasonably estimated using this model, assuming that the medium is sufficiently homogeneous and that resistivity variations are predominantly controlled by temperature. Figure 11 illustrates the temperature distribution along the profile NW estimated from electrical resistivity measurements acquired at different dates between June 2020 and June 2022. The estimated temperatures consistent with previous analyses and highlight two permafrost zones located above and below the gallery. A clear temperature gradient with depth is observed, with positive temperatures around and in the infrastructure. It can also be observed that temperature decreases with depth, reaching values lower than -5 °C in the zone where ERT sensitivity is low or absent (see lower part of profile NW Fig 11). At higher depths, the reduced sensitivity affects the reliability of temperature estimates. Finally, data collected under frozen surface conditions (i.e., measured in winter and spring with high contact resistance) show large discrepancy between the estimated and measured temperature and therefore cannot be reliably used for temperature estimation".

Figure 11: There are a few things I don't like about this colour scale. I find the colour variability above zero distracting and would prefer something more perceptually uniform. I also think that the blue should start at zero – right now, the beige color represents frozen material, which is not intuitive. And by using the same color for everything below ~-3.5, you lose detail. **Response:** We thank the Editor for this valuable comment. Following this suggestion, we have revised the color scale to improve its perceptual uniformity and interpretability. We adjusted the scale so that blue colors start at 0 °C, and warmer colors (white to red) represent positive temperatures. Additionally, we used a uniform color for temperatures below −5 °C, as we consider that variations in this range are mainly related to numerical artefacts of the inversion process.

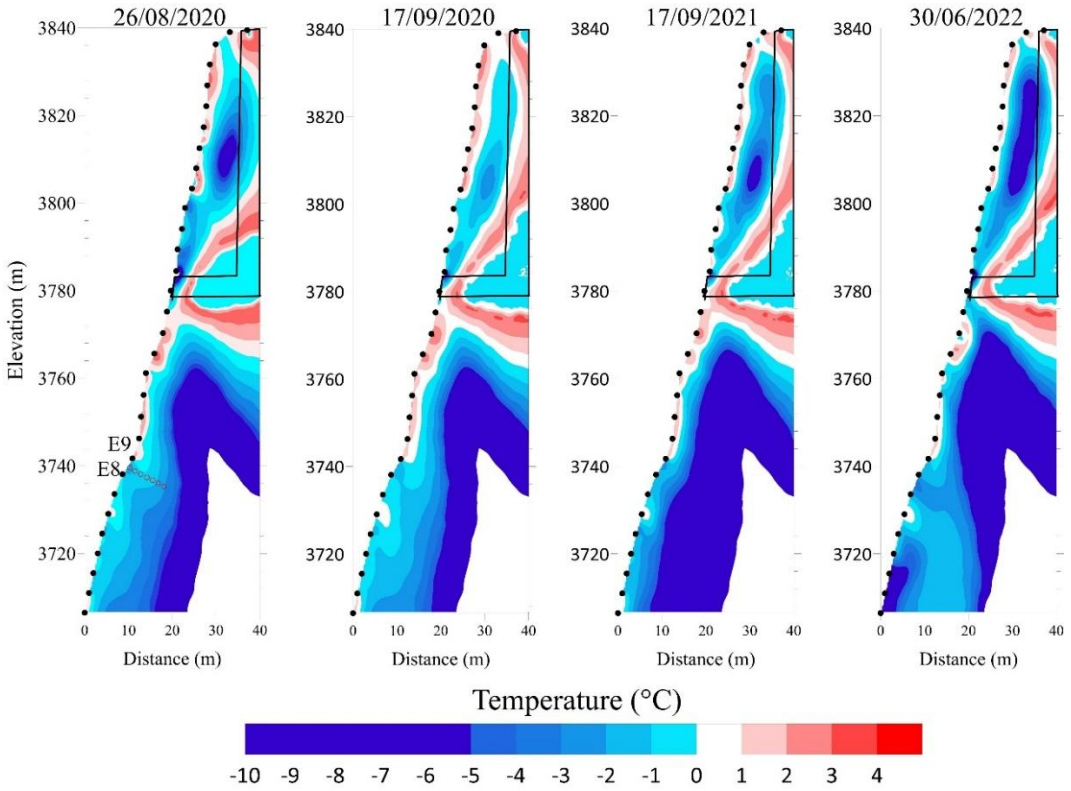

Figure 11. Spatio-temporal evolution of subsurface temperatures along the NW profile derived from electrical resistivity measurements, using Equation (2) and parameters obtained from laboratory measurements. Black dots indicate the electrode positions. The red circles indicate the location of borehole BH-NW, while the black lines mark the relative positions of the gallery and the elevator. The blanked zones in the lower part of the profile correspond to areas of low sensitivity of the geophysical measurements and are therefore not reliable to temperature estimation.

Figure 11: Why are some parts (in the lower part of the profile) blank?? This needs to be explained. **Response:** The blanked zones in the lower part of the profile correspond to areas of low sensitivity of the geophysical measurements and are therefore not reliable to temperature estimation. This has now been clarified in the figure caption.

Line 547: "data measured in co-located BH-NW": **Response**: We agree and the text has been changed accordingly.

Line 583: Makes more sense to say "we interpret that seasonal variations in resistivity are influenced by the presence of fractures". **Response**: We agree. Change has been made.

Line 585: "is exposed to strong insolation in summer". **Response**: We agree and the text has been changed accordingly.

Line 586, line 587: Did you mean to use fig 13a as an example of both high and low resistivity? Maybe this is a typo. **Response**: this is a typographical error. It is Fig 13b as example for high resistivity and Fig 13a for low resistivity. Changes have been made in manuscript.

Figure 13: Add tunnel to all subplots. **Response**: We agree and the text has been changed accordingly.

Figure 13: It really feels like this figure belongs section 5.3 where you report the time-lapse ERT results. I suggest moving this figure and your observations to line 471, right after figure 8. However, I can see why it is relevant to your discussion of hydrological dynamics. If you opt to keep the figure in section 5.5, add a sentence at line 424 saying something like "Results from the south profile are shown later in Section 5.5". **Response**: We added a sentence at line 424: "Figure 8 shows the tomograms of resistivity distribution after a time-lapse inversion of datasets acquired along the NW profile at different time intervals, and results from the south profile are shown later in section 5.5."

Line 610: Consider rephrasing for clarity: "High CR is the main challenge preventing the year-round collection of high quality data at high altitude rockwall sites such as this.". **Response**: we thank the editor for this suggestion that we considered in the MS: "High CR is the main challenge preventing the year-round collection of high quality data at high altitude rockwall sites such as the site investigated in this study".

Line 618: "such as also revealed" -> "which has also been revealed". **Response**: Change has been made. "We observe that resistivity decreased over time at greater depths (*e.g.,* at P1 and P2, comparing data from July 30, 2020, and July 30, 2022), indicating degradation of the permafrost, as also revealed by borehole measurements (Magnin et al., 2024)."

Line 640: I'm not sure why this sentence is included "even though internal permafrost temperatures typically lie just a few degrees below freezing (e.g., Noetzli et al., 2024)". What point is being made here? I would omit this. **Response**: We thank the editor for this comment. The purpose of this sentence is to place the reader in the context of the study and to highlight the limitations of our approach, given that permafrost temperatures are typically close to the freezing point. We believe that this information helps clarify the significance and constraints of our interpretation; therefore, we have retained the sentence in the revised manuscript, while slightly rephrasing it for clarity.

Line 642: Change to "However, a precision of…". **Response**: We agree and the text has been changed accordingly.

Line 686: "coherence" -> "good agreement". **Response**: We agree and the text has been changed accordingly.

Line 691: Include caveats – only in frozen ground and only in summer/fall. **Response**: we added the following sentence: "frozen granite during summer and autumn monitoring".

Line 697: A-ERT does not require substantial maintenance everywhere! Rephrase to "Although installation of A-ERT system is relatively low cost, it can require substantial maintenance in high-risk areas like unstable high mountain rockwalls where rockfalls and lightning edects can damaging equipment.". **Response**: We agree and the text has been changed accordingly.