Author comment:

Dear Referee #2,

Thank you for your review of our manuscript *"Pressurised water flow in fractured permafrost rocks revealed by joint electrical resistivity monitoring and borehole temperature analysis" (egusphere-2024-893).* We sincerely appreciate your comprehensive, constructive and positive feedback. We have carefully considered your comments, and our detailed responses are provided below, highlighted in blue, with proposed changes in the revised manuscript indicated in bold. We believe that these revisions and accompanying explanations effectively address your concerns and thereby improve the quality and clarity of our manuscript.

With kind regards,

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

The paper entitled *"Pressurised water flow in fractured permafrost rocks revealed by joint electrical resistivity monitoring and borehole temperature analysis"* presents a combination of repeated electrical resistivity tomography (ERT) data and borehole temperature data on a high mountain rock wall site in Austria to discuss potential effect of pressurised water on rock wall temperature and destabilization.

The paper addresses an important topic in high alpine permafrost and geomorphology community that is the characterization of water flows and their impacts for permafrost dynamics and morphodynamics. Addressing this topic is challenging due to the difficulty to observe and measure water flow processes in high mountain and the non-linearity of the related processes. Geophysical approaches are for sure one of the most promising method to investigate these processes.

Overall, the paper is well written and well structured. The ERT dataset is also quite unique and was gained through challenging field work. The figures are very nice and clear. However, I find some major limitations and I would recommend publication after major revisions.

(A1) Thank you for appreciating the uniqueness of the dataset and the careful design of the figures.

GENERAL COMMENTS

One of the major issue is that some of the main findings that are reported are not appropriately demonstrated (see further comments). Furthermore, in the current state, I find it difficult to understand what is the novelty of the conclusions of this paper that echoes a former paper from Keushing et al. (2017). Therefore, I am not convinced by the last sentence of the abstract, especially by the expression "shows for the first time".

(A2) In the revised manuscript, we will address your concerns by including the missing main findings, specifically piezometric measurements (see detailed response (A13)). While Keuschnig et al. (2017) suggested that pressurised water flow warms the surrounding rock upwards, their conclusions were based primarily on fracture inventories, visual observations of cleftwater and near-surface temperature measurements. The focus of the former paper was on testing automated ERT as an early warning system, and it did not include geophysical observations during the peak season of water flow (i.e. snowmelt season between June and September) nor deep borehole temperature and piezometric measurements. Our study, however, incorporates these critical observations, which are necessary to substantiate the hypothesis of water flow and its related processes. In the submitted manuscript we "show for the first time" a comprehensive analysis of direct and indirect observation methods which enables a characterization of the thermal and spatial impact of water flow, and regarding slope stability the build-up of critical hydrostatic levels. In response to your concerns, we will revise the abstract to highlight the novel contribution of our study more precisely and to distinguish our work from the earlier study by Keuschnig et al. (2017). We propose to modify the last sentence to:

(Line 17-19) ***"This study provides for the first time direct and indirect observations of pressurised water flow which shows that, in addition to slow thermal heat conduction, permafrost rocks are subjected to sudden push-like warming events and long-lasting rock temperature regime changes, favouring accelerated bottom-up permafrost degradation, and contributing to the build-up of hydrostatic pressures potentially critical for rock slope stability."***

A detailed explanation for the mentioned "long-lasting rock temperature regime changes" is given in (A13).

INTRODUCTION/ STUDY SITE

Since the core of the paper is about water infiltration I would suggest to better introduce water infiltration in rock slopes (see Hasler et al., 2011a, Ben-Asher et al., 2023) and in mountain permafrost ground in general.

(A3) We agree that a more thorough introduction of water infiltration in rock slopes will enhance the focus and structure of the manuscript. We will incorporate the suggested literature (Halser et al., 2011a, Ben-Asher et al., 2023, Cathala et al., 2024) and include a concise paragraph on this topic in the introduction.

A climate and weather analysis during the measurement period would be highly welcome in the site description, especially for discussing the results afterwards (see further comments). An option would also be to make a general section about Study site and instrumentation as I missed some information about the boreholes (depth, available time series…) and the ERT system (length, number of electrods…).

(A4) To maintain the clear focus of the manuscript, we acknowledge the benefits of providing a weather analysis during the measurement period (2013-2023) and suggest incorporating this without extending a full climate analysis. We will include the air temperature and precipitation recordings from the weather station "Gletscherplateau" (2.940 m asl, distance ca. 500 m) in a new Figure. However, the weather analysis will be provided in the Appendix, since we already show the mean daily air temperature, the estimated snow cover area and snow height at the ERT measurement days in 2023 in the main text in Figure 2. Since the focus of the manuscript is on the seasonal water flow during the thawing period (June-September) and not on decadal permafrost changes (see also A12), the atmospheric conditions during the ERT observations in 2023 are of particular interest. Additionally, we will present air temperatures from January to June 2024 in Figure R1 to correlate with the observed water pressure levels.

We have decided to provide detailed information about the ERT system and boreholes within the methodology, specifically in sections *3.2 ERT data acquisition* and *3.3 Borehole temperature measurements:*

ERT system information: Length/ number of electrodes:

- (Line 129): *"[…] 37 electrodes were permanently drilled into the bedrock at intervals of 2 m."*
- (Line 138-139): *"[…] only the top 30 fixed electrodes could be used in 2023* ***(i.e. 58 m profile length)****."*

Borehole information: Depth/ time series:

- (Line 164-165): *"Both boreholes were drilled perpendicular to the surface and schistisity, reaching a depth of 22 m (B1) and 30 m (B2)."*
- (Line 173-174): *"Sensors were installed at 0.1, 0.5, 1, 2, 3, 5, 7, 10, 15, 20, 21.5 (only B1), 25 (only B2) and 30 m (only B2) depth."*
- (Line 162-163): *"Rock temperature measurements in two deep boreholes […] have been conducted since December 2015* ***and were analyzed until December 2023.****"*
- (Line 178-182): *"Lightning strikes damaged several thermistors throughout the long-term monitoring (2016-2023), leading to data gaps starting in June 2017 (B2 = 0.5, 10 m), July 2019 (B2 = 20 m), June 2020 (B2 = 7 m), September 2020 (B2 = 25 m), April 2023 (B1 = 20 m), June 2023 (B1 = 7, 10, 21.5 m, B2 = 1 m). Warming releases resulting from construction activities in summer 2023, mainly due to drilling operations near B1, could have affected ground temperature measurements. Consequently, we excluded the affected data sets from B1 (August-December 2023)."*

I also wondered why the ERT data and temperature data are not directly compared and discussed since the resistivity values could be used to infer temperature values based on the lab results.

(A5) Giving the constraints of the borehole data, which began in December 2015, a direct comparison of ERT data and borehole temperature is only feasible for the observations in 2023. We have addressed this comparison in Figure 4 by indicating the depth of 0°C in the tomograms, and in greater detail in Figure 7. In Figure 7a, we focus on the 0°C and -0.5°C isotherms (i.e., permafrost table) observed in borehole B2 and compare these with the median resistivity values of the ERT measurements conducted from June to September 2023. Figure 7b illustrates the discrepancy between the temperature-resistivity relationship derived from the lab and field measurements. We thoroughly discuss these in section 5.1, which also forms an important basis of our argument for a widespread water flow injection into the fracture network (see also (A13)).

METHODS

Has tap water some implications on the freezing point? Duvillard et al. (2021) showed that it has a different freezing temperature than snowmelt water that is more representative of the natural environment. I would have first presented the field before the laboratory calibration approach as the latter completes the former.

(A6) Thanks for your remarks regarding the laboratory experiments. We are aware that tap water can have minor implications on the freezing point. Duvillard et al. (2021) conducted electrical conductivity experiments only on one sample saturated with tap water and on one with snow melt, making it difficult to quantitatively separate the bias due to rock heterogeneity (i.e., number of interconnected pores) and water type. In our laboratory study, we tested seven different rock samples with the consistent preparation and measurement procedures, demonstrating the influence of rock heterogeneity by revealing a range of freezing points between 0.22°C and -0.31°C (see Table A1). Regarding your concerns, we determine the conductivity (i.e., concentration of ions) of the snow melt water from the field site to 0.014 S m^{-1}, which is in the same order of magnitude from the used tap water with 0.058 ± 0.002 S m^{-1} (Line 103). Comparing the lab experiments with the field observation from June 2023 (Figure 7b), we observed a slight shift of the freezing point to approximately -1.0℃, likely influenced more by the fractured rock mass rather than snow melt water. This uncertainty is address with the defined transition zone in the ERT color scheme, and we refrain from directly linking electrical field resistivity values to temperature.

To strengthen the focus of the paper, we will follow your suggestion and restructure the subchapters of the methodology and results, beginning with borehole temperature observations, followed by the field ERT measurements and concluding with laboratory calibrations.

The ground contact resistance is not presented while it is a major parameter of the measurement as explained by Herring et al. (2023). But some datasets have huge RMS and this could be partly due to poor contact resistance. This part of the work has to be described and addressed.

(A7) We agree that high contact resistance (i.e., poor contact between electrodes and bedrock) limits the current injection into the bedrock and degrade data quality. As noted by Herring et al. (2023), contact resistances vary with site conditions and the season. In frozen bedrock, high contact resistances remain a key challenge, which can be mitigated e.g. by adding fresh water. However, given that the investigated rockwall is snow-covered during the winter months, it is not feasible from a logistical and safety perspective to access the corresponding electrodes. Our manuscript primarily focusses on the ERT measurements conducted in summer 2023, when contact resistance were low (mostly <200 kΩ, which are accepted values according to Herring et al. (2023)) and RMS values were minimal (Table B1: 3.6-4.3 %). In the revised manuscript, we will include the contact resistivity values of the respective measurements in Table B1. Although the contact resistances were higher during the observations from the winter months, resulting in higher RMS values, we decided to include these ERT measurements to provide a comprehensive dataset covering all seasons.

We have addressed this issue in the submitted manuscript in section 3.2 (Line 154-158 and 323-325):

Line (154-158): *"Resistivity models with a high root mean square (RMS) error between the modelled and observed data are obtained, particularly during the winter months when frozen surface conditions impede the coupling of electrodes. However, an assumption of inaccuracy and subsequent complete exclusion of the affected data sets only justified by a high RMS error is inappropriate. We, therefore, retained the data sets of the winter measurements but withheld detailed interpretation in recognition of the potential presence of noise."*

From L175, images of the rock discontinuities are mentioned but not displayed in any way. That is a pity because the paper attempts to link ERT data to rock discontinuity data. That would be interesting to better show these data.

(A8) Since our discussion relies on the linkage between ERT, piezometric data (will be included in the revised manuscript, see (A13)) and rock discontinuities, we have carefully described the geotechnical setting of the rock face and presented the rock discontinuities data in several sections:

- Section 2 (Study site): Figure 1 shows the geotechnical setting of the rock face by a schematic representation of the main discontinuities and the dip angel and direction of their mean set planes. Additionally, we described the characteristics of the joint sets in the text (Line 77-81): *"The north face of the Kitzsteinhorn exhibits a significant degree of fracturing, characterized by joint openings of up to 20 cm, predominantly along cleavage planes (Schober et al., 2012). The development of the enormous number of joint sets was favored by stress release and intense physical weathering processes (Hartmeyer et al., 2012). The main joint sets are K1, which has a sub-vertical dip to the west, and K2, which features a steep dip to the southwest (Fig. 1). K3 and K4 are less abundant. K3 dips medium-steeply to flat to S-SSE, and K4 dips steeply to NW."*
- Section 4.3 (Borehole temperature and thermal anomalies): As mentioned in Line 175 (section 3.3), optical borehole scanning was performed to identify and locate discontinuities. Instead of simply showing the images, we analyzed the scans and presented the results in Figure 6, illustrating the schistosity and cleft locations along the borehole B1 and B2. Here we linked the occurrences of discontinuities with the frequency of thermal anomalies (Line 243-

247): *"Optical borehole imaging shows a pronounced occurrence of clefts with apertures of up to 5 cm in the first ten meters in B1 and B2 and intact rock mass of calcareous mica-schist with marked schistosity at greater depths (Fig. 6). Thermistors installed close or within clefts or areas of schistosity exhibit a higher frequency of thermal anomalies, as evidenced by the counts recorded (e.g., B1-2 m: 18, B2-3 m: 25), in contrast to thermistors installed at a greater distance, not exceeding 50 cm, from discontinuities (B2-2 m: 10, B1-3 m: 16)"*

- Section 5.1 (Pressurised water flow in permafrost rockwalls): Figure 8 shows an image of one prominent K2 joint with apertures around 5 cm, which may play a particular role for the infiltration of water, as described from Line 277-283.

The calibration is based on an intact rock sample while the paper focuses on specific processes of fractured rock. The fractures might not be entirely filled with water or ice and this is not discussed. The signal of air and ice is the same, and this needs to be discussed and clarified. This means that the results must be considered with caution as well.

(A9) Thanks for your comment, we recognize the importance of distinguish between air and ice signals, as both can produce signals in the same range. To address this, we clarify this point in the results and discussion section, chapter 4.2 and 5.1:

- Line 195-196: *"Nevertheless, electrical resistivity values remained above 32 kΩm, indicating frozen rock and **air-/**ice-filled joints."*
- Line 255: "*High-resistivity sections above 19 kΩm indicate frozen conditions with **air-/**ice-filled joints […]"*
- Line 296: *"[…] we suggest that fractures can act as cooling pathways, favoring the formation of freezing corridors **and air ventilation.**"*

Despite this, we assume high-water levels in the fractures from July to September since the drastic decline of the electrical resistivity values of more than an order of magnitude can only be explained by a widespread water infiltration into the fracture network (see also A13).

Rather than number of electrods, I would find it more convenient to speak in terms of distance along the profile (see also comment on the lack of information on the profile length).

(A10) We will modify the corresponding passages and refer to the distance along the profile rather than number of electrodes.

The calculation of the thermal anomalies must be clearly detailed in the Methods section as this is a central part of the investigation.

(A11) In response to your suggestion, we will provide a description of the determination of thermal anomalies in the methods section (3.3) and shorten the respective sentences in the results section (4.3):

"The thermistor signals in B1 and B2 were analyzed for irregularities and characteristics typical for non-conductive heat transfer. Near-surface temperatures (depth < 2 m) were excluded from the analysis as they are characterized by short-term fluctuations with large amplitudes, making distinguishing between changes induced by non-conductive heat transfer and meteorologically forced changes complex. For the recordings in 2 and 3 m depth, thermal anomalies were identified using the first derivative with a moving average of 12 points (i.e., measurement interval of 2 hours). High signals in the first derivative were manually reviewed for characteristics typical of non-conductive heat transfer, which exhibit a temperature rise of up to 0.7 °C in less than 2 hours. Sudden, significant changes between two measurements (10 min) with a return to the previous temperature

level are caused by overvoltage effects following lightning strikes and were therefore not considered further. Due to the smooth curvature of the thermal signals in 5 m depth, thermal anomalies were directly visible in the data and were manually determined."

RESULTS

Looking at Figure 4, I wonder how the results from Sep/June 2013 and Sep/June 2023 can be so different? Why don't we see the summer signal reaching 10 m depth in early winter? Could the top part of the profile with relatively high resistivity values during the thawing season could be attributed to desiccation (see also comment on air signal)? The decadal permafrost change could be detailed and discussed to take full advantage of the presented data.

(A 12) We will include a short paragraph in the discussion section 5.3 to explain the difference between 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."***

From Line 202-204, we pointed out our interpretation of the relatively high resistivity at the top part of the profile during the thawing season (July to September):

Line (202-204): "*The upper part of the profile (*~ ***x=0-18 m****) is unaffected by the trend. A high resistivity body of ≥ 32 kΩm remains stable during the summer month, probably due to the shielding of water infiltration through the cable car station and* ***consequent desiccation of the surface rock layer,*** *combined with an intact rock mass without major fractures."*

Since the novelty of our manuscript is to reveal pressurised water flow during the thawing period, we refrained from a detail interpretation of the decadal permafrost change. Our initial motivation to include the data from 2013 was to cover all seasons, including the frost period, which was logistically not feasible in 2023, but would probably have yielded comparable results. We will include a short paragraph in the discussion section 5.3 to clarify our choice of ERT data and suggest to refraining from a detailed interpretation of the decadal permafrost change, since we did not present ERT measurements from the same seasonal periods nor a decadal recording of borehole temperature or piezometric data (Figure R1). 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.

(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)."

DISCUSSION

The contradiction with the Archie law is weak as the law is not presented nor discussed in the paper. The same is true with the piezometer data. That is a pity to mention such data without using them extensively nor showing them. L286-288: I do not fully agree with the statement "high impact … on thermal processes". The study shows only short term and minor temperature changes, but great changes in the electrical resistivity that is by essence strongly sensitive to water changes. I would suggest using more balanced wording or to strengthen the demonstration.

(A13) As the missing piezometer data was also addressed by Referee #1, we here include our response to Referee #1 which also concern the contradiction with the Archie Law:

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 newly 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).

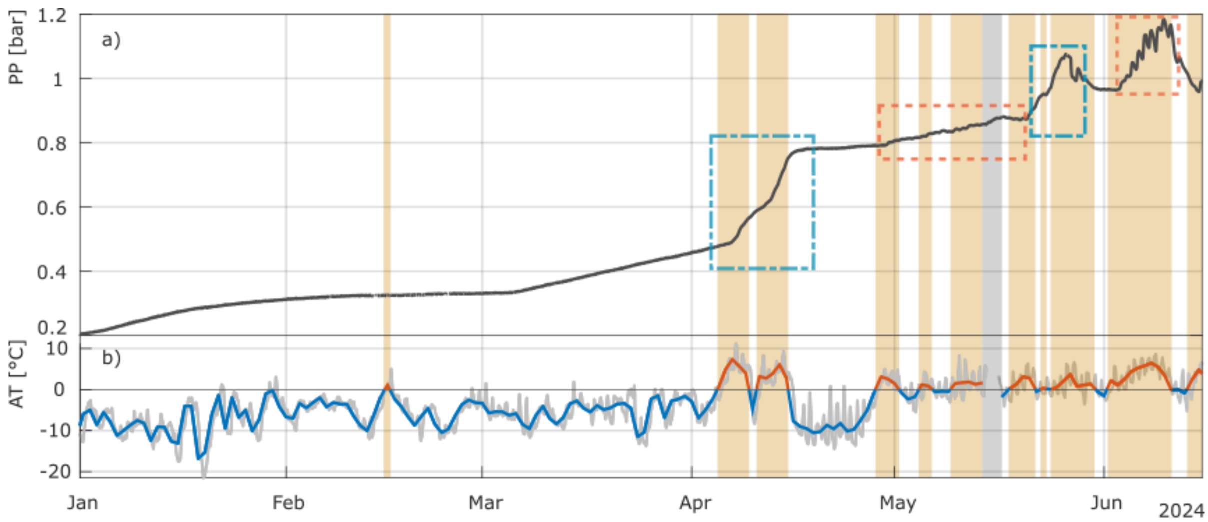

Figure R2. *a) Piezometer pressure (PP) from January to June 2024 recorded near the summit station at a depth of 16.85 m. b) Mean daily air temperature (AT) from the weather station at the Gletscher Plateau (2.940 m asl, distance ~500 m), shown in blue (<0°C) and red (>0°C). The moving mean air temperature (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.

Figure 6 demonstrates the *"high impact of fluid flow in fractures on […] thermal processes"* by showing the thermal signal of borehole B1 in 10 and 15 m depth. We acknowledge that the current layout might the long-term temperature warming effects are rather underrepresented and likely to be overseen. Therefore, we have designed a new Figure R2, which will be included in the revised manuscript. This figure aims to clarify the need to better understand these observed temperature regime changes and to strengthen our conclusions about the major implications of fluid flow on the thermal regime.

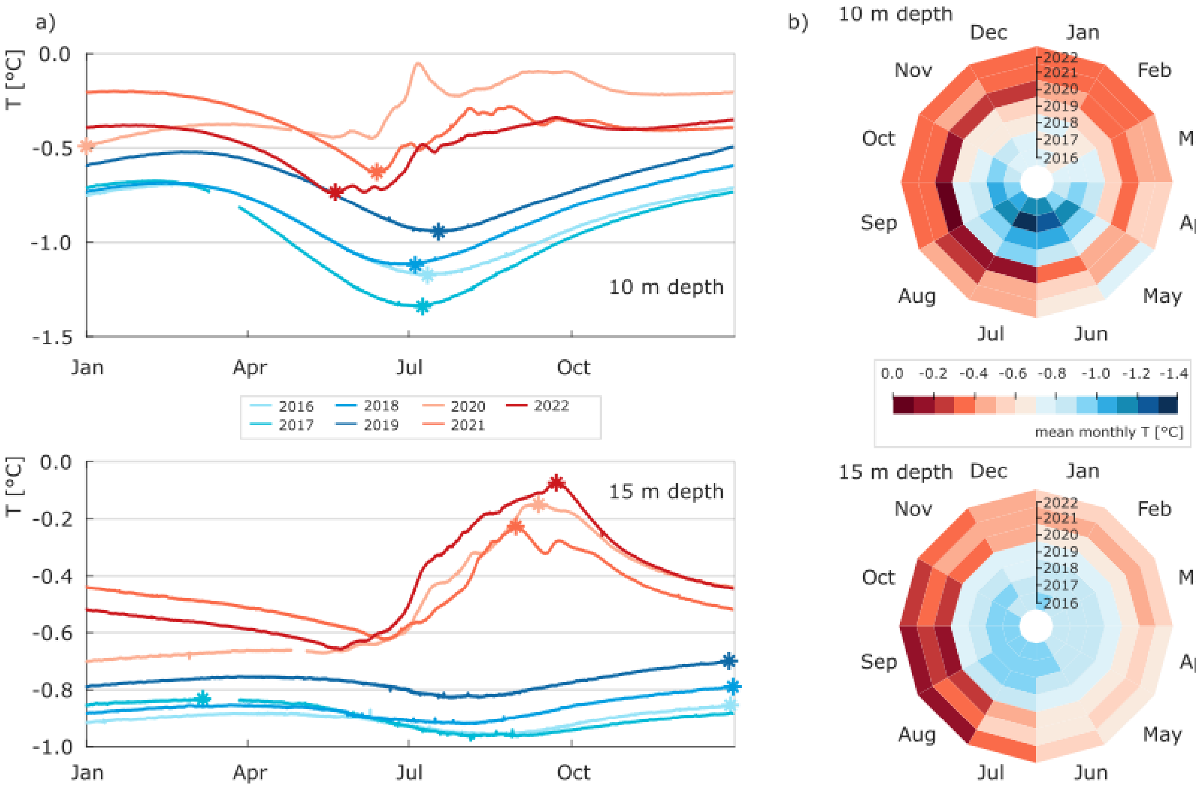

Figure R2. *Borehole temperature at depths of 10 and 15 m between 2016-2019 and 2020-2022: a) Thermal signals in 10 m depth, with minimal values highlighted (top) and at 15 m depth, with maximal values highlighted (bottom). b) Mean monthly temperature values, with each ring representing a measurement year and the radius increasing for more recent observation years.*

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.

Another point that comes to my mind is the effect of anisotropy in such type of rock with a high degree of schistosity. This could be at least discussed and ideally investigated through lab measurements.

(A14) We will consider the effect of anisotropy in the section *5.2 Limitations and uncertainties*:

(Line 313-316): *"However, the problem of extrapolating from laboratory experiments to field observations (Zisser et al., 2007; Krautblatter et al., 2010) was highlighted by our ERT observation of highly fractured rock face* ***with anisotropic characteristics****, which indicated the strong influence of water-saturated fractures and cracks on the electrical properties, less represented by the intact rock mass of the laboratory studies."*

CONCLUSION

The first point rather reminds the initial hypothesis than bringing a demonstration of its validation. In my opinion, the 3rd and 4th points are not demonstrated in the paper.

(A15) We will modify the listing in the conclusion by considering your concerns, the suggestions of Referee 1, and the new included piezometric data set:

(Line 364): *"[…] by combining repeated electrical resistivity monitoring, long-term temperature measurements in deep boreholes,* ***and piezometer observations.*** *The following conclusions are drawn:*

1. ***A massive decrease in electrical resistivity values during the thawing season (July-September) can be indicative for snow melt water infiltration into the rockwall draining along the schistosity and interconnected joints, and subsequently becoming pressurised within a widespread fracture network.***
2. ***Hydrostatic pressure levels of up to 11.8 m indicate a widespread water infiltration into the fracture network, which potentially alters slope stability by favouring bottom-up permafrost degradation and a reduction of shear resistance.***
3. ***Small, abrupt temperatures anomalies registered in the two boreholes (2.0, 3.0 and 5.0 m depth) suggest non-conductive heat flux in fractures. Frozen rock is warmed more rapidly by these sudden push-like events of heat transport from the surface than by slow thermal conduction alone.***
4. ***Long-term regime temperature changes were identified in two boreholes in 10 and 15 m depth between 2016-2019 and 2020-2022, indicating the pronounced heat transfer by infiltrating water.***
5. ***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.***
6. ***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.***

Detailed comments

- Abstract L1: failures do not occur from permafrost itself as permafrost is by definition a temperature, rather use permafrost ground or permafrost-affected slope.
  We will modify it to *"**permafrost rocks**".*

- L 140: what "representative" means here?"
  We will rephrase the sentence without "representative".

- L 148: do you mean average values? (positive values for all days)
  We will change it to *"[…] **indicated positive mean values** […]"*

- L 195: here consider the comment about air and ice signal
  See comment (A9). → "[…] ***air-/****ice-filled joints."*

- L218: where do we see the mentioned zero-curtain? This is crucial to see it and how long it lasts as it provides an information about the ice content.
- The zero-curtain effect can be seen in several thermistor signals in Figure 6. → *"The zero-curtain effect […] was most pronounced at 3 m depth in B2* ***(Figure 6)****."*

- L 223: which construction activity are you talking about?
  We will go into more detailed → *"[…] the year before construction activities* ***for summit station maintenance close to the borehole*** *(August 2022-July 2023) was analysed."*

- L225: "thermal offset" is not an appropriate concept for rockwalls, see Hasler et al., 2011b
  L227-228: the explanation of the "thermal offsets" is not clear
  We recognize that the concept of the "thermal offset" is considered impractical for fractured bedrock due to the high variable mean annual ground surface temperature and active layer thickness, as noted by Hasler et al. (2011b). However, in our specific case, boreholes B1 and B2 both observed similar active layer thickness (B1=4.3 m, B2 =3.9 m, see Line 224), suggesting relatively stable depth of the permafrost table in the investigated rockwall. Therefore, we propose using the concept of "thermal offset" in this context, while acknowledging and clearly indicating the limitations in our interpretation:

  (Line 225): ***"The thermal offset, defined by the difference between the annual mean ground surface temperature (i.e., temperature recording in 0.1 m depth) and the temperature at the permafrost table (Burn and Smith, 1988), is generally considered impracticable for fractured bedrock due to the high variable microclimate and active layer thickness (Hasler et al., 2011). However, in our specific case, both boreholes suggest that the permafrost table depth are within a similar range. Therefore, considering the potential variability in microclimate, we***

propose that the concept of thermal offset is practicable and demonstrate positive values (B1 = 1.5 °C, B2 = 0.9 °C).”

Burn, C. R. and Smith, C. A. S.: Observations of the “thermal offset” in near-surface mean annual ground temperatures at several sites near Mayo, Yukon Territory, Canada, Arctic, 41, 99–104, 1988.

(Line 300): ***“Beside the possibility of varying subsurface thermal conductivity (Hasler et al., 2011b),*** *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.”*

- L230: calculation of these abrupt changes must be clearly explained in the method section
  See comment (A11).

- L233: how is this threshold of values defined?
  See comment (A11): The first derivatives were manually reviewed for high signals and marked in Figure 6, which yielded a temperature rise of up to 0.7 °C in less than 2 hours.

- L296-297: and what about air?
  See comment (A9). We modify it to → *“[…] we suggest that fractures can act as cooling pathways, favoring the formation of freezing corridors* ***and air ventilation.”***

REFERENCE

I suggest to have a look at Hasler et al. 2011b when discussing “thermal offset” that is not an appropriate concept for steep mountain slopes.
See comment above.

I suggest also to consider Cathala et al., 2024 to link pressurized water to rock slope destabilization.
We will consider the literature in the new paragraph in the introduction (see A3).

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