Author comment:

Dear Referee #1,

Thank you for taking the time to review our submitted manuscript entitled *"Pressurised water flow in fractured permafrost rocks revealed by joint electrical resistivity monitoring and borehole temperature analysis" (egusphere-2024-893).* We greatly appreciate your thorough, constructive and positive feedback, which we have carefully considered. Our detailed point-by-point responses are given below, highlighted in blue, with proposed changes in the revised manuscript indicated in bold. We believe that these revisions and explanations in our responses fully address your concerns and thereby improve the quality and clarity of our manuscript.

Sincerely,

Maike Offer, Samuel Weber, Michael Krautblatter, Ingo Hartmeyer, and Markus Keuschnig

This reviewer has expertise in permafrost field observations, numerical modelling of frozen soil, and (to a lesser degree) permafrost geophysics.

This manuscript presents a unique dataset of repeated ERT, borehole temperature observations, and site characterization in steep permafrost rock. The combined dataset is beautifully presented and affords insights into the evolution of frozen, thawed, and wet zones in the rock. The careful design of temperature observations allowed detecting fast thermal events at depth that are attributed to water infiltration. These are important topics for research in the context of better understanding permafrost moderated climate control on rock instability.

(A1) Thank you for appreciating the unique, long-term data sets which were achieved under challenging field work conditions as well as the careful design of the results.

The manuscript did not convince me that the data revealed pressurized water as stated in the title. The authors support this inference by mentioning piezometric measurements from late summer 2023 (which are not shown or referenced) and the assumption (which is not developed in detail) that pressurised water flow explains the observed rapid electrical resistivity decline. While I am enthusiastic about the data and many of the analyses presented, a clearer focus, structure, and methodology are required for publication. I recommend encouraging resubmission of this manuscript after adjusting focus and conceptual clarity.

(A2) We value your insightful feedback. Initially, we chose not to include piezometric measurements as the installation was completed in late September 2023, which did not cover the periods of the presented borehole temperature data (01/2016-09/2023) and electrical resistivity measurements (02-06/2013, 09-12/2013, 06-09/2023). In addition, the key seasonal period of snow melt was not covered at the time of our initial submission of the manuscript in March 2023.

However, in response to your suggestion, we will now include the data set of one piezometer (depth: 16.85 m) from January to June 2024 in the revised manuscript. Therefore, we will prepare new subchapters describing the methodology and results. The new designed Figure R1 will be included in the revised manuscript, demonstrating an increase in piezometric pressure levels from spring to summer, with maximum heads reaching already up to 11.8 m. These direct observations of water pressure levels strongly support our hypothesis, inferred previously from the electrical resistivity data, that the rock matrix is influenced by pressurized water which is most pronounced in the season of snow melt (i.e. days with average air temperature above 0°C).

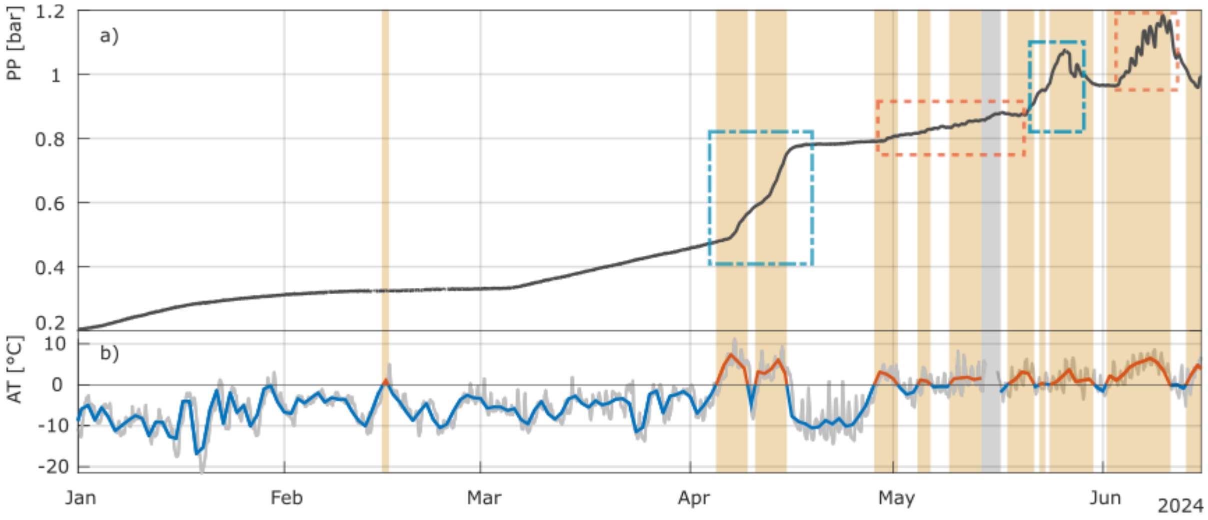

Figure R1. a) Piezometer pressure (PP) from January to June 2024 recorded near the summit station at a depth of 16.85 m. b) Mean daily air temperature (AT) from the weather station at the Gletscher Plateau (2.940 m asl, distance ~500 m), shown in blue (<0°C) and red (>0°C). The moving mean air temperature (AT) over a 2-hour interval is represented in grey. Yellow bars indicate periods when the mean daily air temperature was above 0°C, during which increases (blue rectangle) and short-term fluctuations with 24-hour frequency (orange rectangle) in pressure level were mostly observed. The grey balk marks a data gap in the weather station recordings.

Regarding your addressed need for a more detailed explanation of how pressurized water flow is revealed from the observed electrical resistivity decline, we will elaborate on this in the methodology (*3.1 Laboratory calibration of temperature-resistivity relation*) describing the physical principles of Archie's Law and how we concluded from this to the presence of pressurized water in the discussion section (*5.1 Pressurised water flow in permafrost rockwalls*) to improve the overall conceptual clarity:

3.1 Laboratory calibration of temperature-resistivity relation

(Line 119): ***" [...] The electric properties of water-saturated rocks is determined by the ionic transport in the liquid phase and, therefore, by the amount of interconnected pores. The well-known empirical law develop by Archie (Archie, 1942) relates the resistivity ρ to the functional porosity φ, the resistivity of the pore water ρ_w, and the fraction of the pore space occupied by liquid water S:***

$$\rho = a\varphi^{-m}S^{-n}\rho w$$

where a, n and m are empirically determined constants. At subzero temperatures and under partially frozen conditions, the electrical properties of the rock depends on the remaining unfrozen water content in the pores. As the temperature drops to the equilibrium freezing temperature, pore water saturation decreases while the resistivity of the pore water also decreases due to the migration of electrolytes from the freezing water to the remaining unfrozen water content, resulting in increased electrolyte concentration. Above the equilibrium freezing temperature, the resistivity of the rock is indirectly related to temperature changes, as temperature affects the mobility of the solute electrolytes."

Archie, G.E., 1942: The electrical resistivity log as an aid in determining some reservoir characteristics. Trans. Am. Inst. Min., Metal/my., Petr. Eng., 146, 54- 62.

5.1 Pressurised water flow in permafrost rockwalls

The unique time series of laboratory-calibrated ERT observations presented in this paper enable a quantitative interpretation of seasonal changes in frozen rockwalls. High-resistivity sections above 19 kΩm indicate frozen conditions with ice-filled joints during the frost season (October-May). Slight warming of the rock surface after the snow cover disappears in late spring is indicated by decreasing resistivity at shallow depth (e.g., tomography from June 2023 in Fig. 4). Ice-filled joints probably act as an aquitard, constraining deep infiltration into the joint system, with snowmelt mainly draining along the rock surface. From June to July, rapid changes in resistivity of more than one order of magnitude were observed at ∼ 1−7 m depth coincident with a borehole temperature warming accompanied by active layer deepening from 1.7 to 2.7 m depth between the ERT measurement dates in June and July (Fig. 7a). The low resistivity zone (∼4 kΩm) in July in the lower part of the tomography (∼electrodes 15-30) gradually expands to higher rock slope sections (Fig. 4) and to the bottom of the ERT profile until September (∼10 m depth, Fig. 7a), while the 0 °C/−0.5 °C isotherm (i.e., permafrost table) changes marginally (Aug: 3.5/4.1 m, Sep: 3.5/4.3 m, ***Fig. 7a****).*

The term 'pressurised' here refers to a piezometric head of a few meters. The rapid resistivity decline observed suggests pressurised nature of water flow in fractures, supported by additional evidence. This evidence comprises visually observed water outflow from fractures (Fig. 8) and first piezometric measurements showing rapidly increasing pressure levels in the thawing season, with piezometric heads reaching up to 11.8 m (Fig. R1). Without assuming pressurised flow, the decline in electrical resistivity from July to September (Fig. 4, 7) would be inconsistent with Archie's law. In thawed conditions, resistivity decreases for various rock types at a rate of ∼2.9 ± 0.3 %/°C (Krautblatter, 2009), and according to our laboratory calibrations, by 4.5 ± 0.3 %/°C (Fig. 3, Table A1). Thus, a temperature warming from July to September (Fig. 4, 7) in already fully saturated rock with constant porosity would not cause a significant further and rapid electrical resistivity decline. This can only occur if pressurised water flow contributes to additional hydraulic opening of fractures within days to weeks. *In addition, the coincident rapid changes (Fig. 6) and* ***regime changes*** *in rock temperature (Fig.* ***R2****) cannot be explained solely by diffusive heat exchange (Noetzli et al., 2007; Krautblatter et al., 2010), but only by water flow in open fractures (Phillips et al., 2016), facilitating a thermal shortcut between the atmosphere and the subsurface (Hasler et al., 2011).*

We hypothesize that […]"

Since we present now the piezometric data, we would suggest changing the title of the manuscript to: "***Pressurised water flow in fractured permafrost rocks revealed by electrical resistivity monitoring, borehole temperature and piezometers***".

To achieve a clear structure of the manuscript, the subchapter in methodology and results will be restructured to begin with the borehole temperature data, followed by the electrical resistivity observations and laboratory calibrations, and concluding with the piezometric measurements.

Krautblatter, M. (2009) Detection and quantification of permafrost change in alpine rock walls and implications for rock instability. Ph.D. Thesis. Friedrich-Wilhelms University Bonn.

- Water flow in fractured permafrost rock has been investigated, and detected with ERT, previously. This study adds to the body of knowledge incrementally. Confident detection of pressurized flow would indeed make it a novel and significant contribution. A more detailed analysis of the thermally detected flow events could likewise be interesting.

(A3) While a more detailed analysis of thermally detected flow events would be indeed interesting, we propose to focus on the novel and significant contribution of the detection of pressurised water flow to maintain the scope and coherence of the manuscript. Including extensive analysis of heat transfer or energy balance would dilute this focus and increase the length of the manuscript, which would be not consistent with your previous and last comment.

- The specific objectives of the research are not clearly articulated. Consequently, the exact state of the art is unclear, the approach and methods cannot be judged in their appropriateness, and the conclusions are not as compellingly underpinned by the evidence presented as they could be.

  (A4) To address your concerns, we will introduce the concept of water infiltration in mountain rock slopes in the introduction and explicitly highlight the research gap to clearly articulate the specific objectives of our study. Additionally, we will include new piezometer data (as mentioned in A2) and provide a more detailed analysis of the change of the rock temperature regime at depths of 10 and 15 m between 2016-2019 and 2020-22 in borehole B1 (see A9). These additional analyses will serve as further indicators, alongside electrical resistivity monitoring, of pressurised water flow and will help to compellingly underpin our conclusions.

- Line 300: The cause of the thermal offset stated appears to be speculation. It can equally be explained by transient effects or lateral variation of surface temperature – and neither require invoking thermal effects of water flow.

  (A5) We will revise the text to reflect the possible sources of thermal offsets:

  (Line 300): ***"Beside the possibility of varying subsurface thermal conductivity (Hasler et al., 2011),*** *this water-flow-induced seasonal succession of rapid warming and slow cooling can result in a positive thermal offset, as observed in B1 and B2 (Fig. 5a), which, over long time periods, results in bottom-up oriented permafrost degradation."*

  Hasler, A., Gruber, S., and Haeberli, W.: Temperature variability and offset in steep alpine rock and ice faces, The Cryosphere, 5, 977–988, https://doi.org/10.5194/tc-5-977-2011, 2011.

- Figures 5 and 6: There are strong temporal trends that would provide important background information. Consider showing a depth profile of temporal trends in mean (and maximum?) temperatures over the entire measurement duration. This will help contextualize Figure 4 and its decadal gap.

  (A6) As mentioned in Line 162-163 borehole temperature measurements are available only since December 2015. Therefore, it is not possible to show a temporal trend over the decadal gap between the electrical resistivity observations (2013-2023). Within the available data constrains, we have chosen to focus on the thermal regime in 2023 (Figure 4 and Figure 5) to provide a detailed information of the rock temperature during the electrical resistivity measurements in 2023.

- Line 313: The authors state that obstacles exist for interpreting ERT profiles in fractured rock masses based on laboratory measurements on intact samples (an error). Section 5.1 argues that the differences between lab and field point to pressurized water flow (a signal). Can error and signal be distinguished with sufficient confidence? Explain how.

(A7) We are aware of the upscaling effect between the electrical resistivity measurements on intact rock sample and on the fractured rockwall at the Kitzsteinhorn, as mentioned in Line 313. However, we do not consider the resulting differences between laboratory and field observations as errors. Instead, we interpret them as indicator of conditions at the study site that were not or could not be replicated in the laboratory experiments (i.e. rock masses with water-filled fractures). The full argumentation of how we inferred pressurised water flow from the differences between lab and filed measurements is developed in (A2) and will be included in the revised manuscript in section 5.1.

- Line 21: Is permafrost thaw a hazard?

  (A10) We will change it to: *"[…] including* ***rock slope failures from warming permafrost rocks."***

- Section 4.2: What is the impact of using summer ERT that has been measured ten years after the profiles in other seasons? Are we interpreting the influence of seasons or a decade of atmospheric warming (see Figure 6)? This needs to be addressed clearly.

  (A9) As previously mentioned, the novelty and significant contribution of our study lie in the detection of pressurised water flow and seasonal changes. Consequently, we have focused on the results during the thawing season and refrained from a detailed interpretation of decadal permafrost changes. Logistical constraints made it unfeasible to repeat the ERT measurements in 2023, which is why we included the ERT data from 2013. In addition, the ERT measurements from 2023 show that the signal is influenced by the water content of the rockwall, greatly affecting the detection of permafrost and, thus, making it impracticable to draw conclusions about its evolution. We will clarify our interpretation by modifying the corresponding sentences in the discussion (section *5.2 Limitations and uncertainties*) and include an explanation of the differences in the results from June/September in 2013 and 2023:

  (Line 320): ***"Atmospheric conditions vary slightly between years, affecting the timing of snow melt and hence the change in resistivity regime. The ERT results from June 2013 exhibit higher resistivity values in the upper part of the profile (>64 kΩm) compared to the ERT measurement in 2023 (Figure 4), probably due to colder rock and atmospheric conditions prior to the measurement. However, the trend towards lower resistivity values, particularly in the lower part of the profile, is also clearly visible in the tomogram from June 2013.*** *The penetration depth of the current flow into the subsurface depends on the characteristics of the top layer and may vary seasonally. Dry and frozen conditions can impede current flow, while water-saturated conditions might trap current flow, resulting in an attenuated current flow into deeper layers (Loke, 2022). Poor electrode coupling is often associated with frozen conditions and ice-filled fractures and cracks from autumn to spring, which cause noisy data and can lead to inversion artifacts represented by a high RMS error.* ***This phenomenon was observed, for example, in September 2013 vs. 2023, where cold air temperatures likely caused freezing of the rock surface layer prior to the ERT measurement, resulting in high contact resistance and an inability to resolve the long-lasting summer thermal signal in greater depths."***

  (Line 324): *"[…] Consequently, we refrained from detailed interpretation of the inverted tomograms from February to May 2013 and September to December* ***2013 but included the ERT data to cover all season. We assume that a repeat of the ERT measurements in 2023 during the frost period would have yielded comparable results, as borehole temperature show frozen subsurface conditions from January to June and from October to December (Figure 4), during which no thermal anomalies or irregularities were observed (Figure 6).****"*

- Section 5.3: Some of the statements seem rather confident. They could be shortened and made specific to well supported conclusion and, as such, added as a short outlook paragraph to the conclusion. Some of the other text in the section is better suited for the introduction of a paper.

  (A10) We decided to discuss our findings in detail in section 5.3, as we believe they have significant implications for rock wall instabilities and, more generally, for high alpine permafrost monitoring routines. We have already focused on specific processes and ensured that our statements are well-supported by literature and/ or our study. However, we will follow your suggestions and integrating some of the statements from section 5.3 into the conclusion:

Line (377):

" [...]

4. ***Monitoring of alpine permafrost often relies solely on annually repeated geoelectric measurements, mainly due to complicated logistics and harsh measurement conditions. However, our study suggests that higher ERT measurement intervals are required to decipher the complexity of hydrothermal processes in permafrost rockwalls and fully assess the rate and extent of permafrost evolution. Monthly repeated measurements in this contribution represent a significant advancement compared to annual surveys.***
5. ***We emphasize the key role of complementary temperature measurements and their joint analysis. Low electrical resistivity values in the absence of borehole temperatures may be misinterpreted as permafrost-free rock slopes, yet. They could serve as an indicator of water-saturated conditions above a potential permafrost body.***

This study has broad implications for understanding hydrothermal processes in steep, fractured rock walls, the rate and extent of permafrost degradation, and related hazards. ***Future developments are needed to validate and quantify our observations. Of particular interest would be simultaneous electrical resistivity and piezometric measurements during the thawing season, whereby daily or hourly observation intervals would represent another significant step towards a better understanding of the transient nature of water flow in fractures."***

- The manuscript text should be shortened and edited for clarity in structure and arguments. Some of the referencing could be tightened, giving preference to one good reference backing up a particular argument instead of listing a handful of publications.

  (A11) As mentioned in (A2), we will reorder the subchapters in the methodology and results to improve the clarity and structure. These revisions, along with the other modifications, will significantly strengthen our arguments, particularly through the newly designed Figures R1 and R2 (see author comments for referee 2) and the newly included results from piezometric measurements.