

Brief communication: On the potential of dual-coil frequency-domain electromagnetic (FDEM) systems to detect frozen layers in mountain permafrost environments

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Abstract. Frequency Domain Electromagnetic (FDEM) methods are still rarely applied in mountain permafrost environments, such as rock glaciers. Here, we test a separable dual-coil FDEM system at four alpine permafrost sites and compare the results with Electrical Resistivity Tomography (ERT), the most commonly used geophysical method applied in these environments. The comparison shows that FDEM can reproduce key subsurface features identified by ERT and highlights the potential of separable dual-coil FDEM systems for a straightforward, preliminary, first-order assessment of subsurface structures in mountain permafrost environments.

1 Introduction

Rock glaciers are widespread landforms in Alpine regions and can be used as proxies for the presence of mountain permafrost. Their internal structure is typically highly complex and heterogeneous, consisting of varying proportions of ice, liquid water, coarse blocks and debris, finer sediments, and air-filled voids, which challenges subsurface characterization (Phillips et al., 2023). Geophysical methods are commonly used to investigate the internal structure of rock glaciers in a non-invasive manner. Among these, Electrical Resistivity Tomography (ERT) is the most widely employed technique due to its sensitivity to frozen ground and ice-rich layers (Herring and Lewkowicz, 2022). However, ERT surveys in rock glacier environments are often logistically demanding, time-consuming, and prone to issues with electrode-ground galvanic contact, particularly in coarse-blocky terrains (Pavoni et al., 2022). These limitations motivate the exploration of alternative geophysical methods that are better suited for rapid and preliminary subsurface mapping and characterization.

The Frequency Domain Electromagnetic (FDEM) technique is commonly used in near-surface geophysics to easily and rapidly map subsurface electrical properties without requiring galvanic contact with the ground surface (Boaga, 2017). However, its application in mountain permafrost environments remains limited due to specific methodological uncertainties and challenges, first and foremost the difficulty in inducing secondary eddy currents in highly resistive layers (i.e., frozen ground and dry rock) (Hauck & Kneisel, 2008). Recently, FDEM has been applied by Boaga et al. (2020) and Pavoni et al. (2021) to estimate the active layer thickness of rock glaciers, and by Pavoni et al. (2023) to investigate the internal structure of the Calderone glacieret, although strong limitations in the quantitative characterization of the electrical resistivity of the frozen subsurface remain.

This study investigates the applicability of a separable dual-coil FDEM system across four Alpine sites characterized by distinct permafrost-related landforms, aiming to assess its potential for reconstructing subsurface structures. The FDEM results were compared with ERT profiles acquired at the same locations. The findings demonstrate the effectiveness of the dual-coil

38 FDEM system as a reliable and logistically efficient tool for preliminary subsurface investigations and for detecting frozen
39 layers in mountain permafrost environments, while highlighting its perspectives and current limitations.

40 **2 Sites description**

41 The FDEM dual-coil method was evaluated across four sites near Flüela Pass (Grisons, Switzerland) and Stelvio Pass (Central
42 Alps, Italy), selected to represent contrasting evolutionary stages of Alpine permafrost landforms. At Flüela Pass, the active
43 rock glacier features heterogeneous metamorphic blocks and debris (mainly amphibolite and paragneiss) with patches of fine
44 sediments. In its central area (previously surveyed by Boaga et al., 2023 and Bast et al., 2024), we acquired a 94 m ERT profile
45 (48 electrodes at 2 m spacing) and a co-located 50 m FDEM transect with 10 sampling points (Fig. 1a). At Stelvio Pass, the
46 active rock glacier comprises metamorphic blocks (ortho and paragneiss) and scree deposits overlying subordinate ablation
47 till, with previous studies suggesting a massive ice core (Etzelmüller et al., 2020). Here, ERT (48 electrodes at 5 m spacing)
48 was paired with 16 FDEM stations spaced along a 140 m line (Fig. 1b). Nearby, on a south-facing slope at Le Rese di Scorluzzo,
49 an inactive rock glacier and an adjacent inactive protalus rampart were surveyed (Guglielmin and Tellini, 1992). ERT lines
50 (48 electrodes at 3 m spacing) were matched with FDEM measurement points at 6 m intervals (Figs. 1c–d).

51 **3 Method: Frequency Domain Electromagnetic (FDEM)**

52 The FDEM technique, based on Maxwell’s electromagnetic induction equations, allows the estimation of subsurface electrical
53 resistivity without direct galvanic contact with the ground. FDEM systems consist of a transmitter coil that generates a time-
54 varying magnetic field, inducing eddy currents in the subsurface which, in turn, produce a secondary magnetic field recorded
55 by a receiver coil. Under the low-induction-number (LIN) approximation, the quadrature component of the secondary-to-
56 primary magnetic field ratio is directly proportional to apparent conductivity (McNeill, 1980), where investigation depth and
57 spatial resolution depend primarily on coil separation, orientation, and operating frequency. Lower frequencies and larger coil
58 spacings increase sensitivity to deeper structures, whereas higher frequencies and shorter spacings enhance near-surface
59 resolution. Furthermore, horizontal coplanar (HCP, coils parallel to the ground surface) and vertical coplanar (VCP, coils
60 orthogonal to the ground surface) configurations sample distinct depth ranges (Pavoni et al., 2023). Operationally, since
61 galvanic coupling is not required, once the coils are set at the optimal spacing and orientation, FDEM measurements can be
62 acquired near-instantaneously at each station, enabling efficient coverage of extensive areas or challenging terrains without
63 laying out cables or planting electrodes. Finally, apparent resistivity datasets are inverted into 1D vertical resistivity profiles
64 by iteratively adjusting the model until calculated responses match observed data within an acceptable error threshold (Wagner
65 and Uhlemann, 2022).

66 **4 Data acquisition and processing**

67 Electrical Resistivity Tomography (ERT) surveys were carried out using a Syscal-Pro (Iris Instruments) resistivity meter. 1,250
68 quadrupoles were acquired using a hybrid acquisition scheme combining dipole–dipole and multi-gradient multi-skip arrays
69 (Pavoni et al., 2025). Measurements were stacked three times, and all quadrupoles were acquired in direct and reciprocal
70 configuration for reliable data quality assessment (Binley and Slater, 2022). In the blocky rock glaciers of Flüela Pass and
71 Stelvio Pass, textile electrodes (Bast et al., 2025) and steel-net electrodes (Pavoni et al., 2025), wetted with salt water, were
72 used. In the Le Rese di Scorluzzo sites, characterized by finer-grained surface sediments, traditional steel-spike electrodes
73 were used. A dataset-specific filtering procedure was applied to each ERT survey. Quadrupoles with stacking and/or reciprocal
74 errors above 5% were removed, and the same value was used as the expected data error in the inversion process. Inversion
75 modelling was performed using the open-source Python software ResIPy (Blanchy et al., 2020). All models reached a final

76 RMS misfit close to 1 in a few iterations, indicating a good fit between observed and calculated apparent resistivities. Model
 77 sensitivity was used to define the lateral and vertical limits of the presented resistivity models, with low-sensitivity areas
 78 indicating portions of the model mainly constrained by regularization rather than by data (Fig. S2 in Supplementary Materials).
 79 FDEM measurements were collected with a CMD-DUO system (GF Instruments, 925 Hz) at three standard coil spacings (10,
 80 20, and 40 m), using a thin (3 mm) connection cable specific to each distance. At each location, measurements were acquired
 81 manually and instantaneously once the coils were correctly positioned at the required spacing, orientation, and elevation for
 82 the selected configuration (e.g., as shown in Fig. S1 of the Supplementary Materials for the 40 m coil spacing in HCP
 83 orientation), with the connecting cable oriented orthogonally to the direction of the ERT line. Data were collected using the
 84 HCP configuration along the entire length of each FDEM transect (see Fig. 1), whereas the VCP configuration was only tested
 85 at selected points. Measurement errors were evaluated through signal stacking, and the position of each point was approximated
 86 as the midpoint between the two coils, corresponding to the location of the data logger with its integrated GPS (e.g., Fig. S1).
 87 However, for the profiles acquired on the rock glaciers at Flüela Pass, Stelvio Pass, and Le Rese di Scorluzzo (Figs. 1a–1c),
 88 the FDEM transects do not cover the full length of the corresponding ERT lines. This limitation stemmed from the challenge
 89 of maintaining proper coil spacing, elevation, and alignment across highly irregular topography and steep slopes, issues that
 90 could have been mitigated had the survey not been constrained to strictly follow the ERT line geometries.
 91 For each site and HCP configuration (10, 20, and 40 m coil spacings), the raw FDEM apparent resistivity data were smoothed
 92 using a one-dimensional horizontal Gaussian filter ($\sigma = 2$) to reduce high-frequency noise while preserving the main lateral
 93 variations. The inversion modelling was performed using the open-source Python software EMagPy (McLachlan et al., 2021),
 94 employing a 10-layer model of regular thickness extending to 24 m depth. This 10-layer model parameterization represents an
 95 optimal trade-off in the inversion framework: despite the limited number of discrete coils spacings, smoothness-constrained
 96 inversion provides the necessary vertical flexibility to simulate smooth gradients, accurately delineate sharp resistivity
 97 transitions and prevent unphysical numerical oscillations. The bottom of the model was defined based on the sensitivity
 98 analysis of the surveys (Fig. S3 in Supplementary Materials). While a sensitivity threshold of 70% is commonly adopted for
 99 the largest coil spacing (van't Veen et al., 2022), a higher value of 80% was used in this study due to the challenging field
 100 conditions and the high-resistivity subsurface, which limit the induction of secondary eddy currents. A linearized inversion
 101 with L2-norm regularization, solved using the L-BFGS-B algorithm, was employed to iteratively update the model and
 102 minimize the misfit between observed and predicted apparent resistivities. The optimal regularization parameter was defined
 103 using the L-curve method, and the quality of the final model was evaluated using the Root Mean Square Percentage Error
 104 (RMSPE). Although RMSPE values below 5% are generally considered acceptable, in this study a threshold of 10% was
 105 adopted to account for the high-resistivity environment, measurement stacking errors (approx. 10%), and the practical
 106 difficulties in optimally positioning the coils over complex topography and rough surfaces.

107 **6 Results**

108 Figure 2 shows the ERT resistivity models for the survey sites. At the active Flüela rock glacier (Fig. 2a; 1035 quadrupoles
 109 retained after filtering out of 1250 total), a shallow high-resistivity layer ($\sim 60\text{--}80\text{ k}\Omega\cdot\text{m}$, $\sim 5\text{ m}$ depth) extends from the upper
 110 (southern) section toward the frontal zone (north), with a thickness of $\sim 10\text{ m}$ that gradually thins toward the front and shows
 111 a discontinuity at $\sim 45\text{ m}$ along the profile. A comparable structure occurs at the active Stelvio Pass rock glacier (Fig. 2b; 870
 112 retained quadrupoles), where the high-resistivity layer shows higher values ($80\text{--}100\text{ k}\Omega\cdot\text{m}$) and greater thickness ($15\text{--}30\text{ m}$).
 113 In both cases, the morphology and high-resistivity layer indicate ice-bearing permafrost.
 114 At the Le Rese di Scorluzzo sites, despite surface morphology and vegetation suggesting the possible absence of permafrost,
 115 ERT resistivity models reveal high-resistivity layers characteristic of a frozen subsurface. In the inactive rock glacier model
 116 (Fig. 2c; 790 retained quadrupoles), the top of the high-resistivity layer lies very close to the surface, making it difficult to

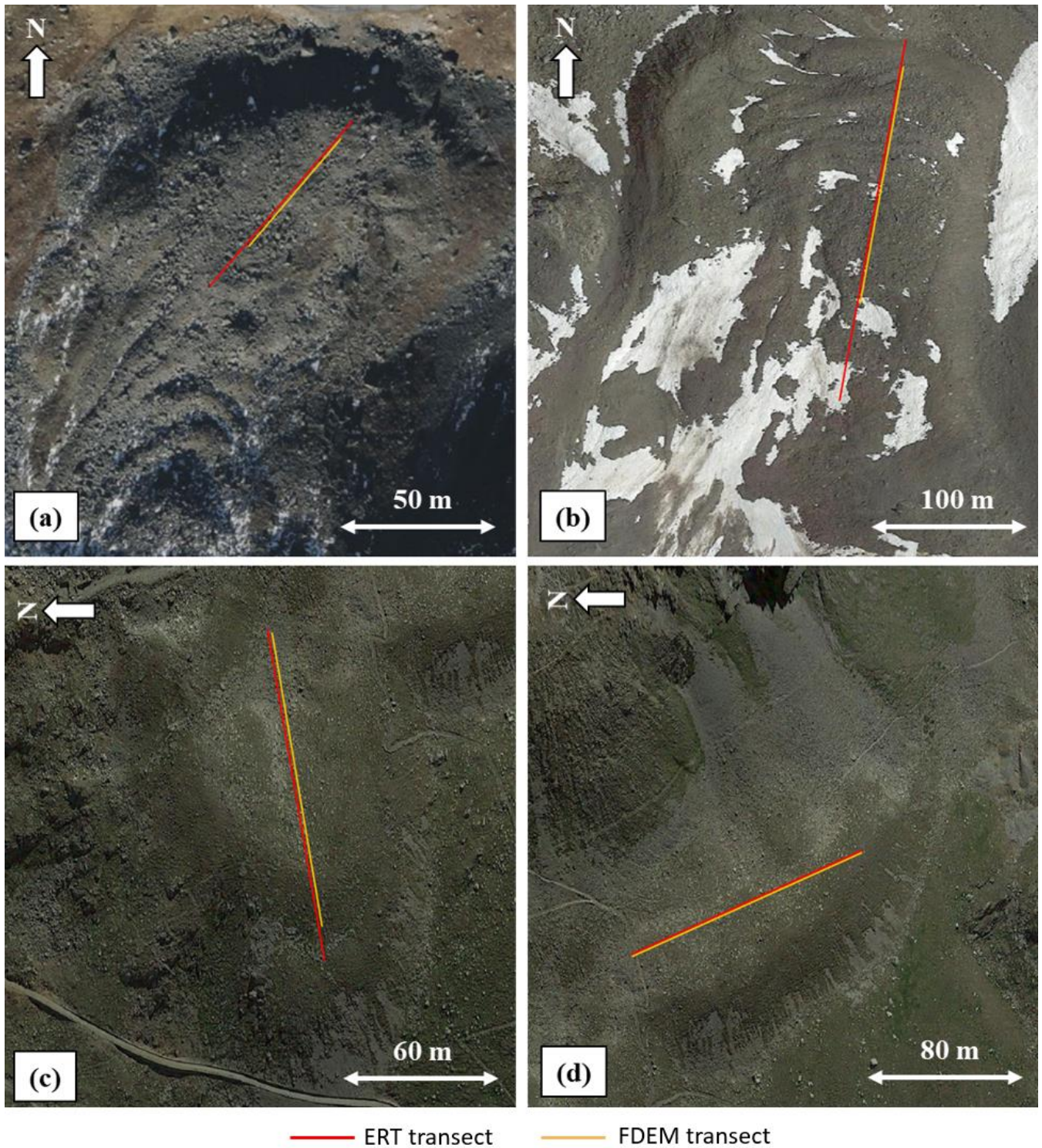
distinguish from overlying air-filled material, whereas its boundary with underlying low-resistivity unfrozen sediment is distinct. In the inactive protalus rampart (Fig. 2d; 995 retained quadrupoles), a discontinuous high-resistivity layer is detected at 5–10 m depth in the central area, likely representing a frozen layer. Figure 3 shows the FDEM inversion results. The pseudo-2D models were generated by kriging 1D vertical resistivity profiles inverted at each measurement station (orange circles, Figs. 2 and 3). Across all sites, FDEM models reproduce the main ERT resistivity patterns, although absolute resistivity values are, as expected, systematically lower. At the active Flüela Pass and Stelvio Pass rock glaciers (Figs. 3a–b), a more resistive layer ($\sim 500\text{--}1000\ \Omega\cdot\text{m}$) is clearly bounded between two less resistive layers ($\sim 100\text{--}300\ \Omega\cdot\text{m}$) and, as in the ERT models, thins and disappears toward the front. At Flüela Pass, the same $\sim 45\text{--}50\text{ m}$ discontinuity detected in the ERT model is evident. Similarly, at Le Rese di Scorzuzzo (Figs. 3c–d), FDEM-derived structures closely mirror ERT results, indicating high-resistivity layers and suggesting a discontinuous frozen layer at both sites.

7 Discussion and conclusions

The results demonstrate that a separable dual-coil FDEM system (925 kHz signal frequency, 10–40 m coil spacings, HCP orientation) can reconstruct reliable subsurface structures in mountain permafrost environments. FDEM-derived resistivity models consistently reproduce the main ERT patterns despite systematically lower absolute resistivity values and spatial resolution. This discrepancy is reasonable considering preferential electromagnetic propagation in conductive media (Boaga, 2017), the device's $10\ \text{k}\Omega\cdot\text{m}$ instrumental sensitivity limit (Gf-instrument datasheet), limited spatial resolution for fine heterogeneities (Carrera et al., 2024), and synthetic modelling constraints. In this context, Pavoni et al. (2023) demonstrated that while the separable dual-coil FDEM system has limited ability to resolve correct absolute resistivity values in highly resistive frozen layers, it accurately captures the overall subsurface structure.

VCP measurements yielded poor results, characterized by anomalous responses including high stacking errors ($>100\%$), apparent resistivities up to an order of magnitude lower than HCP values, and strongly negative in-phase values. These effects relate to poor signal quality: primary field orientation in VCP is less favourable for subsurface penetration than in HCP, where primary fields couple more efficiently with the ground to induce eddy currents. Pavoni et al. (2021) reported similar VCP limitations in rock glacier active-layer FDEM investigations. Excluding VCP reduces vertical apparent resistivity measurements per station, decreasing the vertical resolution. However, given the poor data quality and the doubled acquisition time, acquiring VCP data is not justified. Instead, survey efficiency and lateral resolution can be improved by focusing exclusively on HCP and increasing spatial density. Although intermediate coil spacings could theoretically enhance vertical resolution in inversion models, standard cables (10, 20, and 40 m) ensure operational robustness on complex rock glacier terrain. Furthermore, while continuous FDEM acquisition (e.g., automated sampling every second) would accelerate data collection and increase lateral sampling density, irregular surfaces and complex topography prevent stable antenna positioning while the operators are walking. Consequently, station-to-station manual HCP measurements (static) represent the most practical and robust strategy, provided that precise measurement geometry is maintained through proper coil positioning. In our surveys, severe topography and strict adherence to the ERT transect direction constrained antenna placement in certain positions; however, this limitation is not intrinsic to the method and can be avoided in unconstrained mapping.

Logistically, the low weight of the dual-coil FDEM system ($\sim 5\text{ kg}$ per antenna, $\sim 1\text{ kg}$ data logger, $\sim 5\text{ kg}$ cables) enables deployment by small teams (2–3 operators) without the substantial physical and logistical effort required for ERT. Future work aims to leverage single ERT transects to calibrate extensive pseudo-3D FDEM mapping (McLachlan et al., 2021), optimizing logistics for large-scale permafrost characterization and yielding a more consistent resistivity range between inverted models. Overall, given the minimal transport and acquisition effort, along with straightforward processing and interpretation, the dual-coil FDEM system is a highly promising tool for preliminary investigations in remote areas and large-scale mountain permafrost mapping, efficiently identifying optimal sites for subsequent, more laborious ERT and seismic surveys.



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159 Figure 1. Satellite images of the study sites (Background imagery from Google Satellite; accessed via QuickMapServices in QGIS;
 160 Imagery © Google; map data © Google) showing the ERT (red lines) and FDEM (orange lines) survey profiles. (a) Active rock
 161 glacier at Flüela Pass (Switzerland; 46.746° N, 9.951° E). (b) Active rock glacier at Stelvio Pass (Italy; 46.527° N, 10.441° E). (c) Le
 162 Rese di Scorluzzo inactive rock glacier at Stelvio Pass (Italy; 46.531° N, 10.420° E). (d) Le Rese di Scorluzzo inactive protalus rampart
 163 at Stelvio Pass (Italy; 46.530° N, 10.421° E).

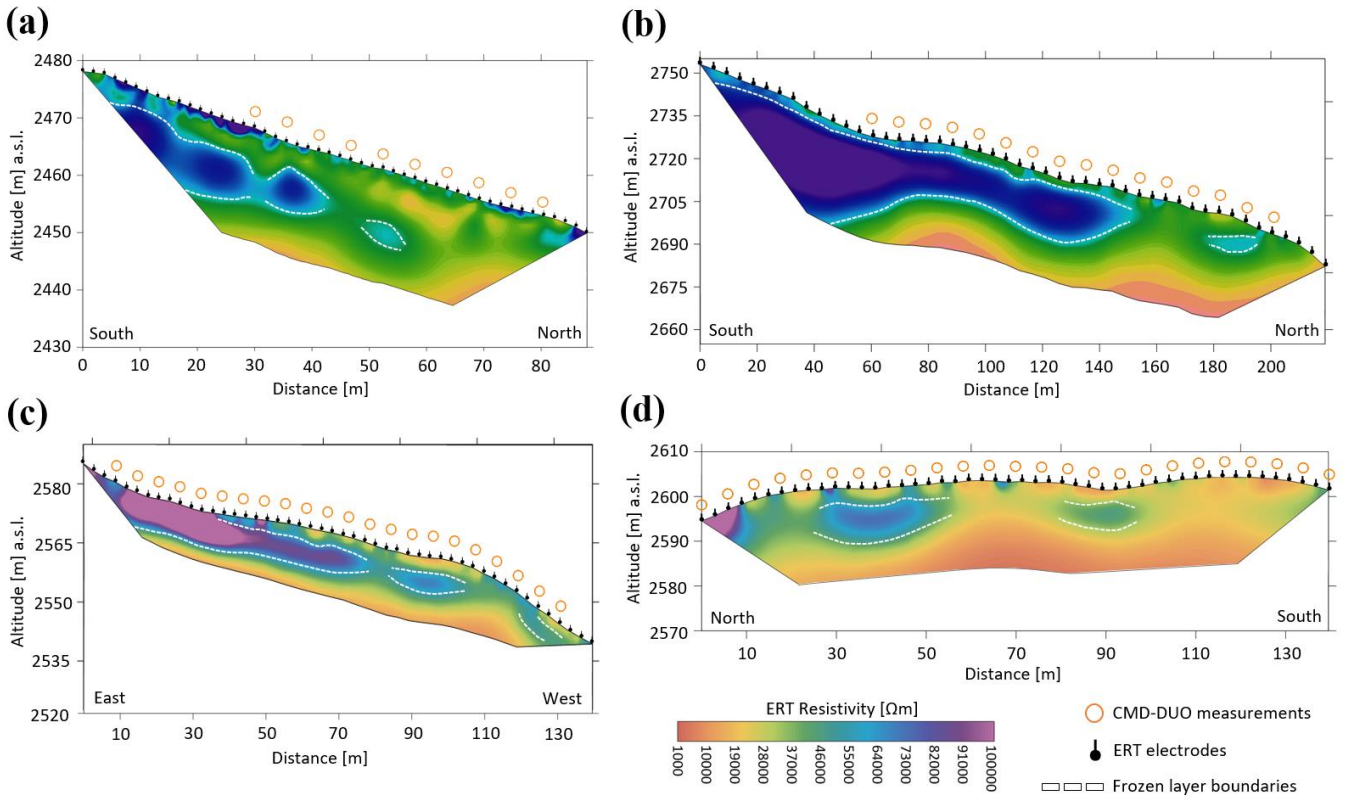


Figure 2. Inverted resistivity models obtained from ERT measurements at (a) the active rock glacier at Flüela Pass, (b) the active rock glacier at Stelvio Pass, (c) Le Rese di Scorluzzo inactive rock glacier, and (d) the Le Rese di Scorluzzo inactive protalus rampart at Stelvio Pass. The positions of the ERT electrodes (black point marker with stem) along the transects and the measurement points acquired with the CMD-DUO FDEM system (orange circle) are shown. The white dashed lines indicate the interpreted boundary of the inferred frozen layer.

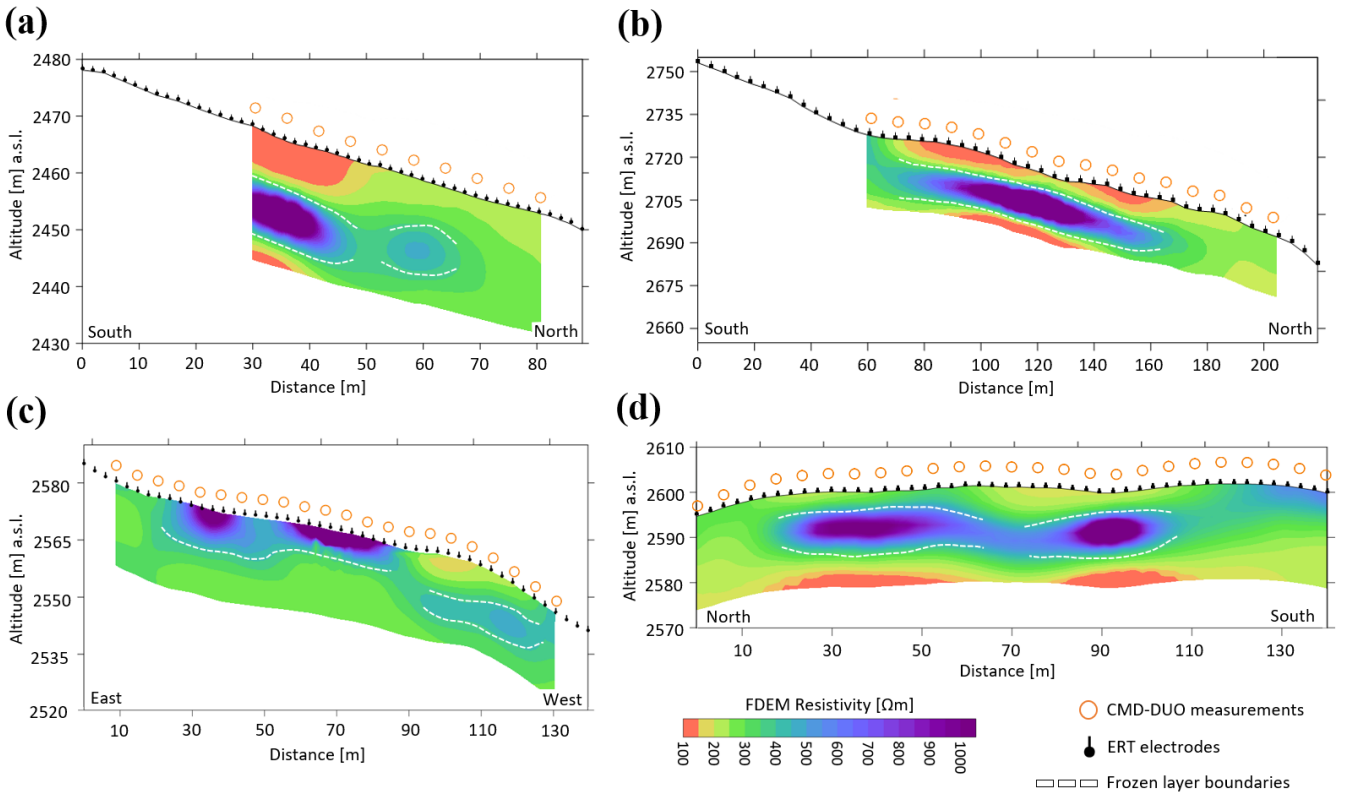


Figure 3. Pseudo-2D inverted resistivity models obtained from FDEM data acquired with the CMD-DUO in HCP configuration at the sites of (a) active rock glacier at Flüela Pass, (b) active rock glacier at Stelvio Pass, (c) Le Rese di Scorluzzo inactive rock glacier, and (d) the Le Rese di Scorluzzo inactive protalus rampart at Stelvio Pass. The positions of the FDEM measurement points are marked with orange circles, and the white dashed lines indicate the inferred boundary of the frozen layer.

175 *Data Availability Statement.* The datasets and source code are openly available in the Zenodo repository at [Insert DOI/URL].
 176 Data processing was performed using EMagPy v1.4.2 (McLachlan et al., 2021).

177 *Author contributing.* MP, MG, EF, JB developed the concept of the study; MP, AB, MG, SPo, JB were involved in the data
 178 acquisition; MP performed the data processing; all authors contributed to the writing and editing of the manuscript.

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