The Cryosphere Discuss.,
https://doi.org/10.5194/tc-2020-306-AC1, 2021
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The Cryosphere
Discussions

Interactive comment on "Active and inactive Andean rock glacier geophysical signatures by comparing 2D joint inversion routines of electrical resistivity and refraction seismic tomography" *by* Giulia de Pasquale et al.

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Received and published: 22 January 2021

Dear editor, With respect to the comments from Referee #1, we have addressed the major concerns indicated by the reviewer in this document and minor changes suggested in tc-2020-306-RC1-supplement.pdf file (attached). The attached files also include figures that have been modified in response to the comments from Referee #1,2 and 3.

1) I feel the title to be too provocative and/or to certain extent misleading. I understand

that the authors want to stress the comparison of results obtained through two different inversion algorithms. However, I am not sure that the comparison is valid taking into account that one refers to a spatial regularization schemes and the other one aims at solving a set of petrophysical models. Moreover, the joint-petrophysical inversion uses a set of calibration parameters (presented in Table 3 and Table 4) to permit the computation of air, ice and water content. However, in the present study, such parameters are taken from the literature, even if these are calibration values than need to be adjusted to each site (see the works from Archie and the reference to the studies by Glover et al., (2000) and Glover (2009)– full references below). In this regard, the comparison is unfair and technically limited. Would not be better to change the title to something like "extended interpretation based on the application of two joint-inversion algorithms"?

Reviewers 2 and 3 commented that the manuscript was lacking a clear focus, required a better structure and according to this review it does not sufficiently investigated the comparison between the two joint inversion results. In an attempt to respond to all of these comments we decided to change the focus of the manuscript to the geophysical signature difference between active and inactive rock glacier and have updated the title accordingly. The new proposed title is now "Geophysical signature of two contrasting Andean rock glacier". In the new version of the manuscript, we focus on the individual inversion results and present the petrophysical joint inversion to aid the interpretation of the differences in the geophysical signature of the two rock glaciers and completely delete the structural joint inversion approach.

2) If the authors decide that the comparison of the results is relevant, then I suggest that the authors provide a quantitative comparison of the parameters obtained through the joint inversion, i.e.,the seismic velocities and electrical resistivity resolved from the 2 inversion algorithms.Right now, the authors present only the plot of the inversion results and force the readers to compare those results by means of color-coded images in different pages and sizes. I feel such comparison to be at best qualitative and open to debate. It would be better if the authors plot the parameters solved for both strate-

gies (for example, Vp from the joint-petrophysical inversion vs. Vp from the structural joint inversion). In this case, deviations between both approaches could be quantified. Moreover, such analysis would be also convenient within a numerical study (with Gaussian error), where deviations from the truth model can be also quantified.

We agree with the referee that such analysis is necessary for a clear comparison of the two joint inversion schemes but we feel that for this paper such a detailed quantitative comparison would make the paper too dense and we have opted to focus on the geophysical signature of the two rock glaciers as stated before. A possible solution as suggested by reviewer 2 would be a follow up paper with a more detailed analysis of the two inversion schemes, where we could focus as well on a numerical study to better quantify the accuracy of the two inversion schemes.

3) In order to perform a proper analysis of the two algorithms, the authors should investigate the variations in the retrieved models after testing different parameters used for the inversion. In this regard,the authors could investigate the resulting seismic velocities and electrical resistivity values after testing a few parameters in the petrophysical joint inversion and a few combinations of the scale-length correlations for the joint-structural inversion. Right now, the study runs a set of inversions with some values extracted from the literature (for the petrophysical inversion), and based on the slope (for the structural inversion. Are we expecting the models to be comparable? – Actually we are forcing the joint inversion to converge with some predefined settings that might not accurately describe the field conditions. In this regard, the users might be causing larger uncertainties in the inversion than just solving for a smooth-constraint independent inversion of the different data sets. I think that the proper comparison of the different joint-inversion algorithms needs to address the use of adequate parameters, or at least assess the deviations in the retrieved models by an inadequate selection of the inversion settings. The use of joint-inversion schemes has been largely investigated in geophysical studies, still they are not widely-accepted as they rely on the use of site-specific models or require of a correlation between the different parameters that

might not exists. I think the authors point out to this problem. The use of a numerical study would be also a good option to extend the analysis to quantify deviations from the truth model.

The revised version of the paper does not compare the two algorithms, so this reviewer comment is no longer relevant (see comments above).

4) Regarding the correlation of the seismic and electrical parameters, I find Figure 9 quite intriguing. Actually,the authors demonstrate no correlation between the seismic velocities and the electrical resistivity. I can see a cloud of points with a large variance and to pattern.However, the authors describe a correlation and quantify a model linking both of the properties. However, the authors do not present the correlation coefficients that actually quantify the actual correlation. The actual lack of correlation observed in Figure 9 is especially disturbing taking into account that the use of the joint-structural constraints aims at improving such correlation. Is such poor correlation due to the inadequate correlation lengths selected in this study? Is this a problem of poor data quality? If the authors cannot address this question in detail, I think that the authors should completely remove Figure 9. If the authors decide to keep the figure, please write explicitly the correlation coefficient and address in detail the lack of correlation.

For the comparison and analysis of the geophysical signature we have modified Fig.9 with a density plot of the resistivity and velocity model inversion parameters (now Fig.8). The corresponding section in the discussion has been changed as follows:

5.4 Towards a diagnostic model representation for the ice presence in rock glaciers. The results from the petrophysical joint inversion help quantify the volume content of air, water, ice and rock and identify El Jote as relict and El Ternero as intact rock glaciers. However, in many cases such an interpretation is limited by the lack of proper petrophysical models (or parameters). When petrophysical model coupling is not possible, the comparison of velocity and resistivity model inversion results can still deliver plenty of information about the rock-glacier's internal structure. In Fig.8 we show resistivity-velocity density plots for each rock glacier, built from the individual model inversion results of figures 4(c),(d) and 6(c),(d). The differences between the two rock glaciers are clearly noticeable, with relatively low resistivity and low velocity clusters for the relict rock glacier, while the intact one is associated with higher velocities and resistivities. The relatively low resistivities and low velocities (Fig. 8a) are in agreement with air filled unconsolidated sediments inferred through the petrophysical joint inversion results (Figs. 5e,f). The lowest resistivities may be associated with liquid water and/or a proglacial aquifer (Fig. 5c; section 5.2). The gradual increase in resistivity and velocity (Fig. 8b) are evidence of material consolidation such as bedrock or ice-rich layers. Given the very high resistivities (over 10ˆ5 Ohm m) our interpretation is that these are ice rich layers (Table 1, resistivity values), which agrees with the petrophysical joint inversion results (Fig. 7d). The rather different appearance of the two density plots (Fig. 8a and b) can be used as an indicator of the distinct nature of the two rock glaciers: overall, the stagnant rock glacier is characterized by lower resistivities and velocities while the intact rock glacier is indicated by higher resistivity and velocity values, reflecting the ice rich layer. The schematic plot (Fig. 8c) summarizes the findings for our two end-member rock glaciers and could be useful for identifying ice-rich landforms using seismic and electrical resistivity methods.

5) I would like to get further information regarding the reasons to select the correlation-lengths used in the joint-structural inversion. Did I understood correctly that the values selected are related to the profile inclination (i.e., the slope)? I think the authors should investigate this in detail. Such value has no statistical-meaning regarding the correlation of the two geophysical parameters. Would not be more convenient to investigate the variograms of the measured data? Or, at least from the two independent inversions (following the smooth-constrained algorithm)? I might be misunderstanding this point, but the main inclination of the profile is not an argument to define the correlation lengths in this inversion.If the authors are really using the slope of the profile as a correlation length-scale,would not be expected then that this inversion provides practically the same inversion result than the smoothness-constraint? Finally, both approaches

would be controlled by a lineal increase in the seismic velocities, which is in both cases forces to the plane defined by the surface geophones.

We agree with the referee that a better study needs to be done in order to include the structural joint inversion; therefore we avoid presenting these results in the paper which are not relevant considering its new focus.

6) I also think that the authors should present information about the data-error. It would be convenient to see the pseudosection of the resistivity data, and maybe the travel times of the seismic measurements to assess the data quality. Maybe the small variations observed between different inversions algorithms result only by fitting the same data to the low error parameters defined by the authors. In this regard, I would be very interested to see more details of the normal reciprocal analysis conducted by the authors. Just based on the principle of the error model, I would like to understand how can the authors solve for a relative error of 1% as mentioned in their manuscript. Such error is too low for the high resistivity solved in the inversion. Such low relative error is not consistent with the description of the authors regarding the high contact resistances and the problems setting the measurements.Is the analyses of the data based on the misfit between normal and reciprocals or the fractional error? Which analysis was used to define the 300 ms error parameter defined in the inversion of the seismic data? I just find such values extremely low and would be critical to understand how were such values quantified. What were the steps used for the identification and removal of erroneous measurements and outliers?I think that the authors could then present the L-curve for their independent inversions (for such low error parameters) as this would make the study more complete. This could also alleviate concerns regarding the accuracy of the fitting in the inversion and remove the redundant Figures 5 and 8.

In responding to this comment we realized that the definition of the error model in the original manuscript was incorrect and it has since been modified. The errors were computed for ERT data using the mean standard deviation of the observations which was of 1.2 % in case of El Jote and 11.4 % in case of El Ternero. These were the actual values used for the inversion schemes and we modified the text and table accordingly. For the error of seismic data we calculated an average error of 0.001 s as an estimate of the average variability in our picking of the first arrival traveltime. In the new proposed manuscript we also present a new section of the Methods: 3.3 Data processing and Inversion where. Here we clarify how the filtering happens: “The ERT observation were automatically filtered by the acquisition software which did not take measurements when the contact resistance was too high, while for the seismic refraction traveltime, we manually picked the first arrivals after applying a gain to the seismic traces and therefore the traces were filtered according to our ability of identify the first arrival times.” Also, we eliminated Figure 5 and 8 and added a new Figure 3 with the L-curve analysis for the individual inversions. Moreover, we provided images of the datasets for both rock glaciers (first arrival traveltimes for RST and pseudosections for ERT) in new Figures 4 and 5 where we presents the individual inversion results.

7) I think that the authors could improve the figures presented. I read the manuscript printed in hard copy and it was just impossible to read Figure 1 and the colour bars (especially in Figure 2). It is clearly needed to read the digital file and zoom-in. Moreover, if the authors decide to keep the visual inspection/comparison of their results, it would be more convenient to have all results for one glacier plotted in a single figure (independent, joint petrophysical an djoint structural inversion). Maybe the plot of the air/ice/water fraction resolved for both glaciers (after the joint-petrophysical inversion) could be plotted together. In this regard,it is possible to compare the resistivity and velocity models obtained by different inversions in a single figure and the retrieved parameters for both glaciers (regarding the discrimination between active and passive). I also do not understand the sense of Figure 5 and Figure 8, as the authors refer to the RMSE and chi-square obtained in the inversion and the values are acceptable. I am not sure which extra details we can obtain from the relative residuals. In this regard, (and although it was already mentioned above), maybe it is still more convenient for the authors to address the data quality and quantification of data-error in detail, as well as to investigate the actual statistical correlation between the data and the effect in the

retrieved models for different petrophysical parameters than those presented in Table 3 and Table 4.

We have improved the quality of the figures as suggested (increasing the font size of the labels and dividing Figure 1 in two new figures 1 and 2). Given the new scope of the paper we eliminated Figures 5 and 8.

Also we would like to specify that it was not possible to upload the figure with the complete caption because of their lengths. Please find below the complete caption of all figures:

Figure 1. (a) Overview map indicating the location of Estero Derecho ($\sim$ 30°S, 70°W) in the Coquimbo Region of Chile. Elevation map from ASTER GDEM. (b) Detailed map of Estero Derecho with an inventory of landforms created by CEAZA. The delineations for El Jote and El Ternero were created specifically for this study from the Esri base-map satellite imagery. Both landforms are labeled with their respective elevation ranges.

Figure 2. (a) Aerial image of El Jote, showing the location of the geophysical survey line and (b) its topography from field differential GPS measurements. (c) Aerial image of El Ternero, showing the location of the geophysical survey line and (d) its topography from field differential GPS measurements. Base maps in (a) and (c) from Esri World Imagery 2018. (e) Scheme of the 50 % roll-along scheme used for ERT surveys on both rock glaciers and RST survey on El Jote. (f) Scheme of geophones and Inline/Offline shot positions for RST surveys.

Figure 3. L-curve analysis for the regularization weights (Lambda) used in the inversion of ERT and RST data on both rock glaciers. In each plot, the values tested are Lambda= 1, 5, 10, 15, 50, 100.

Figure 4. Geophysical observations and inversion model results for El Jote rock glacier. (a) RST first arrival traveltimes. (b) ERT apparent resistivity. (c) Velocity and (d) resistivity tomograms. The velocity model is cut below the lowermost ray-path while the

resistivity model transparency is proportional to the ERT data coverage. The velocity colorbar is linear, while the resistivity one is expressed in logarithmic scale.

Figure 5. Petrophysical joint inversion results of El Jote field data sets. The tomograms represents (a) velocity and (b) resistivity transformed models. The directly inverted parameters are (c) water, (d) ice, (e) air and (f) rock volumetric content. All models are cut off below the lowermost ray path, with only resistivity colorbar expressed in logarithmic scale.

Figure 6. Geophysical observations and inversion model results for El Ternero rock glacier. (a) RST first arrival traveltimes. (b) ERT apparent resistivity. (c) Velocity and (d) resistivity tomograms. The velocity model is cut below the lowermost ray-path while the resistivity model transparency is proportional to the ERT data coverage. The velocity colorbar is linear, while the resistivity one is expressed in logarithmic scale.

Figure 7. Petrophysical joint inversion results of El Ternero field data sets. The tomograms represents (a) velocity and (b) resistivity transformed models. The directly inverted parameters are (c) water, (d) ice, (e) air and (f) rock volumetric content. All models are cut off below the lowermost ray path, with only resistivity colorbar expressed in logarithmic scale.

Figure 8. Density plots of resistivity versus P-waves velocity values for (a) El Jote and (b) El Ternero datasets. (c) Schematic plot of the qualitative ERT and RST signature for intact and stagnant rock glaciers.

Please also note the supplement to this comment:
https://tc.copernicus.org/preprints/tc-2020-306/tc-2020-306-AC1-supplement.pdf

Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194/tc-2020-306, 2020.

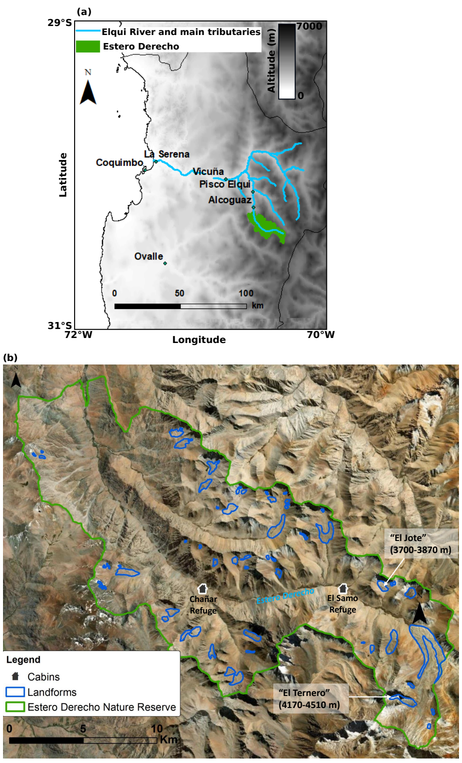

Fig. 1. Overview map indicating the location of Estero Derecho, with (a)elevation map and (b)inventory of landforms (∼ 30°S, 70°W) in the Coquimbo Region of Chile

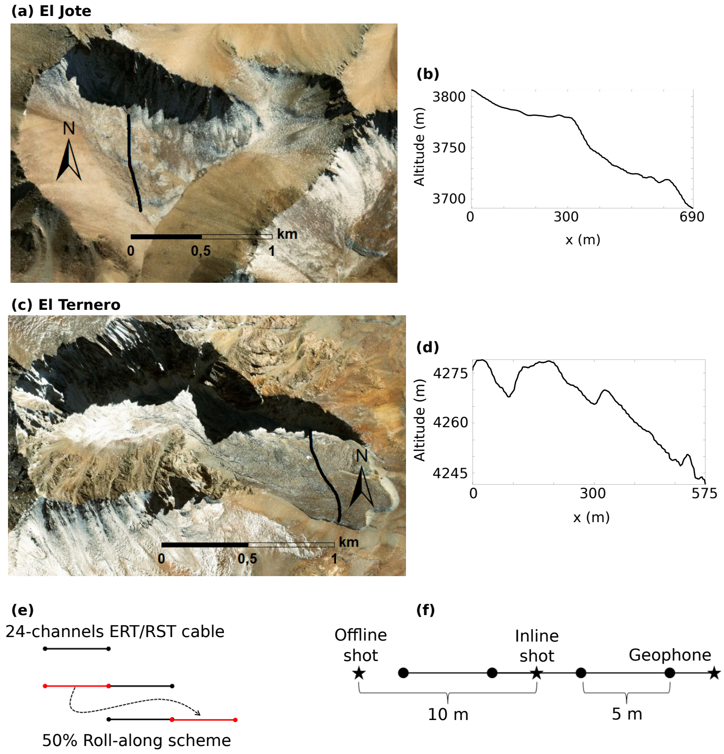

Fig. 2. Aereal images of El Jote and El Ternero with field layout schemes

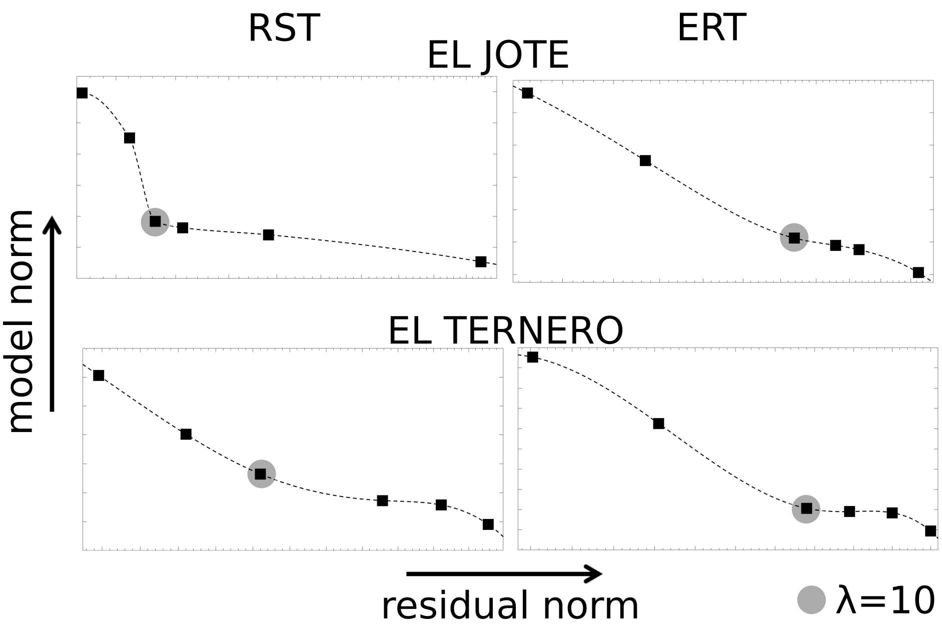

Fig. 3. L-curve analysis for the regularization weights used in the inversion of ERT and RST data on both rock glaciers

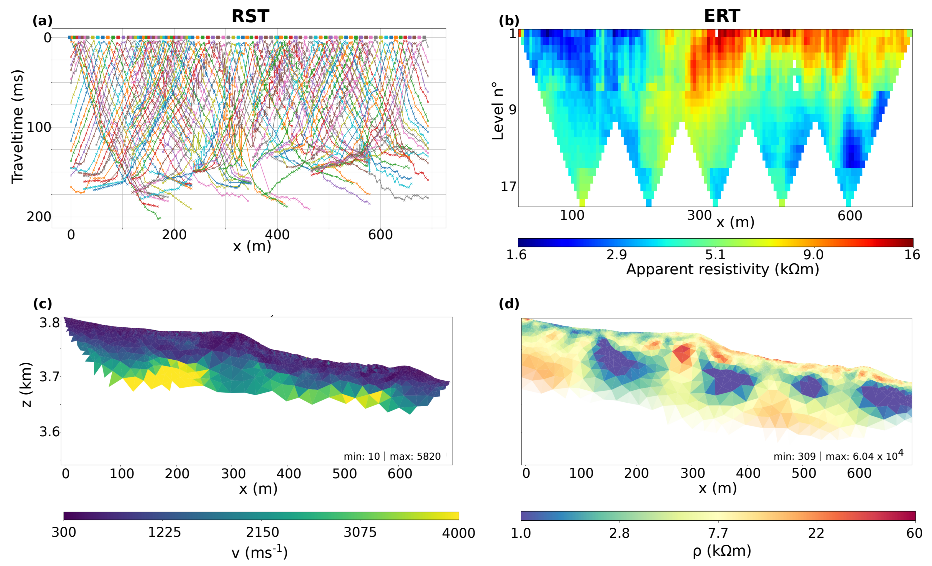

Fig. 4. Geophysical observations and inversion model results for El Jote rock glacier.

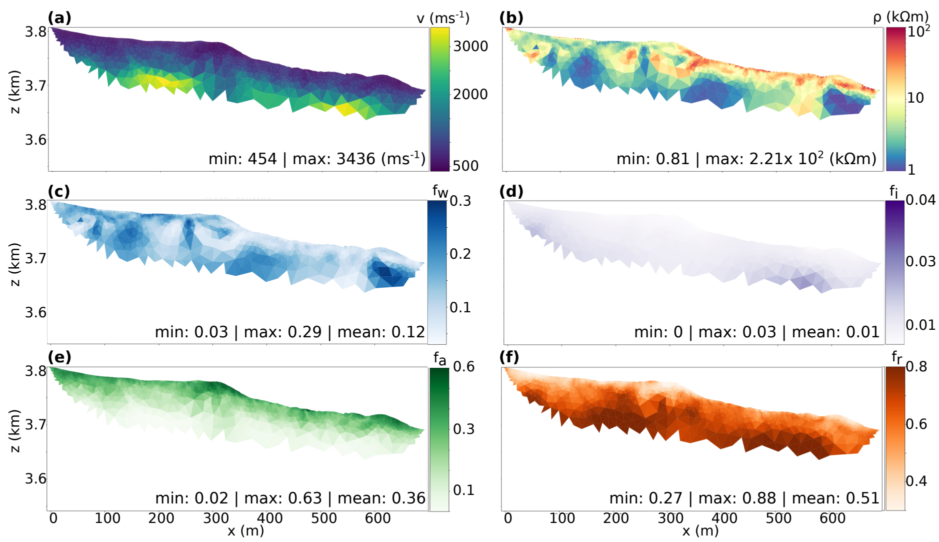

Fig. 5. Petrophysical joint inversion results of El Jote field data sets.

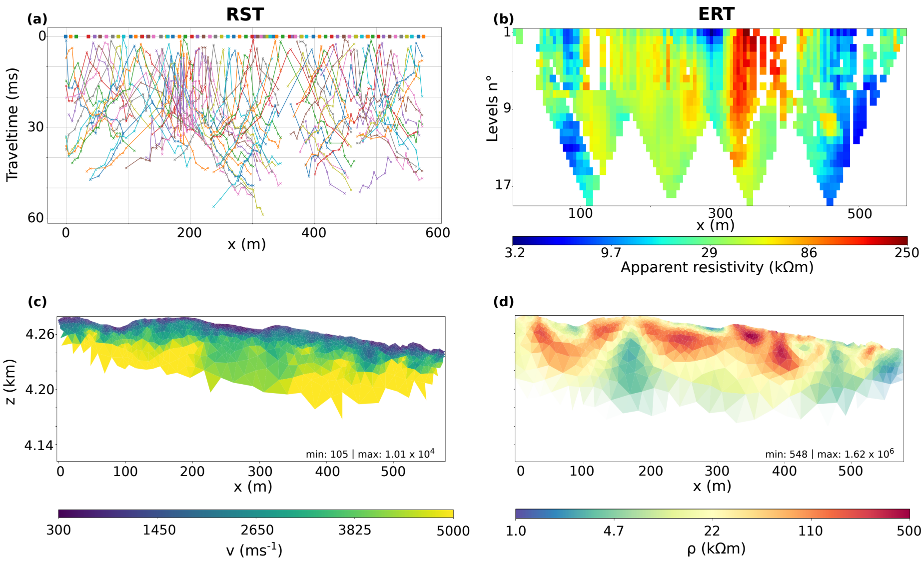

Fig. 6. Geophysical observations and inversion model results for El Ternero rock glacier.

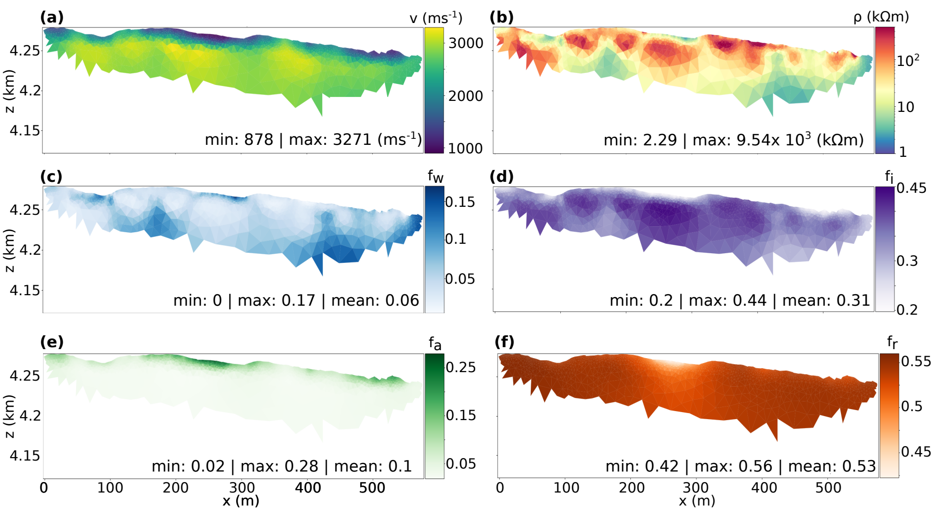

Fig. 7. Petrophysical joint inversion results of El Ternero field data sets.

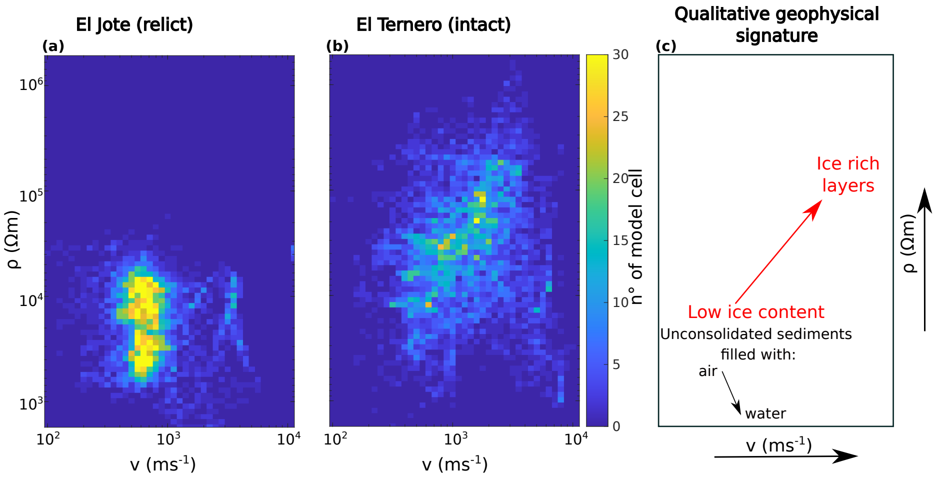

Fig. 8. Density plots of resistivity versus P-waves velocity values with schematic plot of the geophysical signature.