

We would like to thank the anonymous reviewer for his/her comments. While we carefully considered his/her suggestions, we disagree with the assertion that there is a lack of novelty compared to previous papers. Our work Bast et al. (2024) was, in fact, substantially different: to verify the reliability of the conductive textile electrodes proposed by Buckel et al. (2023). This work, which is limited in scope as it is a brief communication, proposes a new approach to electrodes that provides an improved solution for performing ERT surveys in coarse, blocky environments.

Reviewer:

Summary

The manuscript presents a study on a newly developed electrode design, i.e., stainless steel-net electrodes, which the authors propose for electrical resistivity tomography (ERT) measurements in coarse blocky environments. The electrodes facilitate and accelerate ERT surveys and are cheaper and lighter compared to conventional stainless-steel spike electrodes. The authors demonstrate that contact resistances and reciprocal errors are lower when using stainless-steel net electrodes compared to conventional stainless-steel spike electrodes. Correlations of apparent resistivity values between the two electrode types are high for an exemplary landslide deposit and an Italian rock glacier (with an R^2 between 0.91 and 0.99) and slightly lower for a Swiss rock glacier ($R^2=0.8$). The inversion results are similar for both electrode types and successfully reconstruct the known internal structure of the landforms. The results are clearly presented and highlight the relevance of lightweight, easily deployable equipment in harsh alpine terrain with limited accessibility.

However, upon closer examination, the manuscript offers limited novelty and primarily reiterates concepts and methodologies previously presented, particularly in the study by Bast et al. (2024). One of the main concerns lies in the similarity between the figures of the two articles. The representations and analysis of the data are almost identical, with no substantial additions, enhancements or new interpretations. For instance, the authors could have included additional pseudosections to visualize the spatial consistency in the apparent resistivity readings as well as the position of the removed quadrupoles for the different electrode types. In my opinion, the results related to the application of stainless-steel net and textile electrodes could have been presented together in one publication, as the study sites are identical and the data analysis and structure is very similar.

To strengthen the manuscript, I recommend that the authors explore the usability of such stainless-steel net electrodes for induced polarization measurements, as suggested in the Discussion section. Such an investigation would offer a clear advancement over previous research. Another benefit highlighted by the authors consists in the increased durability of stainless-steel net electrodes compared to textile electrodes, which tend to oxidize more rapidly. Showing time lapse ERT data of e.g., hourly measurements could further underline advantages of the stainless-steel net electrodes and enhance the relevance of the article. Clearly, this would require considerable additional effort. Nonetheless, without any further developments compared to Bast et al. (2024) the study lacks substantial new data or insights that would justify its publication as an independent contribution to the field. Additionally, I would include a comparative analysis between net and textile electrodes to clearly demonstrate the advantages of the new design over both textile and traditional spike electrodes. I also suggest revising the Discussion section; vague terms such as “good contact resistances” should be replaced and the discussion points need to be better supported with relevant literature.

Taking these concerns along with a number of specific comments and technical corrections listed below into account, I recommend accepting this manuscript after major revisions.

AUTHORS REPLY

While we agree that the presented study shows a similar analysis to that in our previous work (Bast et al., 2024), this brief communication has a completely different aim. Rather than proposing a comparative

analysis of different electrode approaches, this work aims to propose a new type of electrode with significant improvements compared to the recently tested conductive textile electrodes (Buckel et al., 2023). As highlighted in Bast et al. (2024), conductive textile electrodes are a reliable tool for facilitating the acquisition of ERT measurements on coarse-blocky surfaces such as rock glaciers and landslide deposits. Textile electrodes can be easily inserted and removed between the blocks without the need for steel spikes to be hammered in, which significantly speeds up the preparation of ERT arrays. Nevertheless, in our discussion in Bast et al. (2024), we identified several important problems related to the application of these conductive textile electrodes that this work intends to overcome: i) The same weight of steel spike electrodes (50 steel spike electrodes or 50 conductive textile electrodes weigh about 15 kg in total); ii) The oxidation problem related to the conductive metals used to make the textile (copper and nickel), which will drastically reduce the performance of the electrodes after few surveys; iii) The cost of making (or replacing damaged ones) the textile electrodes (15 euros each, mainly due to the cost of the conductive textile, i.e. 750 euros for a set of 50 electrodes); iv) the conductive textile is fragile and prone to be cut by rough surfaces.

As we highlighted in the submitted BRIEF communication, the proposed steel-net electrodes clearly overcome all these problems: i) each electrode is just 50 g (50 electrodes, which can easily fit in a traditional medium size mountain bag as the textile electrodes, are about 2.5 kg), ii) the net is realized with stainless steel, therefore we don't face any oxidation problem, and this means that the high performance of the electrodes is guaranteed in future surveys; iii) producing the steel-net electrodes is also much more advantageous from an economic point of view, the net can be easily found in hardware stores, and the cost to produce an electrode is around 2 euros, about 100 euro for 50 electrodes; iv) finally, the mechanical resistance of the electrodes is improved, these new steel-net electrodes do not break and last a long time.

Taking all this into account, we believe that the proposed electrodes offer some significant advantages: i) The low weight of the electrodes is a valuable improvement for researchers working in high mountain environments who are accustomed to carrying all the ERT equipment without the support of vehicles (e.g. helicopters); ii) once the electrodes have been made, there is no need to replace them due to oxidation (or to spend time drying the textile at the end of each survey to reduce oxidation) or breakage; iii) even if they need to be replaced, the cost of the net electrode is low and the material is easily available. Therefore, our new solution is a significant improvement on textile electrodes: we have all the advantages presented by Buckel et al. (2023), while overcoming the issues identified by Bast et al. (2024).

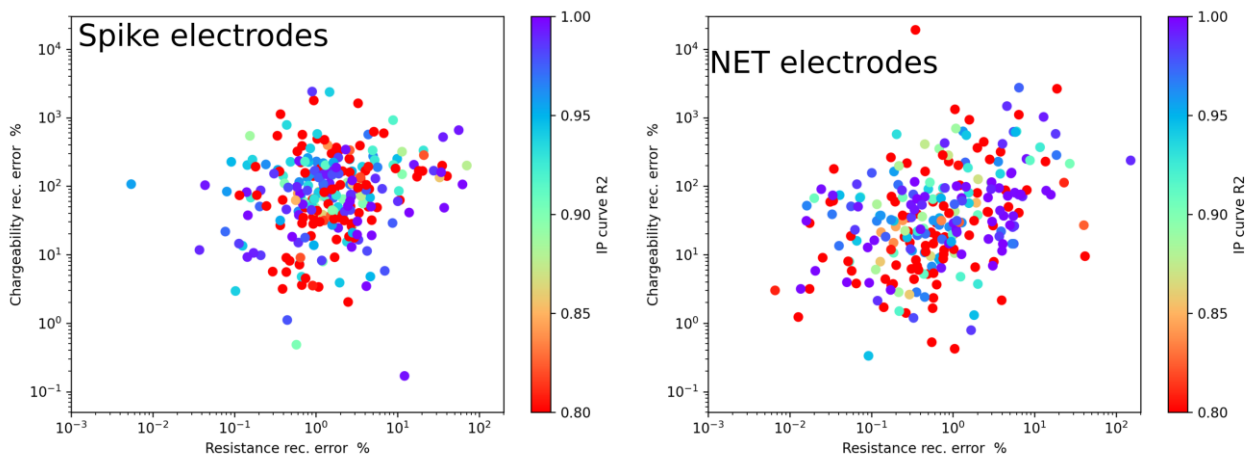
While we agree that the analysis is similar to that of Bast et al. (2024), also here we have considered and compared the relevant parameters in an ERT survey, namely contact resistances, the quality of the measured datasets (via reciprocal error) and the results (i.e. the inverted resistivity model). We could add the pseudo-sections, but we have already plotted the linear regression of the measured apparent resistivities to demonstrate the consistency between the datasets obtained using different electrodes. However, Cs Brief Communications are limited to 3 figures, so we must make a precise and concise selection of what to show readers. In our opinion, the structure of the figures is not exactly the same as that shown by Bast et al. (2024). While it is true that we present and compare the same parameters, this is unavoidable for an ERT survey performance evaluation. Regarding the choice of test sites, the work is not finalised to characterise the subsurface structure/composition, which is already well known, but rather to verify the reliability of the proposed electrodes for acquiring ERT surveys in these environments.

This analysis could not be included in Bast et al.'s (2024) previous work since the steel-net electrodes were developed after the manuscript had been submitted. As the reviewer correctly stated, the performance of textile and stainless-steel net electrodes is substantially the same, as verified at the same study sites. Therefore, we preferred to compare our new electrodes with the commonly used steel spikes coupled with sponges (soaked in salt water), the traditional approach to acquiring ERT datasets in rock glacier environments, and consequently a more representative way to confirm the reliability of the new electrodes.

In each test-site we performed both ERT and time-domain IP measurements. However, the IP data error (considering reciprocal errors and fitting of the curve relaxation) was too large with both the electrode types, and hindered a relevant and significant IP analysis, in our opinion.

The Syscal acquisition parameters were configured for the IP to the best of our knowledge, with a 2-second injection-measurement period and 20 custom sampling intervals increasing from 20 ms to 200 ms. A specific dipole-dipole sequence was used to avoid the use of polarized electrodes as potential electrodes. A 10-minute break between direct and reciprocal measurements was allowed to provide sufficient time for the depolarization of the electrodes. Hence, our understanding is that the very high IP errors were related to the arrangement of the ERT cables. In fact, multicore cables were used without separating current and potential arrays, as extensively discussed by Maierhofer et al., (2022). The IP errors we estimated are in line with this study (see for example the number of discharged measurements in their figure 2), confirming that IP surveys in such rocky and challenging environments likely require separating current and potential cables. Note that, in our study, the choice of not separating the cables reflected the focus on ERT data quality and kept our tests comparable with the vast majority of similar studies and applications.

As an example, from the Marocche test site, the following figure summarizes the IP error analysis. The figure shows how both spike and net electrodes have extremely high reciprocal errors for the chargeability (y axis), also relative to the resistance reciprocal errors (x axis). The scattering highlights how resistance and IP errors are not correlated. The colours represent the error estimated from the fitting of the IP decay curve analysis, following the algorithm suggested by Orozco et al., (2018), which is also not clearly related to the reciprocal errors in this case. We also tried to ignore early and late decay curve samples, but this did not have significant effects.



In conclusion, our understanding is that these IP errors are 1) too large to support a relevant IP analysis, 2) very complex, with no clear relationships between the resistance and IP reciprocal errors, nor between decay curve analysis and reciprocal errors, nor between spike and net electrodes; and 3) in line with previous studies using non-separated cables in such environments, which also limits the possible novelty.

Therefore, as the Reviewer can clearly understand, we decided to not insert the comparison between the collected IP measurements, but we will run new tests in future using different cables for injecting electrodes and potential electrodes, to improve the quality of the IP measurements.

Regarding the oxidation problem of the textile electrodes, we agree that it could be measured using a time-lapse configuration, but only with very long-time monitoring. We doubt in fact that we could verify a performance drop using hourly measurements, given that we have used them with excellent results in several campaigns during the 2023 summer season. The degradation process is much slower, becoming apparent

after several weeks of continuous use of the textile electrodes. Anyway, the aim of this work was not to verify the 'lifetime' of textile electrodes, but rather to propose a new type of electrode that does not oxidise.

Taking all this into account, while we respect the opinion of the anonymous Reviewer but we believe that this BRIEF communication explores significant advantages for permafrost ERT community, since the proposed steel-net electrodes represent a clear cheap and effective improvement.

Reviewer Specific comments and technical corrections

- Line 10: I would also include talus slopes, debris-covered bedrock, moraines, debris-covered glaciers in the description, which also consist of blocky to coarse blocky surfaces.

Reply: We agree with the suggestion of the reviewer, and we will modify it in the revised manuscript.

- Line 12: we have successfully tested alternative electrodes that are more robust, lighter (and cheaper than the recently proposed conductive textile electrodes

Reply: We agree with the suggestion of the reviewer, and we will modify it in the revised manuscript.

- Abstract in general: How do you prove that these suggested electrodes are better than others, because the reciprocal error is lower for these electrodes? You also need to address your main findings and results within the abstract, not only in the conclusion.

Reply: We would like to highlight to the reviewer that, in the abstract or elsewhere in the manuscript, we never presented the proposed steel-net electrodes as superior to other types, such as steel spikes or textile electrodes. In the abstract, which is limited to 100 characters, we just briefly presented the net electrodes and their advantages compared to textile electrodes. The reliability of the latter has already been verified in Bast et al. (2024). Furthermore, in both the abstract and the introduction, we highlighted that we successfully tested the performance of the steel-net electrodes. We believe the details of the experiment can be found in the main body of the manuscript, as well as in the discussion and conclusions.

- Line 22: I would cite here more fundamental studies concerning galvanic coupling between electrodes and ground.

Reply: The work by Pavoni et al. (2022) clearly highlights the link between galvanic contact (or contact resistance) and data quality; in fact, the work focuses entirely on this. We refer to this work and the references cited within it for further specifications, since including a long list of redundant references is beyond the scope of a Brief Communication.

- Lines 22-24: I suggest going into more detail concerning data quality, high contact resistances, what is "high" and what is the influence of high contact resistances on ERT data?

As a BRIEF communication we have with a limited number of pages (4), references, and figures, that limit to go into detail of so common aspects in ERT techniques. Further details about the ERT method, data quality, contact resistance relations etc. can be found in more specific 'fundamental' manuscripts that are insert in the references list (e.g., Binley (2015), Tso et al. (2017), and Binley and Slatter (2020)).

- Line 29: What are excellent mechanical properties? High mechanical strength and durability?

Reply: We agree with the suggestion of the Reviewer and we will modify it in the revised manuscript.

- Lines 30-32: I would change it to: Accordingly, for several decades, electrodes in ERT surveys have commonly been produced as (or made out of) round stainless-steel spikes ...

Reply: We agree with the suggestion of the Reviewer and we will modify it in the revised manuscript.

- Line 36: change “is guaranteed” to “was guaranteed”, and “were added”

Reply: We agree with the suggestion of the Reviewer and we will modify it in the revised manuscript.

- Line 39: I would change “finally easily removed” to “easily removed after the measurements”

Reply: We agree with the suggestion of the Reviewer and we will modify it in the revised manuscript.

- Lines 39-40: I would go into more detail here, what are the main aspects and conclusions of this study, are these textile electrodes reliable compared to traditional electrodes?

Reply: We thank the Reviewer for this comment, and we will strengthen our concept. We successfully tested the performance of the steel-net electrodes against the traditional ones as clearly visible in our figures. We will try to rephrase the details of the study in the main body of the manuscript, considering again that we submitted a Brief Communication, and consequently we have limited space that does not admit repetitions.

- Line 55 and line 61: I would delete “a chaotic electrode arrangement/mixture of”

Reply: We thank the reviewer for his/her suggestion, but the surface of our landslide deposits and of the rock glaciers are effectively composed of a chaotic mixture of debris and boulders with different sizes.

- Line 66: Why did you use these dimensions? Did you test different dimensions of the square and the size of the sponges and analysed contact resistances/ injected current? You do not show the connectors to the cables. How do you connect the steel net electrodes to the cables? Do you have problems with oxidation of the connectors?

Reply: We will add these details. We used a traditional car-wash sponge to create a bag that has the same size of the textile-electrode proposed by Buckel et al. (2023). Since the collected datasets shows acceptable contact resistance values and reliable data quality (based on the reciprocal error), we didn't consider using different size of the bag. As shown in figure 1b and 1c, the steel-net electrodes are connected to the cable with traditional crocodiles and we don't have any oxidation problem with the connectors.

- Line 73: ... with different skips as described in Pavoni et al. (2023), ...

Reply: We agree with the suggestion of the Reviewer and we will modify it in the revised manuscript.

- and included reciprocal (interchanged current and potential dipoles) measurements... I would somewhere include a short description of normal and reciprocal measurements. How did you compute the reciprocal error? Why did you take the reciprocal error as an estimate to evaluate data uncertainty? Explain in more detail.

Reply: as previously, we would like to highlight that this work is submitted as a BRIEF communication with a limited number of pages (4), references, and figures. Further details about the ERT method, data quality, and contact resistances can be found in more specific ERT 'fundamental' manuscript that are insert in the reference list. In the data processing chapter (3.3) we also explained the choice of the reciprocal error threshold.

- Line 77: The two different electrode types were placed at the same location between blocks and boulders.

Reply: We agree with the suggestion of the Reviewer and we will modify it in the revised manuscript.

- Line 89: How did you define the data error within the inversion? I suggest describing it here.

Reply: We thank the reviewer for his suggestion, but we think that in the chapter we clearly explained the choice of the reciprocal error threshold: “At each test site, the datasets were filtered using a

reciprocal error threshold that allowed to obtain a section of apparent resistivities with a homogeneous distribution of measurement points...”

- Line 94: 100 k Ω is still not “optimal”, I would delete/change this word.

Reply: We respect the opinion of the reviewer, but, in our experience and in ERT permafrost literature, reaching 100 k Ω of contact resistance value with large boulders at the surface can be considered a very good result that allows to acquire reliable ERT datasets in this kind of environments. In the revised manuscript we can change ‘optimal’ with ‘acceptable’.

- Lines 99-102: I would somewhere (in the Appendix, in a table) add additional information on the three sites. What is the active layer depth or thaw layer depth of the measurement day for the two rock glaciers? You write that the ERT results reconstruct the known structure of the landslide deposit (Weidinger et al., 2014) and confirm the presence of a frozen layer at the rock glacier (Bast et al., 2024), I would then summarize these validation data for a better comparison to the results.

Reply: We agree with the Reviewer, but as said, editorial guidelines for BRIEF Communication give a limited number of pages (4) and no appendixes are allowed. The information requested by the reviewer can be easily found in other works that we cited in the manuscript. The target of this work was in fact not to characterize the well-known structure of these sites.

- Line 111: Change “excellent” to “high”

Reply: We agree with the suggestion of the Reviewer and we will modify it in the revised manuscript.

- Line 112: “In the first case $R_2 = 0.91$, while for the inverted resistivities $R_2 = 0.93$.” This sentence has no verb, please summarize with previous sentence.

Reply: We agree with the suggestion of the Reviewer and we will modify it in the revised manuscript.

- Line 116: more than half of the electrodes yield contact resistances > 200 k Ω .

Reply: We agree with the suggestion of the Reviewer and we will modify it in the revised manuscript.

- Line 118: inversion process

Reply: We agree with the suggestion of the Reviewer and we will modify it in the revised manuscript.

- Line 119: delete “measured”

Reply: We agree with the suggestion of the Reviewer and we will modify it in the revised manuscript.

- Results section in general: I suggest adding additional pseudosections to visualize the spatial consistency in the apparent resistivity readings as well as the position of the removed quadrupoles for the different electrode types. Additionally, it would be interesting to show injected current for the different electrode types.

Reply: We thank the reviewer for his/her suggestion and, for each site, we will add in Figure 3 a plot of the pseudosection with the difference between the resistance ($R[\Omega]$) values measured with the two types of electrodes. Note that, at each site, only the quadrupoles common to the two datasets after filtering were used for the inversions, as in Bast et al. (2024). We will highlight this better in the revised manuscript. In the results chapter we focused on describing the results and highlighting the high correlation between the data measured with the different types of electrodes. Furthermore, in Figure 2 we added the comparison between the measured injected current values.

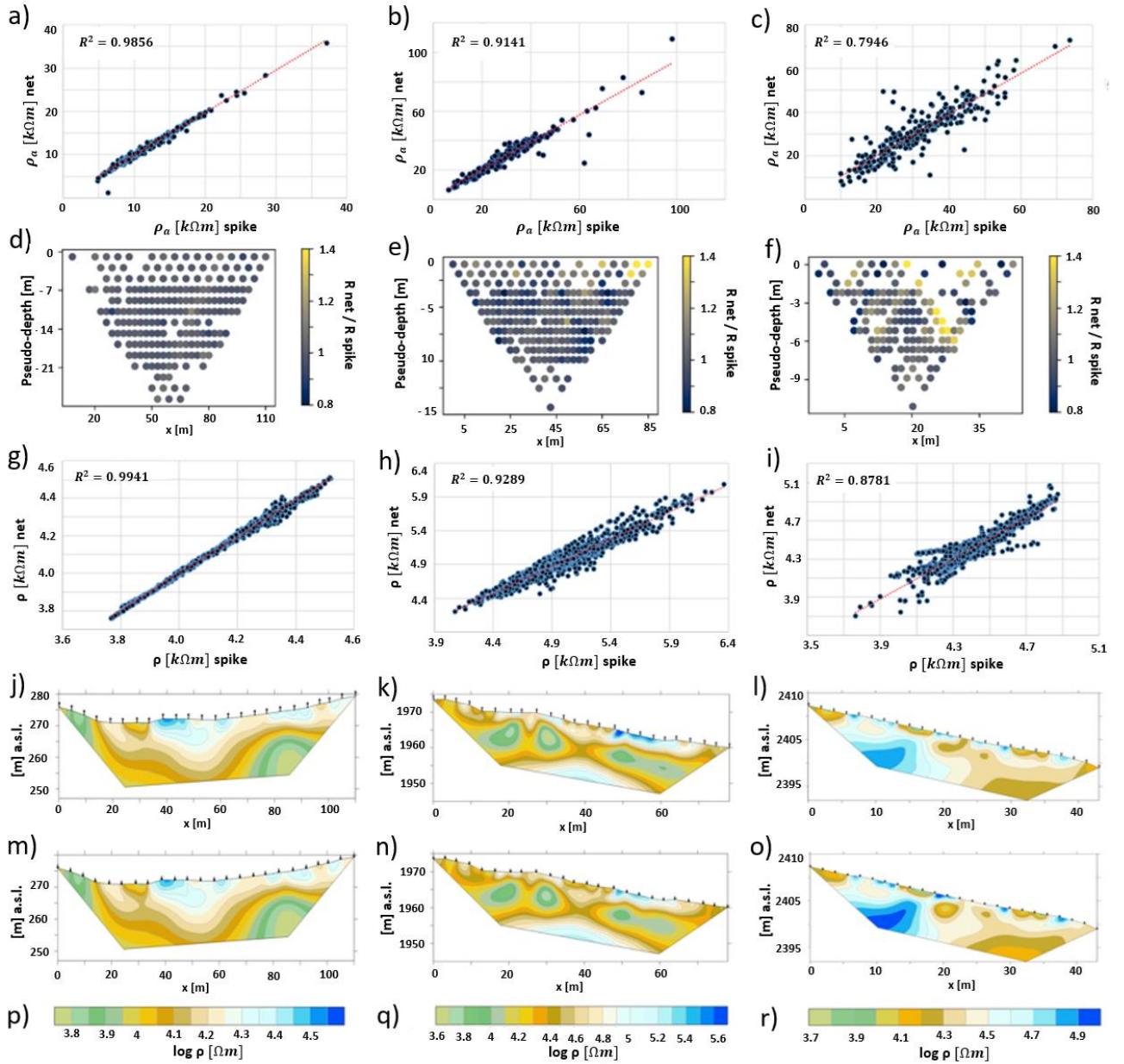


Figure 3: a) Scatterplot with corresponding regression lines (red dotted lines) and R^2 -values of the apparent resistivity values (ρ_a) measured at Marocche di Drò test site with the traditional spike electrodes composed of stainless-steel (coupled with sponges) and the newly proposed stainless-steel net electrodes. d) pseudo-section plotting the ratio between resistance values measured with the spike electrodes and steel-net electrodes (considering the common quadrupoles in the filtered datasets used for the inversion process). g) Scatterplot with corresponding regression lines (red dotted lines) and R^2 -values of the inverted resistivity values (ρ) obtained from the datasets measured at Marocche di Drò test site with the traditional stainless steel-spike electrodes (coupled with sponges) and the proposed stainless steel-net electrodes. j) Inverted resistivity model obtained from the datasets measured with the traditional stainless steel-spike electrodes at the Marocche di Drò test site. m) Inverted resistivity model obtained from the datasets measured with the proposed stainless steel-net electrodes at the Marocche di Drò test site. p) Color bar scale for the inverted resistivity models of the Marocche di Drò test site. b), e), h), k), n) and q) are as a), d), g), j), m) and p) but for the Sadole rock glacier test site. c), f), i), l), o) and r) are as a), d), g), j), m) and p) but for the Flüela rock glacier test site.

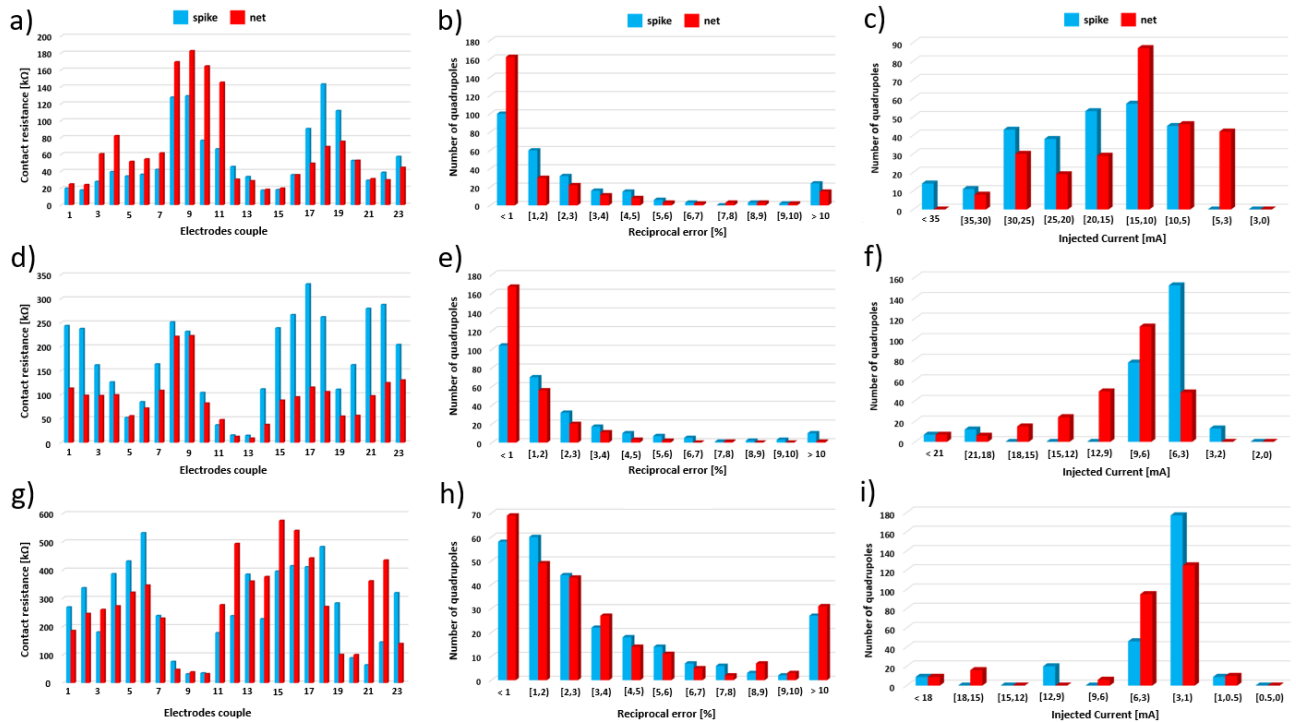


Figure 2: The histograms (a), (d), and (g) illustrate the comparison of contact resistances [kΩ] recorded respectively at the Marocche di Drò, Sadole, and Flüela test sites with the traditional spike electrodes made of stainless steel and combined with sponges (blue bins) and the newly proposed stainless-steel net electrodes that include a sponge (red bins). The histograms (b), (e) and (h) display the comparison of the reciprocal error [%] of the quadrupoles measured respectively at the Marocche di Drò, Sadole, and Flüela test sites with the traditional spike electrodes made of stainless steel and combined with sponges (blue bins) and the newly proposed stainless-steel net electrodes that include a sponge (red bins). The histograms (c), (f) and (i) display the comparison of the measured injected electrical current [%] of the quadrupoles measured respectively at the Marocche di Drò, Sadole, and Flüela test sites with the traditional spike electrodes made of stainless steel and combined with sponges (blue bins) and the newly proposed stainless-steel net electrodes that include a sponge (red bins). Both types of electrodes were wetted with the same amount of salt water and approximately placed at the same locations between the blocks and boulders (Fig. 1b and 1c).

- Line 126: I suggest revising this sentence and providing a more detailed discussion on the effect of high contact resistances on ERT data quality, supported by references.

Reply: again we are forced to a limited number of pages (4) which does not admit too details. The information requested by the reviewer can be easily found in other works, and, as correctly suggested, we will add some references in the revised manuscript.

- Line 128: What is good? I would use low or high

Reply: We agree with the suggestion of the Reviewer and we will modify it in the revised manuscript.

- Line 137-139: You have the reciprocal error as an estimate of data error to evaluate data quality/uncertainty. Why don't you refer to this here?

Reply: We thank the Reviewer for the suggestion, we will add this aspect.

Line 137: "better" → "lower"

Reply: We agree with the suggestion of the Reviewer and we will modify it in the revised manuscript.

- Line 138: "greater" → "higher"

Reply: We agree with the suggestion of the Reviewer and we will modify it in the revised manuscript.

- Line 139: “best” → “lowest”

Reply: We agree with the suggestion of the Reviewer and we will modify it in the revised manuscript.

- Lines 142-143: delete “although excellent”

Reply: We agree with the suggestion of the Reviewer and we will modify it in the revised manuscript.

- Line 145: poorer → lower

Reply: We agree with the suggestion of the Reviewer and we will modify it in the revised manuscript.

- Lines 146-148: I suggest revising these lines to provide a clearer comparison of your findings with existing studies. Please clarify which high-resistivity structure you are referring to.

Reply: We thank the reviewer for his/her suggestion, we can improve this sentence to clarify that the high-resistivity structure found in the resistivity models is interpreted as the frozen-permafrost layer.

- Lines 149-151: How can it be demonstrated that the stainless-steel net electrodes yield results equivalent to those of conductive textile electrodes, given that no direct comparison is provided within your study? Please explain in more detail.

Reply: We agree, we can remove that sentence since we don't have a direct comparison. Anyway, as discussed in the site description chapter (2), in this work we performed the test-transect on the same survey lines that were investigated by Bast et. al (2024), and the results are perfectly in agreement.

- Line 156: induction polarisation measurements → induced polarization measurements!

Reply: We agree with the suggestion of the Reviewer and we will modify it in the revised manuscript!

- Figures: The font size in some parts of the figures is too small and should be increased to ensure readability.

Reply: We agree with the suggestion of the Reviewer and we will modify it in the revised manuscript.