Response to the first referee comments to “Characterizing ground ice content and origin to better understand the seasonal surface dynamics of the Gruben rock glacier and the adjacent Gruben debris-covered glacier (southern Swiss Alps)” by Wee et al. (author comments)

*Reviewer’s comments are shown in black italics.* Responses from the authors are presented in blue regular font below each comment. Citations from the manuscript are in Times New Roman, changes of the manuscript text are underlined.

October 3, 2024

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RC1: 'Comment on egusphere-2024-1283', Adriano Ribolini, 05 Aug 2024

*I read with attention and interest the paper by Julie Wee et al "Characterizing ground ice content..." I found the paper interesting, well written and illustrated, and I see no obstacles to its publication.*

*The Gruben rock glacier / debris-covered glacier is a key site for understanding the permafrost/glacier relationships, and there are numerous papers on various aspects (thermal behavior, geomorphological characteristics, geophysics, etc).*
*The merit of this paper is not that of having used the individual investigations (which are not innovative from a methodological point of view), but of having used a Petrophysical Joint Inversion in this well-known site, which has been at the centre of many scientific discussions. The built dataset consists of a potential distribution of ice, water, rock phases, eventually associated with thermal and surface dynamics data. What derives from this exercise is an integrated synthesis that supports a robust and adequately quantitative interpretation, as is necessary when we want to disentangle complex mechanical processes (glacial sediments transport/deformation, permafrost creep of frozen material) that lead to landforms that are not always clearly distinguishable.*

*The methods are illustrated with the necessary summary, the data are well illustrated and their interpretation clearly exposed.*

*In some points in the text reference is made to the contribution of geomorphological knowledge in integrating the interpretation of the data, or even some choices in the model. I understand that this is not the purpose of the paper, but I suggest adding (even in parentheses) some information about it.*

*In the comparison between the results of the conventional RST and ERT inversions and the PJI-derived ones, the differences relating to seismic velocities are highlighted. I suggest discussing whether those relating to resistivity are irrelevant or could have a weight in terms of data interpretation (especially the minimum resistivity values).*

*I added a few minor annotations to the paper’s PDF file.*

*Hope this helps*

*Best wishes*

*Adriano Ribolini*

Dear Adriano, we would like to thank you for this encouraging and constructive review and careful reading. Our responses to your comments will be addressed below.

*L325: You can consider to add a reference here (ionic ice).*
Thank you, we have added two references: (Colombo et al., 2019; Del Siro et al., 2023).

*L331: Please explain why a potential high water content is inferred here and not at the highest part of the long profile.*
The possibility that a potentially high water content could be found in the uppermost section of the profile GRU-P00 was suggested because the resistivity values are particularly low in this section of the profile. Nevertheless, the interpretation of the resistivity values at the edges of the tomograms must be done with care as the sensitivity of the model to the measured data is lower at the edges than in central parts of the tomograms.

*L346ff: It seems a bit vague to me. Can you please explain what the information deriving from previous geomorphological knowledge consists of?*
The analysis of historical maps and historical aerial images allowed a first geomorphological interpretation of the study area. For instance, the development of thermokarstic depressions in the upper area of the Gruben rock glacier (former contact zone) during the 1970s, as well as documented massive ice outcrops are clear indicators of the near-surface ground ice properties. This allowed to better constrain the resistivity values for each profile and the rock fraction estimate. We will add this reasoning in the revised version of the manuscript.

*L350: "high ice-to-water ratio" or high ice content? This is true, but Fig. 5 does not describe the ice-to-water ratio.*
Thank you for raising this point. We will modify the text accordingly: In contrast, the section between 20 and 75 m, located at the edge of a former thermokarst lake, presents a high ice content.

*L493: See comment before (comment L346ff).*
Please refer to the response given above.

*L511: Is it possible to pass to a quantitative analysis? Is it correct to calculate a percentage of differences between conventional and PJI-derived tomograms?*
Yes, it would be possible to quantitatively compare conventional tomograms with PJI-derived tomograms. However, in the scope of this study, we analyse the tomograms qualitatively to observe the spatial discrepancies and ensure that the PJI-derived tomograms do not produce results that are inconsistent with those from the conventional inversion. The presence of some discrepancies between them does not inherently indicate poor results.

*Figure 12: I suggest adding further comments on the differences regarding resistivities. Can differences in minimum resistivity displayed in some tomograms (e.g. GRU-S04) lead to a different interpretation in terms of ice content or even frozen/unfrozen sediments?*
The observed differences in the minimum resistivity values along profile GRU-S04 are unlikely to result in a significantly different interpretation. This is primarily due to the fact that these variations occur at the edges of the tomogram, where the model's sensitivity to the measured data is inherently lower. Consequently, the influence of these discrepancies on the overall interpretation remains minimal.

*Citation: https://doi.org/10.5194/egusphere-2024-1283-RC1*

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RC2: 'Comment on egusphere-2024-1283', Anonymous Referee #2, 10 Sep 2024

*It is my pleasure to review the manuscript " Characterizing ground ice content and origin to better understand the seasonal surface dynamics of the Gruben rock glacier and the adjacent Gruben debris-covered glacier (southern Swiss Alps)" I appreciate the effort put into characterizing the subsurface of the Gruben rock glacier and its adjacent complex contact zone using a petrophysical joint inversion (PJI) scheme, incorporating both electrical resistivity tomography (ERT) and refraction seismic tomography (RST) data. This study is indeed novel, particularly in its ability to differentiate between the rock glacier and the complex zone, with the integration of remote sensing and in situ data adding significant value. However, the manuscript needed much more clarity on the interaction between ice-free and ice-filled areas, particularly concerning the dynamics of creep within these zones. Understanding how these different ice conditions influence creep behaviour is crucial for interpreting the glacier's overall dynamics and stability. With some minor changes I recommend it for publication.*

We thank reviewer #2 for the constructive and positive assessment of this contribution. We will respond to the individual comments below.

***Introduction***

*I suggest the authors improve the literature review of the introduction by including studies on permafrost and rock glaciers in the other high latitude and high-altitude regions. This will give readers a broader understanding of how these features behave in different environments. In addition, please mention how your studies are helping to know the geohazards due to permafrost thaw in the region. The authors have done an excellent job by combining GNSS, UAV surveys, and continuous dGNSS time series to analyse the surface dynamics of complex periglacial landforms. This multi-method approach is well appreciated. However, it will further enhance the study if the authors also discuss how these methods contribute to understanding geohazards related to permafrost thaw, such as slope instability or ground subsidence. Adding this aspect will highlight the practical implications of the research and its importance in assessing regional risks.*

We have added a reference in L32ff addressing the general behaviour of rock glaciers: (Carturan et al., 2020; Cicoira et al., 2021; Huss and Fischer, 2016; Kellerer-Pirklbauer et al., 2024; Mollaret et al., 2019). A second reference was added in L43 addressing the complexity of the interactions and interconnections between glaciers and rock glaciers: (Monnier et al., 2014; Vivero et al., 2021).

We have now integrated a paragraph in from L125ff addressing how this study can contribute to geohazards understanding in such context: Following two lake outburst events in 1968 and 1979, both triggering devastating debris flows down to the main valley, important hazard protection work was carried out, supported by comprehensive field measurements (Haeberli et al. 2001, Gärtner-Roer et al. 2022). These integrative glacier and permafrost investigations (Haeberli 2005) document specific climate-related aspects for the Gruben site, which seem to be quite characteristic for the evolution of cold mountain regions in general. As part of a complex glacier/permafrost system, long-term creep and advance of perennially frozen debris masses – here Gruben rock glacier – represent a comparably stable element with low hazard potential. Much more dynamic and dangerous are developments, where polythermal glaciers – here Gruben glacier in contact with permafrost – rapidly retreat, leading to the formation and growth of lakes in a highly unstable environment of dead ice, locally frozen ground and thermokarst phenomena (here the various Gruben lakes). Perhaps to most serious and most difficult-to-handle phenomenon is the deep and for very long time periods irreversible warming, degradation and thaw of perennially frozen rock walls – here especially the north-exposed frozen rock walls south of the glacier, where rock-fall and rock avalanche activity increased for decades already. The evolution must be carefully observed, and lake volumes must be kept small in order to avoid dangerous impact and flood waves.

### *Study area*

*The authors have provided detailed information on the study site, including average surface velocity and elevation changes of the glacier, which is highly informative. However, to further enhance the analysis, I recommend adding data on the gradient and aspect of the glacier. This would help in better understanding the factors influencing the high creep movement observed in the glacier and provide a more comprehensive view of its dynamics.*

Thanks for the helpful comment. We have added a map comprising the slope gradient of the rock glacier and the debris-covered glacier tongue of the Gruben glacier (panel c). In addition to this recommendation, we have also added the permafrost distribution map by Kenner et al. (2019).

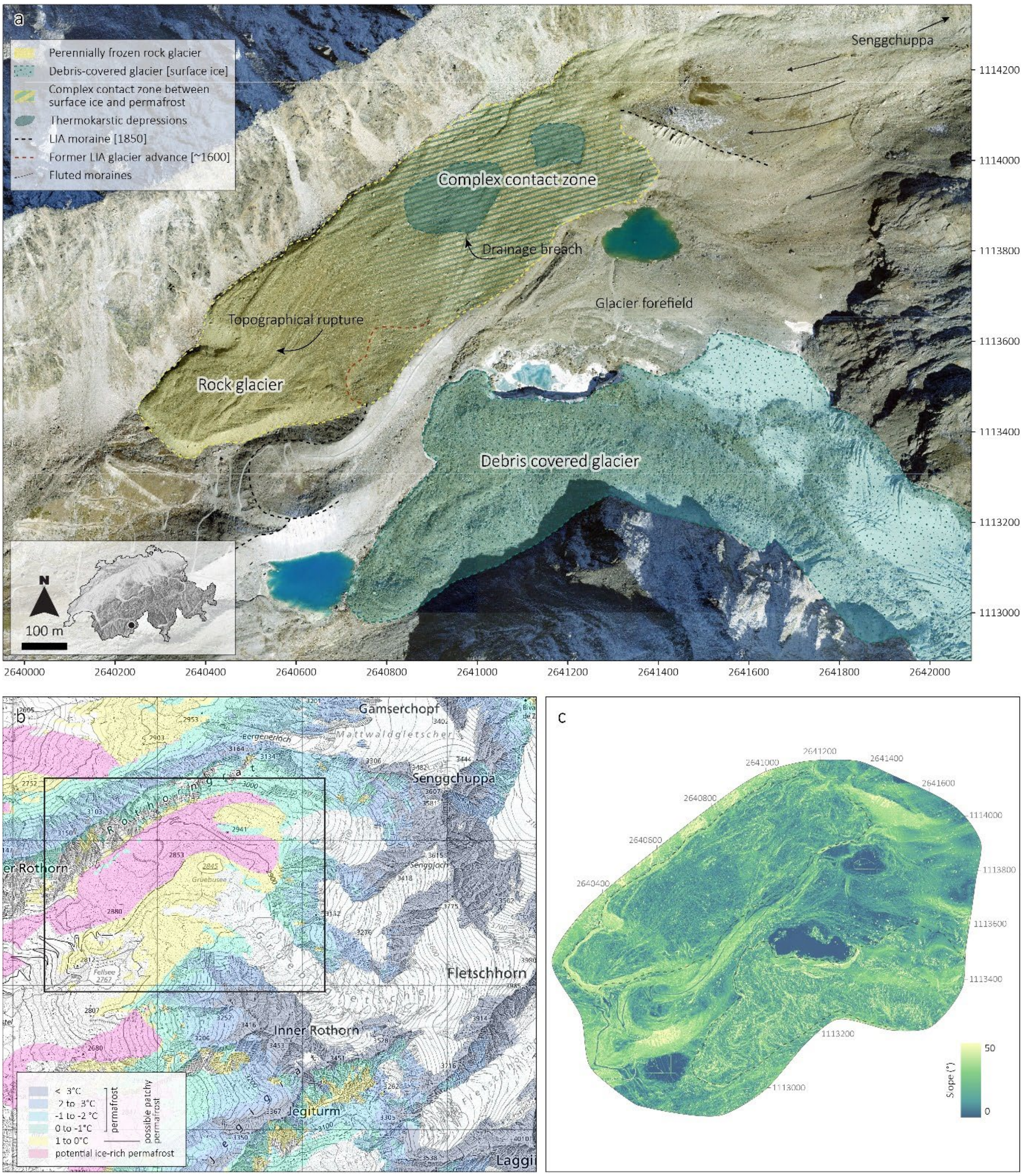



**Figure 1: General geomorphological description of the Gruben site (a). The Gruben rock glacier is highlighted by the yellow dashed lines. The complex contact zone is highlighted by alternating yellow and blue dashed lines. The delineation between the rock glacier and the complex contact zone (faded hatched lines) is here not clearly defined but**

**based on geomorphological knowledge and prior studies (Kääb et al., 1997; Gärtner-Roer et al., 2022). The Gruben debris-covered glacier terminus is highlighted in blue. Black dashed lines indicate part of the LIA maximal extent of the Gruben glacier. Red dashed lines indicate a probable former (~1600) LIA glacier advance. Fluted moraines indicate the basal flow direction of the adjacent Little Ice Age Senggchuppa glacier. Background: SWISSIMAGE 2017 (swisstopo). Permafrost distribution map (Kenner et al., 2019) of the Gruben area (b), and slope gradient of the study area (c).**

***Methods***

*ERT is considered a reliable and well-established method for assessing subsurface properties in permafrost regions, particularly when integrated with other geophysical techniques. However, its accuracy has been questioned in certain studies, eg. Herring et al., 2023. These studies highlight that while ERT can provide valuable insights, its effectiveness may be limited in areas with complex subsurface conditions or high salinity, which can reduce the contrast between frozen and unfrozen ground. Therefore, it is essential to consider the limitations and uncertainties associated with ERT when interpreting permafrost data, and where possible, complement it with other methods to improve accuracy.*

We fully agree to this statement, which led us to develop and apply the petrophysical joint inversion approach which uses two complementary methods to improve the accuracy of the individual techniques.

*The authors have shared velocity estimates from the dGNSS survey over both annual and intra-annual scales, which is helpful. However, it would improve the understanding if they also included the average temperature and precipitation during this period. This would give readers a clearer idea of how weather conditions, like temperature and rainfall, affect the glacier's creep movements in the region. Additionally, it's unclear how the intra-annual and bi-annual studies differ since both seem to cover the same period. Clarifying the specific timeframes and how they are analysed would help readers understand the differences between these studies and their impact on assessing glacier movement.*

Figure 9 shows daily horizontal and vertical surface velocities, as well as daily mean ground surface temperature measured on the Gruben rock glacier and complex contact zone. Regarding precipitation data, the closest meteorological station from which data is available is located in Saas-Balen (46.148778 / 7.928353, 1535 m a.s.l.), which is most likely not representative of the field site.

Regarding the temporal scale of the geodetic measurements, we differentiate between seasonal (bi-annual or intra-annual) and daily (continuous) measurements.

***Results***

*In Figure 6, the flow fields of the Gruben rock glacier are presented along with various topographic details. While the authors note that the flow field is "considerably more complex," it would be helpful to include the gradient of the glacier for additional context. Providing this information would offer a clearer understanding of the factors influencing the glacier's flow dynamics and enhance the overall interpretation of the flow field data.*

Thank you for addressing this point. In accordance with a previous recommendation, we have adapted Figure 1, in which now the slope gradient of the investigated landforms is presented.

*Authors have mentioned "The upslope and downslope sections of the debris-covered glacier tongue". It would be helpful to specify the elevation range for the uppermost and lowermost sections of the glacier tongue according to their definitions.*

We appreciate this thoughtful comment. The upslope section of the debris-covered glacier tongue corresponds to "zone 4" and the downslope section corresponds to "zone 3" (Figure 6).

The text has been adapted as follows for more clarity: The upslope (zone 4, Fig. 6) and downslope (zone 3, Fig. 6) sections of the debris-covered glacier tongue are strikingly distinguishable in terms of flow field direction and velocity.

*In line 449-450, authors mentioned that "The reactivity of surface displacements to the thermal state of the ground surface can likely be attributed to the presence of embedded surface ice buried under a relatively shallow layer of debris" is not clear. please elaborate it.*

The magnitude of ice melt-induced subsidence is highly dependent of the ground ice properties, the surface debris thickness and coarseness, and the temperature of the ground surface. The results from the geodetic and temperature measurements show direct and high-magnitude responses of subsidence to summer ground surface heating in areas where the debris mantle is shallow enough for allowing a direct heat transfer from the atmosphere to the ice underlain by debris. The warmest temperatures are hereby associated with the largest subsidence. In this context, this shows that surface lowering is dominated by ice melt, a thermally driven process occurring at the permafrost table or ground ice surface. To bring clarity, we have adapted the text as follow: The reactivity of surface displacements to the thermal state of the ground surface can likely be attributed to the presence of embedded surface ice buried under a relatively shallow layer of debris, allowing effective direct heat transfer from the atmosphere to the permafrost table (Fig. 4).

*The authors mention that "peak velocities are reached in early summer." It would be useful to confirm whether this period corresponds to the maximum temperatures reported in the region. Providing this information would help link the observed peak velocities with temperature patterns.*

Here, at the dGNSS station GRU-036, and during the investigation period, we observed two-phases of "peak velocities": one after the zero-curtain period, in early summer, and the second one in late autumn. The first phase of acceleration is likely influenced by water from snow melt initiated during the zero-curtain phase (Cicoira et al., 2019b). The second phase can be attributed to the time for the temperature signal to propagate from the surface down to the permafrost table. The seasonal displacement pattern observed in this part of the rock glacier is thermally driven, however the influence of temperature alone cannot explain the details of seasonal displacement rate variations (Cicoira et al., 2019a). We will add this reasoning in the revised version of the manuscript.

***Discussion***

*The session is well-written, but it would be beneficial to include a brief overview of the geology and geomorphology, particularly concerning the development of the moraine patterns of the glacier in this part, 5.3 Internal structure and surface dynamics of the Gruben rock glacier and complex contact zone.*

Thank you for this positive comment. We added a brief description in the Figure 13 caption regarding the LIA moraine as follows: **Interpretation of the influence of the LIA glacier-permafrost interaction on the mechanical behaviour of the rock glacier and its adjacent complex contact zone is based on the analysis of high-resolution photogrammetry. The dashed black line represents the LIA (1850) moraine, and consequently the maximal extent of the Gruben glacier during its LIA apogee.**

***Figures***

*Figure 1: The greyish labels (e.g. topographical rupture) are masked due to the label colour. I suggest you use a different colour that is visible. What is 1850 and ~ 1600 in the legend. Are they years? Also could be better to use lat long in decimal degrees for axis grids.*

The labels have been modified accordingly to improve their readability. Yes, 1850 and 1600 are years. We have decided to use the Swiss coordinate system to maintain some coherence with previous studies on Gruben (Gärtner-Roer et al., 2022). Please refer to the modified Figure 1 in the above response.

*Figure 2: panel a, put the legend on the right side so that it doesn't cover the data line. Panel b, change the colour or increase the colour brightness for the trend line.*
The legend of panel a. was modified for it not to cover the data. In panel b., the colour of the trend lines were changed to increase readability.

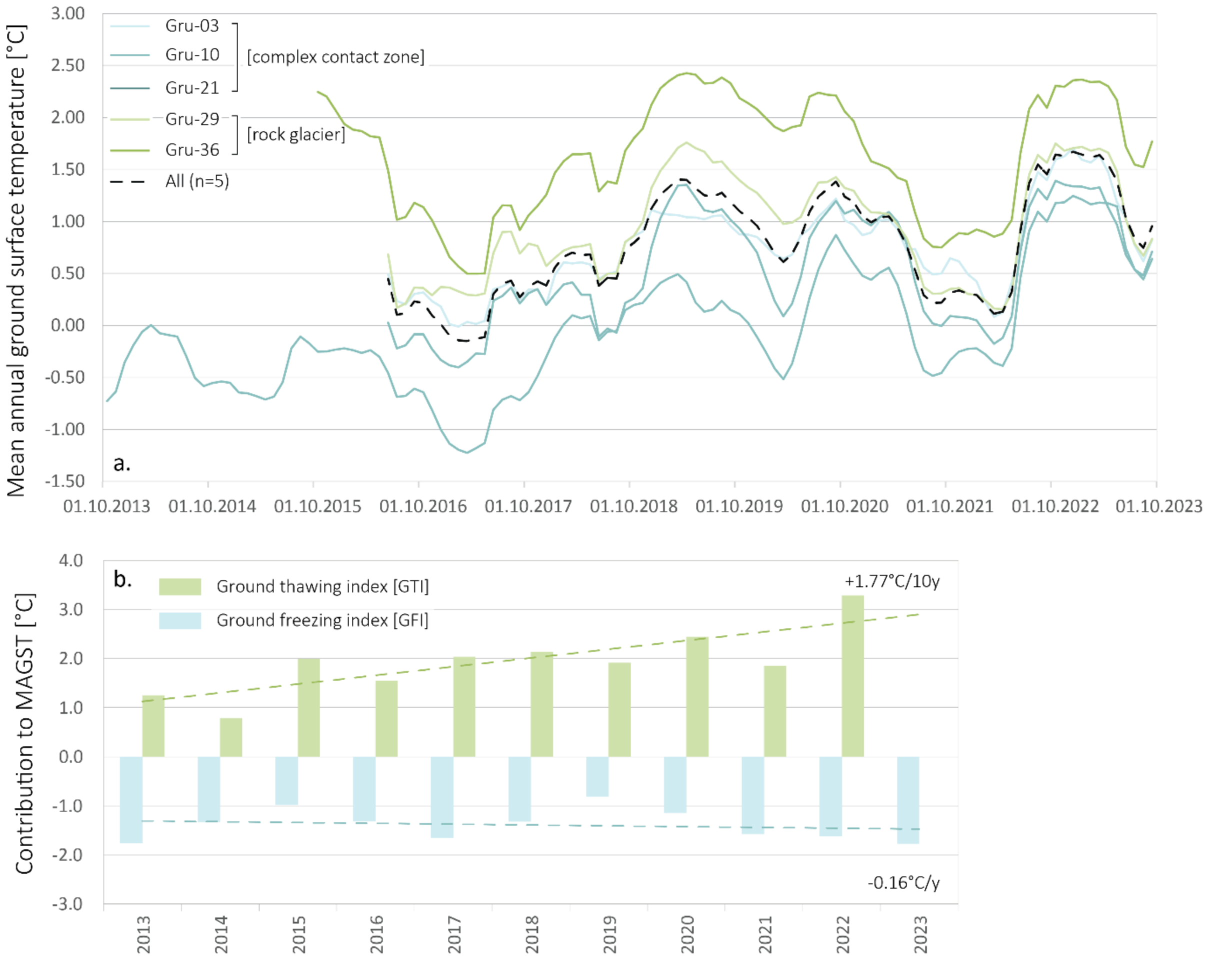
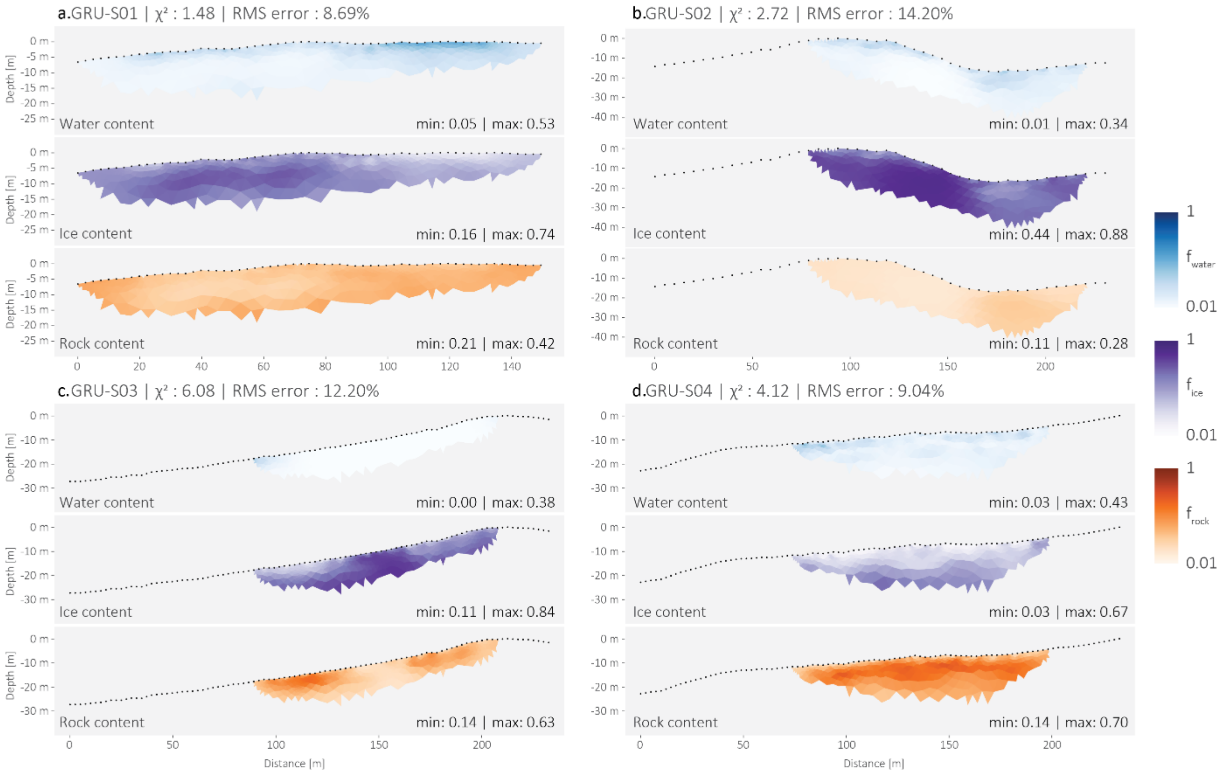


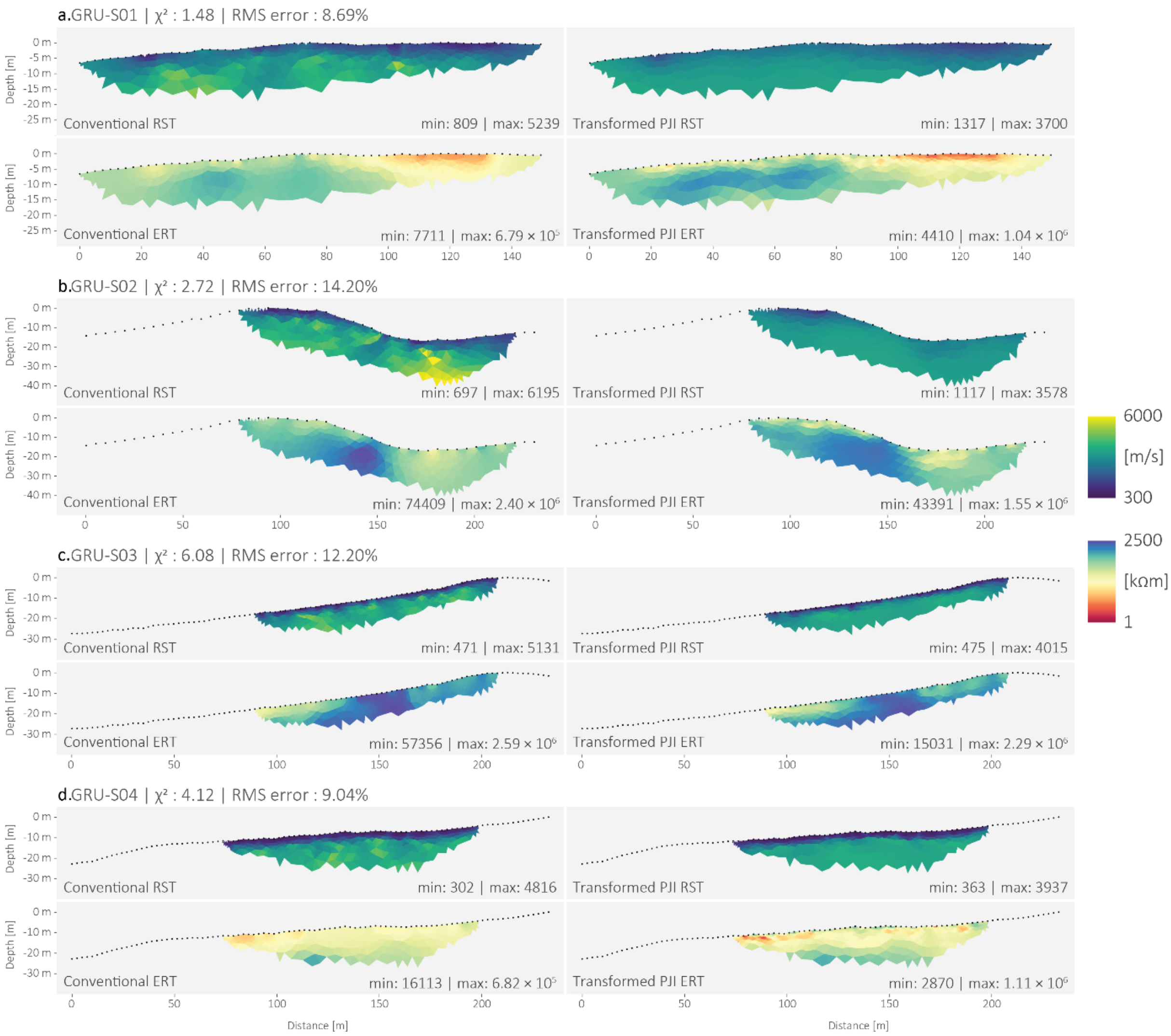

*Table 1 and 4: Use the variable names for the parameter column instead of symbols.*
The variable names are described in the legend of Table 1 (cf. L210ff), and the symbols in Table 4 are referred to in L197 and L206, therefore there is no necessity to provide these changes.

*Table 2 is incomplete? Especially the first four columns?*
Table 2 is complete. It gives the list of the different metrics of each parameter when applying the looping process.

*Figure 5 and 12: the x and y axis ranges need to be increased and rescaled. Also what is the x axis label?*
We have adapted Figures 5 and 12 accordingly. The x-axis represents the distance and the y-axis represents the investigation depth.



a.GRU-S01 | χ² : 1.48 | RMS error : 8.69%
Water content
min: 0.05 | max: 0.53
Ice content
min: 0.16 | max: 0.74
Rock content
min: 0.21 | max: 0.42
b.GRU-S02 | χ² : 2.72 | RMS error : 14.20%
Water content
min: 0.01 | max: 0.34
Ice content
min: 0.44 | max: 0.88
Rock content
min: 0.11 | max: 0.28
c.GRU-S03 | χ² : 6.08 | RMS error : 12.20%
Water content
min: 0.00 | max: 0.38
Ice content
min: 0.11 | max: 0.84
Rock content
min: 0.14 | max: 0.63
d.GRU-S04 | χ² : 4.12 | RMS error : 9.04%
Water content
min: 0.03 | max: 0.43
Ice content
min: 0.03 | max: 0.67
Rock content
min: 0.14 | max: 0.70
Depth [m]
Distance [m]
f water
f ice
f rock
1
0.01

a.GRU-S01 | χ² : 1.48 | RMS error : 8.69%
Conventional RST
min: 809 | max: 5239
Transformed PJI RST
min: 1317 | max: 3700
Conventional ERT
min: 7711 | max: 6.79 × 10⁵
Transformed PJI ERT
min: 4410 | max: 1.04 × 10⁶
b.GRU-S02 | χ² : 2.72 | RMS error : 14.20%
Conventional RST
min: 697 | max: 6195
Transformed PJI RST
min: 1117 | max: 3578
Conventional ERT
min: 74409 | max: 2.40 × 10⁶
Transformed PJI ERT
min: 43391 | max: 1.55 × 10⁶
c.GRU-S03 | χ² : 6.08 | RMS error : 12.20%
Conventional RST
min: 471 | max: 5131
Transformed PJI RST
min: 475 | max: 4015
Conventional ERT
min: 57356 | max: 2.59 × 10⁶
Transformed PJI ERT
min: 15031 | max: 2.29 × 10⁶
d.GRU-S04 | χ² : 4.12 | RMS error : 9.04%
Conventional RST
min: 302 | max: 4816
Transformed PJI RST
min: 363 | max: 3937
Conventional ERT
min: 16113 | max: 6.82 × 10⁵
Transformed PJI ERT
min: 2870 | max: 1.11 × 10⁶
Depth [m]
Distance [m]
6000
[m/s]
300
2500
[kΩm]
1

*Figure 7 is brilliant. What is LoD?*
Thank you for this enthusiastic comment. LoD is the abbreviation for 'limit of detection', cf. L300.

*Figure 9: the colour of raw data points (now in light grey) needs to be changed. I understand your focus is only on the running mean but raw data also needs to be emphasized.*
We have completed and modified Figure 9. We have also clarified in the figure caption that the grey points correspond to the measured data points.

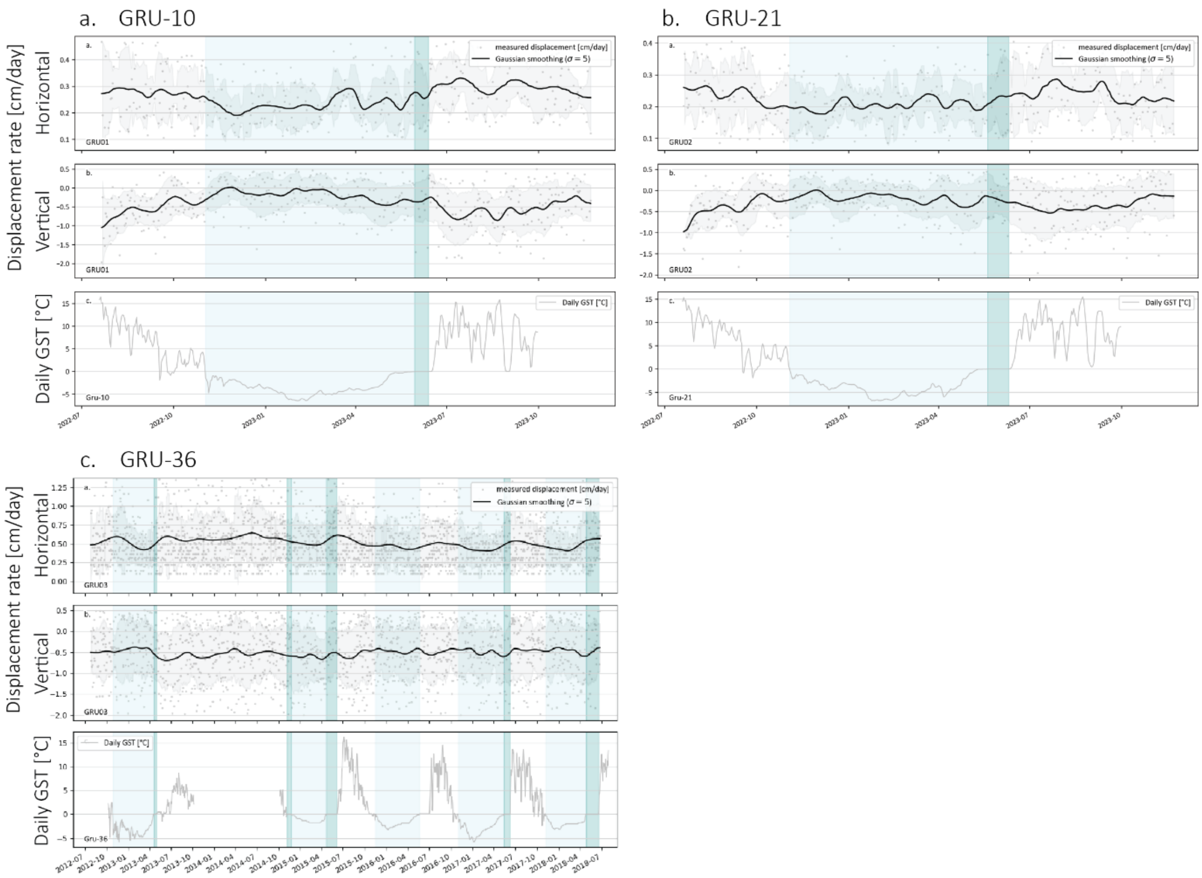



**Figure 2: Ground surface temperature and horizonal and vertical velocity time series in the complex contact zone Gru-010 (a) and Gru-023 (b), and in the rock glacier zone Gru-036 (c). The time series recorded by the stations GRU-010 and GRU-023 span from July 2022 to early October 2023, whereas the time series recorded by the station GRU-036 spans from July 2012 to June 2018. The period highlighted in light blue represents GST below 0°C, the period highlighted in dark blue represents the zero-curtain period. Grey points represent the measured data.**

*Citation: https://doi.org/10.5194/egusphere-2024-1283-RC2*

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