Reviewer Recommendation and Comments for Manuscript Number egusphere-2023-671

SPECTRAL INDUCED POLARIZATION IMAGING TO MONITOR SEASONAL AND ANNUAL DYNAMICS OF FROZEN GROUND AT A MOUNTAIN PERMAFROST SITE IN THE ITALIAN ALPS

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Summary

The authors present an improved version of their interesting and relevant manuscript. They addressed all my general and specific comments on the original version of the manuscript. Specifically, they removed redundancies, included a detailed discussion of the expected broadband response of ice-containing sediment and rock, which improves the understanding of the mechanism underlying the new "phase frequency effect", and provided some additional discussion on the risk of misinterpreting the effect of electromagnetic coupling in terms of ice content.

However, as detailed in my general comments below, there are still parts of the discussion section that remain hard to follow for the reader. More clearly structuring the manuscript (introductory considerations in the introduction section, results in the results section,…) would improve the clarity and readability of these parts of the manuscript. In addition, the authors might overestimate the scope of the newly added electric circuit experiments, which – from my point of view may only represent a lower bound of the coupling effects to be expected. These issues together with a number of specific comments and technical corrections listed below, should be straightforward to address. Therefore, I recommend accepting the revised manuscript after an additional minor revision.

General comments

Structure and clarity of the discussion section

Mainly in the discussion section, there are still some parts of the manuscript, which are hard to follow as they mix literature reviews (introduction), data processing (methods), presentation of data (results) and discussions. In my specific comments below, I provide some suggestions on how these passages could be improved by more clearly structuring the manuscript.

Reference circuit experiment (section 4.1.1)

The new electric circuit experiment provides interesting extra information on the performance of the field equipment in a high-resistance environment. However, strongly suggest moving the entire section to the supplementary material for two reasons:

Structure: An entire experiment should not be presented in the discussion section. In case you decide to leave the study in the manuscript, please consider presenting the experimental method in the methods section, show the results in the results section and discuss the implications in the discussion section.

Scope of the experiment: I doubt that this experiment carried out under laboratory conditions (perfect coupling of current into the test circuit, no significant spatial extension of the layout, etc.) would be able to assess the full error due to the various coupling effects occurring in a real field measurement. It should rather be taken as a lower bound of the expectable error, i.e. the error in the field data might be much higher than this.

Specific comments and technical corrections

Line 34: about -> of

Line 50: … the interpretation… are… -> … the interpretation… **is**…

Line 67: … the enhanced polarization response at… -> … the enhanced polarization response **of water ice** at…

Figure 1: If the shaded map comes from TINITALY, why the credit "Google Maps" in panel 1?

Line 137-139: Refer to (Fig. 2b).

Figure 2, caption: Please specify at which point in space the snow height is measured!

Line 154: Add a "." after "(not shown)"

Line 158: "sums are" -> "is"

Line 176: "for low frequencies < 1 kHz" -> this limitation is not necessary here, please consider removing!

Line 189: "to fit a" -> "to reliably fit a"

Line 201: "polarization effect… are…" -> "polarization effect… **is**"

Line 217: Please consider adding a brief explanation of the concept of super cooling!

Line 237, equation (9): In "S_w" the S should be upper case.

Line 242: "at relatively low temperatures" -> "at temperatures below 0 °C"

Line 254: Please consider substituting "electronic conduction" by "high electrical conductivity".

Line 265: "These MG" -> "**The** MG"

Line 283-285: In Fig. 3, low current injections are listed as additional filter criterion. Please check and add here or remove from Fig. 3!

Line 300: "in the error parameters" -> please consider adding "(i.e., ΔZ and $\Delta\phi$)"

Line 301: "…winter and higher…" -> "…winter, which are expected to result in higher…"

Line 315: "the error model" -> "**an** error model"

Line 315: Please consider introducing the error model and its parameters and explaining how the error model parameters are obtained from the NR misfits of magnitude and phase!

Line 320-322: This explanation of the DOI is not clear. What are m_1 and m_2 for a given inversion result?

Line 334: "was chosen" -> "**were** chosen"; "and 2 m" -> "**at** 2 m"

Line 338: Please define the error model (by stating the equation) – here or further above (see comment on line 315)

Line 356-357: "We used a surface conductivity…" -> "We tested **inversions with** a surface conductivity…"

Line 373: Please also introduce geometry, arrangement and material of the current electrodes!

Line 376: From this description of the experimental setup its seems as if no measures were taken to avoid polarization of potential electrodes by the current through the sample. Most experimental setups remove the potential electrodes from the tested sample to avoid this

effect. Please add a sentence or two to discuss this aspect and explain why this was not needed/possible!

Line 399: “no variation” -> “no **significant** variation”

Figure 5a: Add a blank space between numbers and units (two times “2 m”).

Line 410: “absolute phase values” consider adding “(only ϕ_{75})”

Line 414-416: At which (approximate) depth is the bedrock being detected? Please add this information to the sentence!

Line 420, table 2: What do the abbreviations AL and PF mean and where exactly can these materials be found along the profile?

Line 459: Fig 7a and 7b do not show freezing and thawing cycles, respectively.

Line 461: “and cooling” -> “and **during** cooling”

Line 464-468: units and “per” should not be type set in italic.

Line 472-474: “Additionally, we observe a lowering of the freezing point of water due to ions being excluded from ice formation and accumulating in the liquid phase”. Which specific observation supports this interpretation? Please provide a short explanation/justification for this statement!

Figure 7: Add labels “a)” and “b)” to the panels of the figure! Add unit “(-)” to the phase frequency effect in 7b.

Line 490 and caption to Figure 8: How are the “vertical 1D logs” obtained (extraction from 2D sections or borehole log)? Please provide a brief explanation!

Figure 9: Please consider using the same colors for both the variations of temperature and electrical parameters at the identical depths. This would reduce the legend and make it easier to compare the various time series amongst each other.

Line 616: “and unfrozen” -> “and **the** unfrozen”

Line 621-622: “Supercooling… at the same temperatures…” This is discussed in the context of Figure 12, which does not contain temperature information. Please detail!

Line 634-654: This section is quite confusing: It introduces complicated concepts and approaches used by other authors (which do not directly link to the section title “Temporal variability of the phase-frequency effect and unfrozen water content”) but finally reaches the conclusion that these concepts and approaches cannot be applied to the present data set.

In order to improve the clarity of the (still lengthy) manuscript, I strongly suggest removing this section.

Figure 12:

- c) Add unit “(-)” to UWC on vertical axis
- c) What is “S”? Please explain in the caption or remove from vertical axis!
- Please consider stretching the legend over the entire width of the figure to reduce the large white space.
- Legend: “20m” -> “20 m”

Line 671: Figure 12 does not show ice-content data. Please check and eventually rephrase!

Line 671: Actually, only Figure 8d shows a clear relation between ϕFE and the PJI ice content. Figures 8a and 8c do not show a clear relation between these two parameters.

Line 672: "the proposed parameter" -> "ϕFE"

Line 691-692: Fig. 13a and 13d show ϕFE, not Fig. 13b and 13c. Please check!

Figure 13:

- a) Add labels "z (m)" to all vertical axes.
- a) Add unit "(-)" to phase frequency effect on horizontal axis.
- b) Add unit "(-)" to phase frequency effect difference on horizontal axis.
- c) Make sure the legend does not mask the data!
- Caption: "difference", "Aug22" and Aug20" should not be set in italic.

Line 719-721: Please consider breaking down this confusing sentence into clear sentences.

Line 721-733: Please consider moving this part to (or merging this part with the corresponding part of) the introduction! There is no direct link with the section title "Comparison of the phase frequency effect and PJI ice and water content estimations".

Lines 733-738: These practical considerations do also not have any direct link to the section title but rather describe the research gap addressed by this study (move to introduction?).

Line 747-765: These are rather considerations regarding the inversion approach. Please consider discussion these inversion-related aspects in a separate subsection to help improving the clarity of the manuscript!

Line 760: "int" -> "in"

Line 766: Which particular observation in Figure 14 "evidences an over-estimation of the ice-content in the active layer through the PJI"? Please detail!

Line 787: "… due to changes in porosity such as fractures at depth…" As this manuscript does not present any data on fractures etc., this statement remains completely unsupported/speculative. Please check and eventually rephrase!

Figure 14:

- Upper panel: To which date does the resented phase frequency effect data correspond?
- Lower panels: The legends should not mask any of the data points
- Lower panels: What does the symbol size indicate?

Line 800: Empirical petrophysical models linking SIP response and ice content have been proposed earlier (e.g., Zorin and Ageev, 2017).

Line 815: As discussed in the respective general comment, I strongly suggest not to consider the error level observed in the electric circuit experiment as "the accuracy" but rather a lower bound of the error level to be expected in the field.

Line 828: "Cole-Cole" -> "Cole-Cole **model**"

Additional references

Zorin, N. and Ageev, D.: Electrical properties of two-component mixtures and their application to high-frequency IP exploration of permafrost, Near Surf Geophys, 15, 603 – 613, https://doi.org/10.3997/1873-0604.2017043, 2017.

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