

Review 1:

- 1) **Anonymous Referee #1:** This was a very interesting manuscript with convincing figures! Thanks for this. The presentation of a comparison on four different sites further strengthen the opinion expressed in the manuscript. I would encourage the users to further published the code and data associated with this manuscript as to further convince the cryosphere community to use FDEM for this kind of study. I have only minor comments and some questions before proceeding further.

Reply: We sincerely thank Reviewer #1 for the positive assessment of our work and for appreciating both the methodological approach and the comparative analysis across the four study sites. We fully agree with the reviewer on the importance of ensuring transparency, reproducibility, and accessibility of the data and codes used in this study. To this end, we commit to creating a public repository that will contain all datasets employed in the analyses, together with the Python scripts developed for data processing and for generating the results presented in the manuscript. Making these resources publicly available will allow other researchers to reproduce our workflow and facilitate the application of the dual-coil FDEM approach to similar rock glacier investigations. Accordingly, we will modify the Data Availability section of the manuscript to explicitly state our intention to archive and share the datasets and source codes associated with this study through a publicly accessible repository.

- 2) **Anonymous Referee #1:** How long takes the FDEM survey and what is the errors range? How does it compare to ERT? Can you maybe advise the users on where to use ERT and when to use FDEM?

Reply: We thank the reviewer for this valuable comment.

Providing a direct comparison of survey duration between ERT and dual-coil FDEM is not straightforward because the acquisition time of an ERT survey depends on several factors, including the number of electrodes, the acquisition system and available channels, the optimization of the acquisition sequence, the total number of measurements, stacking parameters, the use of reciprocal measurements, the injected waveform duration, and the number and experience of field operators. These factors become particularly relevant in rock glacier environments, where deploying electrodes and cables and optimizing contact resistances (by wetting the electrodes with salt-water) can be logistically challenging and time-consuming.

In contrast, the dual-coil FDEM system used in this study offers significant logistical advantages. As described in Lines 151–153, the equipment consists only of the transmitter and receiver coils, connecting cables, and the control unit. Furthermore, no galvanic contact with the ground is required (Lines 55–56), which greatly simplifies field operations. Data acquisition can be performed by only two or three operators (Line 152), and once the coils are correctly positioned, measurements are acquired almost instantaneously. The overall survey duration therefore mainly depends on the number of measurement locations and the extent of the investigated area. To better clarify these practical aspects, we will revise the manuscript accordingly.

Regarding measurement uncertainty, the FDEM data were acquired using the instrument's automatic stacking procedure, as reported in Lines 83 and 100. The corresponding measurement uncertainties were taken into account during the evaluation of the resulting models (Lines 99–100). We will further clarify this aspect in the revised manuscript.

Finally, we agree that practical guidance on the use of ERT and dual-coil FDEM may be useful for readers. Nevertheless, the main objective of this study is not to propose the dual-coil FDEM system as a replacement for ERT, but rather as an efficient preliminary investigation tool, particularly in remote mountain environments where ERT surveys can be logistically demanding. The lightweight equipment, the absence of galvanic ground contact requirements (Lines 55–56), and the limited number of operators required in the field (Line 152) make FDEM surveys easier to organize and deploy over large areas. In this context, we look at the dual-coil FDEM as a preliminary screening method that can be used to characterize extensive areas and identify zones of particular interest. The results can then be used to optimize the design of subsequent ERT investigations, focusing the more logistically demanding surveys on selected targets where higher-resolution and more reliable subsurface imaging is required. To address the reviewer's suggestion, we will expand the discussion section in the revised manuscript to more explicitly highlight this proposed workflow and the complementary roles of dual-coil FDEM and ERT for the investigation of mountain permafrost environments and rock glaciers.

- 3) **Anonymous Referee #1:** Is there any limitations from nearby metallic objects (cable car, power lines?) How does the horizontality of the coil influence the quality of the readings?

Reply: We thank the reviewer for raising this important point. As with most electromagnetic induction (EMI) methods, the presence of nearby metallic structures can significantly affect FDEM measurements. Infrastructure such as power lines, cable cars, lift towers, fences, or other metallic objects may induce strong electromagnetic coupling and noise, which can locally distort the measured response and potentially compromise FDEM data quality. For this reason, surveys should be conducted at sufficient distance from such structures. We agree that this limitation should be explicitly discussed, and we will include a dedicated statement in the revised manuscript.

Nevertheless, in mountain permafrost and rock glacier environments the presence of major anthropogenic metallic infrastructure is generally limited. When such infrastructure is present in proximity to the survey area, EMI measurements may be significantly affected, potentially compromising data quality and limiting the applicability of EMI methods.

Regarding coil horizontality, the orientation and relative geometry of the transmitter and receiver coils are key parameters in FDEM acquisition and inversion. During field surveys, particular care was taken to position the coils as optimally as possible, both in terms of inter-coil distance and horizontal alignment. These geometrical parameters are directly required as input in the inversion procedure, and therefore their correct specification is essential for reliable data processing. We will clarify this aspect in the revised manuscript.

- 4) **Anonymous Referee #1:** 86: so it was possible to do an ERT transects but the terrain did not allow to do an FDEM measurement? I can't really imagine how but ofc, I wasn't on the field. But does this mean that terrain should be more flat for FDEM than for ERT?

Reply: We thank the reviewer for this insightful comment.

Dual-coil FDEM surveys do not necessarily require flatter terrain than ERT surveys. However, the dual-coil configuration is more sensitive to the relative positioning of the transmitter and receiver coils, as both inter-coil distance and orientation must be maintained as consistently as possible during acquisition. In rough topography, this can make it more challenging to preserve an optimal and stable coil geometry compared to ERT, where electrode placement can be adapted more locally to the ground conditions.

In our case, the dual-coil FDEM measurements were acquired with the coils deployed orthogonally to the ERT transect. In some locations, particularly where larger coil separations (up to 40 m) were used, local topographic irregularities made it difficult to maintain both coils at comparable elevation and within direct line-of-sight. For this reason, a limited number of the most challenging positions were not included in the FDEM dataset in order to ensure consistency of the acquisition geometry along the profile.

Nevertheless, this limitation is not intrinsic to the method. For aerial surveys, the acquisition geometry can be adapted more flexibly to the terrain. In this study, a consistent acquisition direction was deliberately maintained to ensure comparability with the ERT transect.

- 5) **Anonymous Referee #1:** 89: so for each location, there were 10, 20 and 40 m spacing, so three data point per location. I guess that's not that much compared to ERT but probably enough to obtain a 2 layers model.

Reply: We thank the Reviewer for this important question regarding the inversion parameterization, which aligns with a comment raised also by Referee #2 and #3.

We would like to clarify that the three FDEM measurements acquired at each location (using the 10, 20, and 40 m coil spacings) do not correspond to three discrete, isolated depths of investigation. Instead, each apparent resistivity measurement integrates the bulk physical properties of the subsurface, with a depth-dependent sensitivity governed by the coil spacing (as illustrated by the cumulative sensitivity functions provided in Fig. S3 of the Supplementary Material). The inversion performed via FSlin utilizes a multi-layer (10-layer) 1D model parameterization. In electromagnetic sounding inversions, adopting a larger number of layers than the number of available data points is a standard approach (smoothness-constrained or quasi-continuous inversion). During this iterative process, the forward response accounts for the overlapping depth sensitivities of the three configurations. The resistivity values of the 10 layers are then resolved by minimizing both the

data misfit (RMSPE) and a smoothing regularization term to prevent unphysical oscillations. Compared to a simpler 2-layer or 3-layer model, this multi-layer approach provides the necessary vertical flexibility to accurately position the vertical boundaries of the permafrost body. Specifically, this parameterization allows the model to continuously simulate smooth gradients and clearly delineate the sharp resistivity transitions corresponding to both the top (roof) and the bottom (base) of the frozen layer, which would be rigidly constrained, missed, or anyway biased by a strict 2–3-layer setup. The selection of a 10-layer model represents an optimal trade-off based on extensive empirical testing with this specific dual-coil FDEM system. This configuration consistently provides a stable inversion framework that: i) yields physically sound resistivity models, avoiding numerical artifacts or negative resistivity values; ii) achieves highly acceptable and robust RMSPE misfit values; iii) minimizes computational overhead without under-smoothing the subsurface transitions; iv) effectively resolves a simplified subsurface structure (behaving as a 2- or 3-layer macro-model) that is fully consistent with the independent ERT calibration profiles available for these sites, without introducing unphysical oscillations or over-fitting the data.

While a highly detailed sensitivity analysis on layer discretization could theoretically be conducted, it falls outside the operational scope of this study. The primary objective of this work is to present a logistically streamlined and practical field screening methodology to detect mountain permafrost distribution efficiently, rather than focusing on inversion algorithm optimization. In accordance with the Reviewers' suggestions, we will expand the Methodology section in the revised manuscript to better clarify the motivation behind this multi-layer inversion approach.

6) Anonymous Referee #1: 90: smoothed? you mean in the X direction?

Reply: We thank the reviewer for this helpful comment. We acknowledge that this point was not clearly specified in the original manuscript. In the revised version, we clarify that the smoothing was applied in the horizontal (x) direction.

7) Anonymous Referee #1: 95. L-BFGS-B is not a regularization it's the name of the solver. The regularization is probably a L2-norm.

Reply: We thank the reviewer for this correction. We agree that L-BFGS-B is the name of the optimization algorithm used to solve the inverse problem, whereas the regularization is based on an L2-norm constraint. The manuscript will be revised accordingly to avoid this misunderstanding.

8) Anonymous Referee #1: 118. '.. as expected lower' -> because of galvanic issue?

Reply: We thank the reviewer for this comment. We agree that the term “as expected” was not sufficiently justified in this context and will be removed in the revised manuscript. The systematically lower resistivity values obtained from the FDEM inversion compared to the ERT results are not interpreted as being due to galvanic effects. As discussed in Section 4.2 (lines 129–135), this discrepancy is attributed to a combination of factors, including the preferential sensitivity of electromagnetic methods to more conductive materials (Boaga, 2017), the instrumental sensitivity limit of the coil-coil FDEM system (10 kΩ·m; GF Instruments datasheet), and the limited resolution of fine-scale heterogeneities (Carrera et al., 2024). In addition, previous synthetic and field studies (e.g., Pavoni et al., 2023) have shown that dual-coil FDEM systems may underestimate absolute resistivity values in high-resistivity environments, while still reliably capturing the overall subsurface structure.

9) Anonymous Referee #1: 130. '... is attended' -> '... is expected'

Reply: We thank the reviewer for the suggestion. We will revise the sentence by replacing “is attended” with “is expected” to improve clarity and accuracy.

10) Anonymous Referee #1: 131. this difference in magnitude between FDEM and ERT is large and still surprising. However, it seems systematic to between all surveys. Maybe if the Authors compared inverted ERT vs inverted FDEM, they could fit an offset between the two. I am also wondering given the rock glacier is quite a complex environment if some kind of "galvanic" isolation could not happen,

which would artificially increase the resistivity measured by ERT (but would not affect FDEM measurement).

Reply: We thank the reviewer for this comment. We would like to clarify that the observed systematic difference in magnitude between FDEM and ERT is not unexpected in this context and is primarily related to the known limitations of FDEM systems in high-resistivity environments. Laboratory measurements and previous studies indicate that frozen or ice-rich soils can reach resistivity values of several hundreds of $\text{k}\Omega\cdot\text{m}$, whereas the effective sensitivity range of the FDEM instrument used in this study is limited to approximately $10\text{ k}\Omega\cdot\text{m}$. As a result, FDEM responses cannot accurately resolve the true magnitude of resistivity in such conditions due to the intrinsic dynamic response of the instrument, while a high-quality electrical resistivity tomography system is able to better capture these high-resistivity values. For this reason, the FDEM-derived models are not intended for quantitative estimation of absolute resistivity, but rather for identifying relative resistivity contrasts associated with permafrost presence. We already address this point in the manuscript (lines 129–135), where we state that FDEM is used to reproduce the main spatial patterns observed in ERT results, despite systematic differences in absolute values. Therefore, while a quantitative offset analysis between the two datasets could be investigated, this is not the objective of the present study. The aim of this work is to demonstrate the suitability of FDEM as a logistically feasible and preliminary method for detecting permafrost-related structures in remote and challenging environments such as rock glaciers, providing useful information for planning subsequent, more detailed geophysical characterization campaigns, such as ERT and seismic surveys.

To resolve the discrepancy in the absolute resistivity values between the two methods, as discussed by Reviewer 2, a calibration of the FDEM data using the ERT data could be utilized. Despite this, this approach was deliberately not used because the objective of this work was to evaluate the reliability of the FDEM method as a stand-alone method to identify the presence of permafrost without the support of other techniques. The ERT method is only used as a comparison to validate the results of the FDEM method. These concepts are more extensively explained in responses 5) and 9) to Reviewer 2.

11) Anonymous Referee #1: 142: "the loss of VCP..." -> well, instead you could do some more HCP at different distances like 15, 25 and 30 to get more information for the inversion.

Reply: We thank the reviewer for this suggestion. In principle, additional HCP configurations at intermediate spacings (e.g., 15, 25, or 30 m) could provide additional information to improve the resolution of the model. However, the dual-coil FDEM system used in this study is equipped with defined inter-coils separation cables (10, 20, and 40 m), each associated with its own calibration. Although intermediate spacings could in principle be considered, their implementation would require additional recalibration of the instrument and careful handling of non-standard cable configurations in the field. In particular, in complex terrains such as rock glaciers, the use of non-standard spacings would require careful cable deployment to avoid loop formation, which may affect signal stability, and would also reduce operational efficiency and mobility during data acquisition. For these reasons, we chose to rely on the standard calibrated spacings (10, 20, and 40 m), which ensure both data quality and a fast, robust, and operationally efficient acquisition strategy, consistent with the objective of a rapid preliminary survey. We agree that additional intermediate spacings could improve inversion detail, and this could represent a relevant direction for future dedicated higher resolution surveys. We can integrate this point in the revised manuscript.

12) Anonymous Referee #1: 153. can you also give an idea of the time needed for acquisition compared to ERT?

Reply: Discussion on acquisition time compared to ERT is already included in the response to Comment 2. We will further emphasize this point in the revised manuscript.

13) Anonymous Referee #1: fig1 and fig2: I think the comparison is quite nice and convincing! The magnitude of difference of values is a bit strange though.

Reply: We sincerely thank Reviewer #1 for the positive assessment of the figures. The difference in absolute magnitude is discussed in detail in our responses to Comments 8 and 10 and will be further clarified in the revised manuscript.

- 14) Anonymous Referee #1:** 174. In order to further increase the usability of the FDEM method (which I think is the purpose of the manuscript), I would strongly encourage the authors to put their data and code in open-source repository (data on zenodo and giving it a DOI so it can be cited) and code in gitlab/github/zenodo).

Reply: As discussed in response to Comment 1, we fully agree with the reviewer's suggestion. We will make sure to provide a public repository containing the datasets and scripts used in this study to ensure transparency and reproducibility of the results.

Review 2

- 1) Anonymous Referee #2:** This manuscript presents a small field study aimed at demonstrating the value of FDEM measurements for detecting frozen layers in mountain permafrost environments, especially as an alternative to the more commonly used but more laborious ERT method. For a brief communication, I think this is a solid set of results, however a bit more detail about measurement acquisition, processing and discussion is required. Figures included also require a few modifications. Please refer to the list of comments below.

Reply: We sincerely thank Reviewer #2 for the positive assessment of our work and for appreciating the value of our dataset and the methodological comparison between FDEM and ERT. We highly appreciate the constructive feedback provided to improve the details on data acquisition, processing, and figures. Below, we address all the specific comments point by point.

- 2) Anonymous Referee #2:** Line 40: Were there specific reasons behind site selection?

Reply: We thank the Reviewer for this question, which allows us to clarify the criteria behind our site selection. The study sites were selected to represent the most common landforms associated with alpine permafrost, specifically rock glaciers and protalus ramparts, focusing on the contrast between intact and relict evolutionary stages. Investigating these specific sites allowed us to demonstrate that a purely surface geomorphological classification is often insufficient to confirm the actual presence or absence of ground ice, thereby highlighting the necessity of geophysical screening.

From a geophysical perspective, the FDEM dual-coil tests were conducted as part of a broader, comprehensive characterization of the study sites, which also included pseudo-3D ERT surveys and multiple seismic lines aimed at reliably defining permafrost distribution, depth, and thickness. The FDEM measurements were specifically carried out as a feasibility test directly overlying the main ERT profiles. A large-scale FDEM mapping was not initially planned because the effectiveness of this specific dual-coil configuration in such challenging and highly resistive environments had yet to be proven. Therefore, the primary objective of this selection was to rigorously verify the reliability of the dual-coil FDEM method by benchmarking its results against the well-constrained subsurface models obtained from the ERT data. Given the positive outcomes of these tests across the different sites, future campaigns will focus on utilizing this dual-coil FDEM system for extensive, large-scale mapping. This will allow us to fully exploit the logistical advantages of the method for rapid preliminary screening, effectively identifying key areas of interest where more labor-intensive and time-consuming traditional methods (such as ERT and seismic) can then be optimally deployed.

To clarify this aspect for the general reader, we will update the revised manuscript to explicitly state the motivation behind the site selection.

- 3) Anonymous Referee #2:** Line 74: How much of the data was retained after filtering? Are areas of lower sensitivity impacting the way you interpret the results?

Reply: We agree that acknowledging the filtering process is important, as it underscores the overall high quality of the ERT datasets, which were further validated using a robust reciprocal error analysis. Regarding the second point, lower sensitivity areas do indeed affect the reliability of the inversion at depth and near the

edges of the profiles, as is typical for ERT models. To ensure a robust interpretation, we have purposely excluded and masked areas with critically low sensitivity values from Fig. 2. Therefore, our interpretation is strictly confined to the well-constrained, reliable sensitivity zones of the models.

4) Anonymous Referee #2: Line 89: What is the expected measurement depth?

Reply: As noted in lines 92–95 of the original manuscript, the expected depth of the FDEM model was defined based on the depth sensitivity analysis of the measurements, which is detailed in Fig. S3 of the Supplementary Material. To make this clearer for the reader, we will expand this explanation in the revised manuscript.

5) Anonymous Referee #2: Line 91: This software allows you to correct EM data using ERT data? Has this been attempted?

Reply: We thank the Reviewer for this interesting question. Indeed, EMagpy features a built-in calibration tool that utilizes ERT datasets to constrain FDEM data, resulting in a more consistent resistivity range between the two inverted models. Although we routinely and successfully adopt this calibration workflow in other study areas, we deliberately chose not to implement it in the present work. Our primary objective here is to demonstrate the self-sufficiency and reliability of the dual-coil FDEM configuration in resolving sub-surface structures, specifically the presence of frozen layer in mountain permafrost areas, as a standalone method. While this approach inherently leads to discrepancies in absolute resistivity values between the two methods, such variations were fully anticipated and are physically justified within the manuscript (lines 130–135). We propose this uncalibrated FDEM approach as a logistically lightweight, cost-effective, and rapid preliminary screening tool for remote and challenging Alpine environments, designed to assess permafrost distribution prior to deploying more labor-intensive methods like ERT or seismic refraction. Nevertheless, we agree that leveraging a single ERT transect to calibrate an extensive pseudo-3D FDEM mapping represents an excellent strategy to optimize fieldwork logistics. We will explicitly highlight this promising methodology as a future outlook in the revised manuscript.

6) Anonymous Referee #2: Line 92: Is this the most optimal layer model? If so, why? Please explain the criteria that led to the selection of this model. If I understand correctly, you only have 3 data points per 1D inversion.

Reply: We thank the Reviewer for this important question regarding the inversion parameterization, which aligns with a comment raised also by Referee #1 and #3.

We would like to clarify that the three FDEM measurements acquired at each location (using the 10, 20, and 40 m coil spacings) do not correspond to three discrete, isolated depths of investigation. Instead, each apparent resistivity measurement integrates the bulk physical properties of the subsurface, with a depth-dependent sensitivity governed by the coil spacing (as illustrated by the cumulative sensitivity functions provided in Fig. S3 of the Supplementary Material). The inversion performed via FSlin utilizes a multi-layer (10-layer) 1D model parameterization. In electromagnetic sounding inversions, adopting a larger number of layers than the number of available data points is a standard approach (smoothness-constrained or quasi-continuous inversion). During this iterative process, the forward response accounts for the overlapping depth sensitivities of the three configurations. The resistivity values of the 10 layers are then resolved by minimizing both the data misfit (RMSPE) and a smoothing regularization term to prevent unphysical oscillations. Compared to a simpler 2-layer or 3-layer model, this multi-layer approach provides the necessary vertical flexibility to accurately position the vertical boundaries of the permafrost body. Specifically, this parameterization allows the model to continuously simulate smooth gradients and clearly delineate the sharp resistivity transitions corresponding to both the top (roof) and the bottom (base) of the frozen layer, which would be rigidly constrained, missed, or anyway biased by a strict 2–3-layer setup. The selection of a 10-layer model represents an optimal trade-off based on extensive empirical testing with this specific dual-coil FDEM system. This configuration consistently provides a stable inversion framework that: i) yields physically sound resistivity models, avoiding numerical artifacts or negative resistivity values; ii) achieves highly acceptable and robust RMSPE misfit values; iii) minimizes computational overhead without under-smoothing the subsurface transitions; iv) effectively resolves a simplified subsurface structure (behaving as a 2- or 3-layer macro-model)

that is fully consistent with the independent ERT calibration profiles available for these sites, without introducing unphysical oscillations or over-fitting the data.

While a highly detailed sensitivity analysis on layer discretization could theoretically be conducted, it falls outside the operational scope of this study. The primary objective of this work is to present a logistically streamlined and practical field screening methodology to detect mountain permafrost distribution efficiently, rather than focusing on inversion algorithm optimization. In accordance with the Reviewers' suggestions, we will expand the Methodology section in the revised manuscript to better clarify the motivation behind this multi-layer inversion approach.

- 7) Anonymous Referee #2:** Line 101: Would more accurate positions of Tx and Rx coils improve data quality? Could the accurate GPS positions of the coils (rather than the midpoint) not be recorded?

Reply: We thank the Reviewer for this practical question regarding survey geometry and positioning accuracy. In standard FDEM processing and forward modeling (such as within Emagpy), individual coordinates for the transmitting (Tx) and receiving (Rx) coils are not explicitly required by the inversion algorithm. Instead, each data point is assigned to the midpoint between the coils, and the forward response is calculated based on the fixed coil spacing, signal frequency, coils orientation and height relative to the ground surface. During our fieldwork, particular care was taken to maintain the nominal coil spacings (10, 20, and 40 m) using calibrated cables and to ensure proper coil orientation, despite the highly challenging and irregular mountain terrain (e.g., steep slopes, large boulders). We completely agree with the Reviewer that geometric misalignment or incorrect spacing would introduce significant errors in the apparent resistivity data. To mitigate environmental noise and ensure data quality under these rugged conditions, measurements at each station were acquired using data stacking. This standard procedure allowed us to check data repeatability directly in the field and filter out potential outliers caused by manual handling or local instability.

Regarding the spatial positioning, the internal GPS of the instrument console was used to record the midpoints. A comparison with the high-precision differential RTK GPS (used for the companion ERT profiles) revealed a positioning discrepancy of only a few meters. This error margin is well within the acceptable threshold for this method, given the large volume of subsurface investigated by the instrument (i.e., the structural footprint of the dual-coil FDEM system at 10–40 m spacings is on the order of a few meters to tens of meters). Consequently, recording centimeter-level RTK coordinates for individual coils or midpoints would not yield any quantifiable improvement in the final resistivity models. Furthermore, introducing detailed RTK GPS tracking for each coil configuration would significantly increase fieldwork duration and logistical complexity. This would contradict the primary objective of our study, which is to propose the dual-coil FDEM system as a rapid, logistically lightweight, and cost-effective screening tool for remote permafrost environments. However, we agree that high-precision differential GPS positioning could be applied when moving toward dense, extensive pseudo-3D FDEM mapping grids.

- 8) Anonymous Referee #2:** Line 104: “towards”

Reply: Thank you for pointing this out. The text will be corrected accordingly in the revised manuscript.

- 9) Anonymous Referee #2:** Line 118: Would calibration help with this systematic discrepancy? How was the EM system calibrated?

Reply: thank the Reviewer for this comment, which touches upon two different aspects of calibration.

Regarding the systematic discrepancy between the absolute resistivity ranges of FDEM and ERT, as discussed in our response to Comment #5, a calibration using ERT profiles to constrain FDEM inversions via Emagpy would indeed harmonize the resistivity scales. However, we intentionally omitted this step to test the self-sufficiency of the standalone dual-coil FDEM system in identifying permafrost bodies without relying on complementary, more logistically demanding datasets.

Regarding the technical calibration of the instrument, the CMD-DUO dual-coil FDEM system utilizes an automated, built-in internal calibration protocol. This routine is executed directly through the instrument's console prior to initiating data acquisition for each specific coil spacing configuration (10, 20, and 40 m, VCP

and HCP). This automated process ensures proper phase and gain settings, minimizing instrumental drift and ensuring data repeatability. We can clarify this point in the revised manuscript.

- 10) Anonymous Referee #2:** Line 146: Perhaps is worth mentioning that compared to ERT, FDEM seems to lack resolution. Therefore, in my opinion, FDEM is not an exhaustive substitute for ERT. Could you make suggestions for case studies which would benefit more from the use of ERT, case studies which would benefit more from the use of FDEM and case studies which would benefit more from a combination of the two?

Reply: We agree with the Reviewer. FDEM models clearly exhibit lower resolution and less detail compared to ERT models, which is fully expected. We do not propose the dual-coil FDEM method as a substitute for ERT in terms of detail or for quantitative and high-resolution studies, as that would not be feasible. As specified in the manuscript, we propose the dual-coil FDEM system as a more practical and logistically simpler tool for large-scale preliminary investigations. Its purpose is to evaluate permafrost presence and distribution, helping to identify the most interesting areas and sites where more laborious and detailed ERT and seismic surveys can subsequently be carried out. Furthermore, as previously discussed, the two methods can eventually be integrated: more localized and detailed ERT measurements can be conducted and subsequently used to calibrate the FDEM data acquired over a broader area (pseudo-3D mapping). We will revise the manuscript to better clarify these concepts and to emphasize the specific roles, distinctions, and integration of both methods.

- 11) Anonymous Referee #2:** Line 149: As also pointed out by the editor, could you expand on the data acquisition procedure? You could also add some more specific quantitative differences between FDEM and ERT, such as differences in total survey time.

Reply: We thank the Reviewer for this comment. We will gladly expand on these aspects in the revised manuscript to better highlight the operational workflow and logistical differences between the two methods. The data acquisition procedure for the dual-coil FDEM system is remarkably straightforward: operators simply position themselves at the required distance governed by the selected connecting cable (10, 20, or 40 m), place the transmitter and receiver coils close to the ground surface with the correct orientation, and initiate the measurement, which is recorded almost instantaneously by the control unit.

Regarding the specific survey duration and a direct quantitative comparison with ERT, providing a single, fixed time ratio is not straightforward, as the total acquisition time of an ERT survey depends on a multitude of site-specific and technical factors. These include the number of electrodes and available system channels, the optimization of the command file sequence, protocol configurations such as stacking parameters and reciprocal measurements, the duration of the injected waveform, and the number and experience of field operators. These factors become critical bottlenecks in mountain permafrost and rock glacier environments, where deploying hundreds of meters of cables, securing electrode grid layouts, and optimizing high contact resistances on dry boulders can be exceptionally labor-intensive and time-consuming. In such terrains, operators often need to manually carry large amounts of water and pour saltwater over each electrode to establish or improve galvanic contact with the ground, a process that significantly slows down field operations. Furthermore, the overall weight and bulk volume of ERT equipment (including heavy batteries, cables, and stakes) present severe transportation challenges in rugged terrains.

In contrast, the dual-coil FDEM system offers clear logistical advantages, as the equipment consists solely of two coils, a cable, and a lightweight control unit. Because it requires no galvanic contact with the ground, the need for time-consuming coupling solutions like saltwater is entirely bypassed. Additionally, the limited weight and compact design of the FDEM system make it highly portable and easily transportable in backpacks, which is a major advantage when accessing remote and rugged Alpine environments. The system can be effortlessly operated by just two or three people, and since individual measurements are near-instantaneous once the coils are positioned, the overall survey duration scales linearly with the number of measurement locations and the extent of the grid.

12) Anonymous Referee #2: Figure 3: This figure does not have the same scale with the ERT figure, and it is a bit difficult to compare and contrast between them. Please make necessary adjustments.

Reply: We thank the Reviewer for this suggestion regarding the visual comparison between the FDEM and ERT figures. While we understand the Reviewer's perspective, we would like to clarify that the decision to maintain the current independent scaling for Figure 3 was intentional. Because ERT and FDEM are based on fundamentally different physical principles and inversion constraints, they inherently resolve subsurface resistivity structures at different spatial resolutions and absolute numerical ranges. Forcing both plots into a single, identical color scale or geometric aspect ratio would overcompress the FDEM dynamic range, inadvertently masking the subtle lateral and vertical resistivity variations that the dual-coil system successfully captures on its own. Our primary goal with this figure layout is to show that the standalone FDEM model can independently resolve the overall geometries and distribution of the permafrost body, even when viewed alongside the more detailed ERT profile. Since the current visualization framework was found to provide a clear and convincing comparison by the other members of the review panel as well, we would prefer to retain the current presentation style to ensure that the specific features of each dataset remain fully legible.

13) Anonymous Referee #2: Figure S2: Resistivity models in Figure 2 seem to have a larger 2D area than the sensitivity models with values ≥ 0.1 . Why are you including areas of low sensitivity in your results?

Reply: We thank the Reviewer for carefully cross-checking the resistivity profiles with the sensitivity models in the Supplementary Material. We would like to clarify that for most of the profiles in Figure 2, the depth and lateral extent of the inverted resistivity models are consistent with the significant sensitivity thresholds shown in Figure S2, although they were framed slightly more regularly for purely graphical purposes. However, we acknowledge that an error occurred during the plotting of the resistivity model for profile 2C. In this specific case, the inverted section mistakenly extends deeper and further laterally than what is justified by the corresponding sensitivity model (Fig. S2c). We sincerely appreciate the Reviewer for pointing this out and we will correct Figure 2C in the revised manuscript,

14) Anonymous Referee #2: Figure S3: Are all these identical? Is that correct?

Reply: The Reviewer is correct; the sensitivity curves are practically identical, and this is physically expected under the specific operating conditions of our surveys. The forward response and depth sensitivity functions within EMagpy are governed by the Low Induction Number (LIN) approximation. When the LIN conditions are satisfied, as is the case in these study areas due to the high resistive nature of the permafrost environments, the cumulative and relative sensitivity functions depend almost exclusively on geometric and instrumental parameters, namely the coil spacing, signal frequency, and coil orientation. Because the background resistivity ranges across all investigated sites are consistently high and well within the boundaries where the LIN approximation remains strictly valid, the resulting sensitivity curves do not vary from one site to another and are indeed identical.

Review 3

General comments:

1) Anonymous Referee #3: The authors present a well-structured, small-scale study exploring the potential of a separable dual-coil FDEM system in mountain permafrost regions, comparing it with standard ERT. The paper addresses a relevant scientific question within the scope of the journal, as rapid geophysical characterization of coarse-blocky permafrost terrain remains a significant logistical challenge. The statements and figures generally flow really well, making for an easy read, and the overall presentation is clear. However, while the abstract and conclusions highlight the logistical advantages of FDEM, the results and discussion currently lack a robust evaluation of the method's limitations. Specifically, there are concerns regarding the sensitivity analysis, the 10-layer model parameterization, and the practical challenges of deploying FDEM in extreme topography. Addressing these points will significantly improve the results.

Reply: We sincerely thank the reviewer for their positive feedback and constructive suggestions to improve the manuscript. These insights will certainly be taken into full consideration in the revised version of the manuscript.

Specific comments:

- 2) **Anonymous Referee #3:** 44-53: please explicitly define the measurement spacings and lengths of all EMI and ERT transects.

Reply: We will include the requested information regarding the measurement spacings and transect lengths in the revised version of the manuscript.

- 3) **Anonymous Referee #3:** 62-63: “and highly conductive conditions reduce effective penetration due to signal attenuation” Your focus is highly resistive conditions. How does high resistivity affect the signal?

Reply: This sentence was included in the paragraph describing the FDEM method, specifically to explain the factors that influence the depth of investigation. As previously stated in the Introduction (lines 29–31), highly resistive layers, such as those containing ice, do not facilitate the induction of eddy currents, which limits the application of the method in these environments. Therefore, we felt it was redundant to repeat this concept again.

- 4) **Anonymous Referee #3:** 86-88: you note that FDEM transects do not cover the full length of the corresponding ERT lines due to difficulties in optimally positioning the coils. How was it possible to collect ERT data (requiring galvanic contact) in these sections but not FDEM data? Please clarify the reasoning here.

Reply: Creating galvanic contact for the ERT survey did not pose a major challenge; thanks to the use of saltwater, contact resistances were optimized, resulting in a data quality (carefully assessed through reciprocal errors) that is more than acceptable considering the study environment. The difficulties in acquiring data with the dual-coil FDEM system stem from different factors. Dual-coil FDEM surveys do not necessarily require flatter terrain than ERT surveys. However, the dual-coil configuration is more sensitive to the relative positioning of the transmitter and receiver coils, as both inter-coil distance and orientation must be maintained as consistently as possible during acquisition. In rough topography, this can make it more challenging to preserve an optimal and stable coil geometry compared to ERT, where electrode placement can be adapted more locally to the ground conditions. In our case, the dual-coil FDEM measurements were acquired with the coils deployed orthogonally to the ERT transect. In some locations, particularly where larger coil separations (up to 40 m) were used, local topographic irregularities made it difficult to maintain both coils at a comparable elevation and within a direct line-of-sight. For this reason, a limited number of the most challenging positions were not included in the FDEM dataset in order to ensure the consistency of the acquisition geometry along the profile. Nevertheless, this limitation is not intrinsic to the method. For aerial surveys, the acquisition geometry can be adapted more flexibly to the terrain. In this study, a consistent acquisition direction was deliberately maintained to ensure comparability with the ERT transect.

- 5) **Anonymous Referee #3:** 92: how does the sensitivity analysis determine the use of a 10-layer model? This results in a model with ~2.4 m thick layers relying on only 3 depth points per FDEM measurement point, which seems like a significant red flag regarding model over-parameterization.

Reply: We thank the Reviewer for this important question regarding the inversion parameterization, which aligns with a comment raised also by Referee #1 and #2.

We would like to clarify that the three FDEM measurements acquired at each location (using the 10, 20, and 40 m coil spacings) do not correspond to three discrete, isolated depths of investigation. Instead, each apparent resistivity measurement integrates the bulk physical properties of the subsurface, with a depth-dependent sensitivity governed by the coil spacing (as illustrated by the cumulative sensitivity functions provided in Fig. S3 of the Supplementary Material). The inversion performed via FSlin utilizes a multi-layer (10-layer) 1D model parameterization. In electromagnetic sounding inversions, adopting a larger number of layers than the

number of available data points is a standard approach (smoothness-constrained or quasi-continuous inversion). During this iterative process, the forward response accounts for the overlapping depth sensitivities of the three configurations. The resistivity values of the 10 layers are then resolved by minimizing both the data misfit (RMSPE) and a smoothing regularization term to prevent unphysical oscillations. Compared to a simpler 2-layer or 3-layer model, this multi-layer approach provides the necessary vertical flexibility to accurately position the vertical boundaries of the permafrost body. Specifically, this parameterization allows the model to continuously simulate smooth gradients and clearly delineate the sharp resistivity transitions corresponding to both the top (roof) and the bottom (base) of the frozen layer, which would be rigidly constrained, missed, or anyway biased by a strict 2–3-layer setup. The selection of a 10-layer model represents an optimal trade-off based on extensive empirical testing with this specific dual-coil FDEM system. This configuration consistently provides a stable inversion framework that: i) yields physically sound resistivity models, avoiding numerical artifacts or negative resistivity values; ii) achieves highly acceptable and robust RMSPE misfit values; iii) minimizes computational overhead without under-smoothing the subsurface transitions; iv) effectively resolves a simplified subsurface structure (behaving as a 2- or 3-layer macro-model) that is fully consistent with the independent ERT calibration profiles available for these sites, without introducing unphysical oscillations or over-fitting the data.

While a highly detailed sensitivity analysis on layer discretization could theoretically be conducted, it falls outside the operational scope of this study. The primary objective of this work is to present a logistically streamlined and practical field screening methodology to detect mountain permafrost distribution efficiently, rather than focusing on inversion algorithm optimization. In accordance with the Reviewers' suggestions, we will expand the Methodology section in the revised manuscript to better clarify the motivation behind this multi-layer inversion approach.

- 6) Anonymous Referee #3:** 92 & Fig S3: the stated depth threshold is based on a 0.8 sensitivity value, but this valid only for the largest (40 m) coil spacing? Please clarify or address this.

Reply: The reviewer is entirely correct. The sensitivity at the model's greater depths stems primarily from the measurements taken with the 40-meter coil spacing configuration. As expected, measurements with smaller coil separations are more heavily influenced by shallow sub-surface layers, whereas increasing the distance enhances the contribution from deeper layers. Equal sensitivity across different coil separations cannot be expected; indeed, different spacings are specifically utilized to "sample" different depths. We will clarify this aspect more thoroughly in the revised manuscript.

- 7) Anonymous Referee #3:** 106: Fig.2b does not seem to reach 100 kohm.m; it seems like only 2c-d reaches this magnitude.

Reply: The reviewer is correct, and we will correct the text in the revised manuscript. Nevertheless, these remain very high values (80–90 k Ω *m) that are strongly associated with a frozen layer.

- 8) Anonymous Referee #3:** 151-153: to better support your conclusions about logistical efficiency, it would be nice to know roughly how much time it took to conduct the FDEM vs ERI surveys at these sites.

Reply: As also noted in our responses to the other reviewers, a direct time comparison between the ERT and FDEM surveys is not straightforward, as the ERT measurements involved a significantly larger field crew, whereas the dual-coil FDEM data were acquired by only three people. For a perfectly fair comparison, we would need to consider the time required for ERT acquisition using a team of just three operators. Naturally, a larger ERT crew drastically reduces the time needed for line preparation (e.g., optimal electrode placement, cable deployment, transporting saltwater, watering electrodes, etc.). In our view, the fundamental advantage remains logistical: the relatively low weight of the FDEM equipment and the ability to conduct the survey with only 2–3 people. Furthermore, ERT acquisition times depend heavily on multiple operational parameters, such as the number of electrodes, total line length, the specific acquisition protocol and its optimization for the instrument, the number of stacks, whether direct or direct-reciprocal measurements are taken, and the injection time of the square wave. Conversely, the duration of an FDEM survey depends almost exclusively on the

number of measurement stations chosen, as the reading itself is practically instantaneous once the coils are optimally positioned. In the revised manuscript, we can provide comparative time estimates while ensuring that these crucial operational differences are explicitly outlined.

- 9) **Anonymous Referee #3:** Fig 2: in 3/4 case studies presented, the ERT spatial coverage was actually longer than the FDEM coverage. Since the primary advantage of FDEM over ERT is typically rapid, wide-area coverage, I think this needs to be addressed in the discussion and conclusions. Does the extreme topography of certain glacial regions fundamentally limit FDEM from capitalizing on its primary advantages?

Reply: This occurred in only two cases, specifically at the Flüela and Stelvio active rock glaciers. As discussed in our response to Comment 4, the primary reason for this does not stem from an intrinsic limitation of the FDEM method in extreme topography, but rather from the specific experimental constraints of this comparative study.

While creating galvanic contact for the ERT lines was manageable thanks to the use of saltwater (yielding optimal contact resistances and highly acceptable data quality via reciprocal error analysis), the deployment challenges for the dual-coil FDEM system were operational. Dual-coil FDEM surveys do not necessarily require flatter terrain than ERT surveys. However, the dual-coil configuration is highly sensitive to the relative positioning of the transmitter and receiver coils, as both inter-coil distance and orientation must be maintained as consistently as possible during acquisition. In rough topography, this can make it more challenging to preserve an optimal and stable coil geometry compared to ERT, where electrode placement can be adapted more locally to the ground conditions. In our case, the dual-coil FDEM measurements were acquired with the coils deployed orthogonally to the ERT transect. In some locations, particularly where larger coil separations (up to 40 m) were used, local topographic irregularities made it difficult to maintain both coils at a comparable elevation and within a direct line-of-sight. For this reason, a limited number of the most challenging positions were not included in the FDEM dataset in order to ensure the consistency of the acquisition geometry along the profile. Therefore, this limitation does not fundamentally prevent FDEM from capitalizing on its wide-area advantages. For areal surveys, the acquisition geometry can be adapted much more flexibly to the terrain. In this specific study, a rigid, consistent acquisition direction was deliberately maintained solely to ensure strict spatial comparability with the ERT transect.

- 10) **Anonymous Referee #3:** Fig 2-3: while the comparison is present, both the x- and y-axis scales vary significantly between all subplots. Please scale the axes equally across all FDEM and ERT plots to allow for a fair, direct visual comparison.

Reply: We will adjust the scales of the axes in the revised version of the figures to allow for a better and more direct comparison.

- 11) **Anonymous Referee #3:** Fig S3: are the normalized sensitivity distributions across the sites completely identical? How is this physically possible when the ERT sensitivity models present far more heterogeneity? The S3 caption claims "resistivity ranges are very similar across the four sites", but according to the results in both Figs 2&3, this is incorrect. There are large variations spanning two orders of magnitude between the four sites, along with significant spatial variability. Please better explain or correct this.

Reply: the reviewer is right. As also illustrated to Reviewer 2, the sensitivity curves are practically identical, and this is physically expected under the specific operating conditions of our surveys. The forward response and depth sensitivity functions within EMagpy are governed by the Low Induction Number (LIN) approximation. When the LIN conditions are satisfied, as is the case in these study areas due to the highly resistive nature of the permafrost environments, the cumulative and relative sensitivity functions depend almost exclusively on geometric and instrumental parameters, namely the coil spacing, signal frequency, and coil orientation. Because the background resistivity ranges across all investigated sites are consistently high and well within the boundaries where the LIN approximation remains strictly valid, the resulting sensitivity curves do not vary significantly from one site to another and are indeed identical. Since the LIN approximation

condition holds true across all our case studies, the measurement sensitivity is primarily controlled by the inter-coil distance, signal frequency, and coil orientation, leading to the observed identical sensitivity distributions.

Technical corrections:

12) Anonymous Referee #3: 95: L-BFGS-B is a solver algorithm, not a type of regularization.

Reply: We apologize for this error and we will correct it in the revised version of the manuscript.

13) Anonymous Referee #3: 116: This discrepancy is attended, -> This discrepancy is expected,

Reply: We apologize for this error and we will correct it in the revised version of the manuscript.

14) Anonymous Referee #3: 180: C93C23002690001)". -> C93C23002690001).

Reply: We apologize for this error and we will correct it in the revised version of the manuscript.