Dear Professor Ntarlagiannis

we appreciate your positive feedback regarding our manuscript titled "Short-term cooling, drying, and deceleration of an ice-rich rock glacier (egusphere-2024-269)" and thank you for your review. We addressed your comments, outlined in the attached PDF document, and provide detailed responses to each point below (our responses are denoted in blue, with suggested changes highlighted in **bold**). We are confident that the modifications made to the manuscript, along with the explanations provided in our responses, address all your concerns and enhance the quality of our manuscript.

With kind regards,

Alex Bast, Marcia Phillips and Robert Kenner

Reviewer Comments for Manuscript Number egusphere-2024-269

Short-term cooling, drying and deceleration of an ice-rich rock glacier

Bast et al.

The manuscript discusses a multi year glacier monitoring project using a variety of monitoring tools. The manuscript is well written and logically organized. The authors provide a lot of information, collected data and robust statistical analysis, that could aid in describing the glacier kinematics.

Although not an expert in this field (cryosphere), data, processing and conclusions seem logical and supported by the data presented an analysis.

Thank you for your positive feedback on our study. Based on your statement, and to avoid any possible misunderstanding regarding the landform and the process area, we would like to underline the specificity of the landform, an ice-rich rock glacier. In contrast to glaciers, rock glaciers are landforms that are part of the periglacial process system, formed by the deposition of material from mass movements (snow avalanches and rock fall) at the base of steep slopes. Rock glaciers have a completely different internal structure than glaciers. Their structure typically includes layers of blocks, coarse-grained material, fines and ice, with varying contents of ice and/or water.

My only concern are the presented ERT data (my area of expertise). The environment is difficult to perform ERT with very high contact resistances (need to be described) that could degrade the quality of the data. The subsurface resistivity images provided, show an interesting, to say the least, structure that does not seem to change over time (very minor changes at certain time periods). The described subsurface stratigraphy does not fully explain/support such resistivity structure where the dominant conductive (relative) feature is oriented vertically - with significant lateral variability; the stratigraphy provided does not seem to support such variability in such close distance. The authors need to explain what subsurface stratigraphy can create such resistivity distribution, and they can achieve that through modeling. I fear that this resistivity image might be the result of systematic error with the ERT data acquisition, maybe due to poor contact resistance (or erroneous electrode mapping), that creates the observed anomaly and any variability detected could be the effect of water freezing/thawing on contact resistances.

I am not suggesting that the data are bad, but due to the local environmental conditions all the options should be explored and discussed in the manuscript. Of course the glacier subsurface can be very variable that creates this resistivity image, but this need to be investigated.

We agree that it is difficult to carry out ERT measurements in such environments with very high resistances. This challenge can degrade the quality of ERT data, as the application of geophysical techniques is not as straightforward as their application in unfrozen, homogeneous and fine-grained soils. However, geophysical methods have been successfully applied in permafrost regions for decades (Kneisel et al., 2008; Scott et al.), and ERT is now one of the standard geophysical techniques for detecting and characterising permafrost (Hauck, 2013; Herring et al., 2023). Nevertheless, we are aware that geophysical surveys in these harsh environments require special techniques for sensor coupling, data acquisition and interpretation (Hauck and Kneisel, 2008).

To our knowledge, we are the first to apply cross-borehole ERT in permafrost and/or rock glacier environments. To improve electrode coupling, we used stainless steel electrodes integrated on a multi-core ERT cable in combination with steel clamps and used a finer-grained material (sand-gravel mixture) to establish contact between the electrodes and the borehole walls. We suggest that this be added to the Methods section, Chapter 2.4:

"We used stainless steel electrodes (l = 100 mm; d = 13 mm) integrated on a multi-core ERT cable. To improve contact with the ground, we installed stainless steel clamp collars (h = 11 mm; D = 34 mm). To establish contact between the electrodes and the walls of the boreholes, we filled the boreholes with a mixture of sand (grain size ≤ 2 mm) and gravel (> 2 – ≤ 4 mm) in a ratio of 1:1."

In terms of data collection, we are aware that ERT permafrost investigations are often susceptible to data quality problems associated with high contact resistance, and to obtain reliable inversions, it is important to remove the influence of poor-quality data (e.g., Hilbich et al., 2011). To do this, we apply a multi-stage filtering approach to our collected data. We believe that by collecting reciprocal data, we can improve data quality, as reciprocal data provides a good estimate of the precision of the resistivity data (Binley, 2015; Binley and Slater, 2020; Oldenborger and Leblanc, 2018).

Our ERT cross-borehole data show a relatively conductive feature that is vertically oriented with some variability. The reviewer, Dimitrios Ntarlagiannis, agrees that a rock "glacier subsurface can be very variable that creates this resistivity image, but this needs to be investigated". We believe that our manuscript clearly investigates and demonstrates that the ground in rock glaciers can indeed be very heterogeneous over small distances. We demonstrate this with the stratigraphic records of three boreholes drilled within a few metres of each other. In addition, at the same depth as the low resistivity structure, we detected a significant amount of unfrozen water (wet sludge layer) during drilling in 2020, which can cause the described low resistivities. We have added a new paragraph in the Discussion of our revised manuscript to emphasise the presence of unfrozen water content under frozen conditions. Furthermore, the ERT data are consistent with previous surface geophysical measurements by Boaga et al. (2020) and Pavoni et al. (2023) and with the piezometric pressure and temperature data presented in our manuscript. We attribute the small seasonal changes in resistivity within this wet sludge layer to latent heat effects and additionally refer to (Phillips et al., 2023). In general, the latter highlights the high potential of combining borehole temperature and piezometric pressure data with cross-borehole ERT data in rock-glacier environments.

We certainly agree that synthetic modelling can make a valuable contribution to better understanding cross-borehole ERT data and their interpretation for permafrost regions. However, this is outside the scope of our study, which presents measurements of relative water and/or ice content in rock glaciers for the first time, with the aim of understanding variations in rock glacier kinematics and the conditions leading to rock glacier deceleration. We are currently planning a more detailed study of cross-borehole ERT measurements in ice-rich permafrost, including different geometries, synthetic modelling and sensitivity analyses, using data from this site and two others where we will be installing similar instrumentation this summer.

Minor comments on the annotated pdf:

L 45: truth

We have changed “ground truths” to “**ground truth**”.

L110: Table 1 is missing

We have corrected the reference to “**Table S1**”.

L139 & L146/147: What is an: ERT cross-borehole sounding? correct language

We now use “**cross-borehole ERT measurements**”.

L154 – 160: ResIPy inverts for the difference of only common measurements - how can the background data have 355 data points, but thre is a subsequent inversion with more data points?

We ran the ResIPy routine according to the developer's instructions. The first model, the background data, was inverted independently using Occam's inverse method. Subsequent data sets subtracted the background data and inverted using the difference inversion algorithm. The data points remaining after applying our filters and reading in for the inversion routine are shown in parentheses.

To be clearer, we reformulated the text:

“ResIPy’s time-lapse algorithm is based on the difference inversion method of Labrecque and Yang (2001). **Based on Occam’s inverse method (Binley and Slater, 2020), the background data were inverted in the first step. Subsequent data sets subtracted the background data before inverting the data with the difference algorithm, which attempts to reduce the misfit between the difference in two data sets and the difference between two model responses (Labrecque and Yang, 2001)**. According to the reciprocal error check (Binley, 2015), fitting a power-law error model, and evaluating the normalized inversion errors (Blanchy et al., 2020), an expected data error of 10% was defined for the inversion process. **The 20 August 2021 model (ERT01) is used as a reference (background model), i.e. changes in resistivity are expressed as a percentage difference from this first reference survey. The inversion** converged after five iterations (final RMS misfit: 1.09; remaining data points: 355). All other models (ERT02 – ERT23) converged after a maximum of two iterations (average of remaining data points **after filtering**: 457; range: 242 – 635).”

L170/171: reference the relevant figures, or comment that they will be shown in the results section.

We included the reference to the relevant figures.

L252: all includes ERT01

We modified the text: “across all tomograms (**ERT01** to ERT23)”.

Fig. 6: very resistive environment (as expected); what range were the contact resistances?

We agree that it would be useful to have the contact resistances, but unfortunately, we do not have information on contact resistances, which we stated in L356/357 and refer to Phillips et al. (2023). As this was also raised by reviewer 1, we have already suggested to mention this challenge in the Discussion. We include our response to Reviewer 1 here:

We discussed recording the contact resistance when setting up the experiment as it is an excellent idea. It is certainly possible to measure the contact resistance at each measurement. However, for energy reasons this is not feasible. We suggest to further discuss this topic in the Discussion section of the manuscript, and suggest adding the following paragraph:

"Despite uncertainties in the contact between electrodes and ground material (Phillips et al., 2023), the consistent structure in all tomograms and the similarity to the August 2020 borehole stratigraphies (Phillips et al. 2023) across the summer images promotes confidence in data reliability. ***To avoid the uncertainty of the contact resistance between the electrode and the substrate material, it is in principle possible to record the contact resistances for each ERT measurement. However, we run the system on a solar panel in a harsh alpine environment, with sufficient power for a daily measurement including data transfer, which already reaches the limits of the power supply during the winter season, i.e. data transfer is not always possible. To avoid data loss due to power supply, we have accepted not to record the contact resistance. However, we do record reciprocal data to gain information on data quality (see chapter 2.4), and*** *our modelled resistivities are in line with recent surface geophysical measurements near B3 and B4 (Boaga et al., 2020; Pavoni et al., 2023)."*

Fig. 6: I would suggest removing log10 from the colro bar, and change the number to actual resistvity (e.g. 1000, 10000 etc) makes the graph more readable.

For better readability we restyled the colour bar and added the actual resistivities next to the log10 numbers on kΩm.

L383: catalyst?

We corrected the word as suggested.

L392: not that evident from the ERT data

We refer to our general response above and believe that our ERT data, presented in combination with ground temperature and piezometric pressure data, confirm that rock glaciers at or near their melting point can contain a considerable amount of unfrozen water.

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