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Interactive comment on "Electric resistivity and seismic refraction tomography, a challenging joint underwater survey at Äspö Hard Rock Laboratory" *by* Mathias Ronczka et al.

Mathias Ronczka et al.

mathias.ronczka@tg.lth.se

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We like to thank all the reviewers and the editor for their constructive critics that will help to improve the manuscript significantly. In most cases we have additions to the text, one case (going over several points of reviewer 2) we are going to add another figure about the use of different measures (coverage and resolution radius) for appraising model uncertainty. This will, along with the other changes, help to be a guideline to use geophysics in similar settings and thus be of wide interest for the non-geophysical readership of the journal.

In the following we have answered all points by (a) a direct response and (b) by the intended changes to the manuscript at the given position related to the original

manuscript.

Reviewer 2

1) Add a paragraph in introduction giving some key references regarding the joined inversion methodologies.

a) Information for other joint inversions are indeed missing.

b) Additional paragraph in the introduction will be written.

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2) Paragraph "3.1 Inversion" needs partial rewriting and clarification as it is not very informative. Both ERT and seismic data processing was made using same minimization scheme but the first paragraph of this section refers only to the geoelectrical parameters and ignores seismic. Further, the joined inversion approach is not clearly explained. It is understandable that part of joined inversion approach is published before but still the reader needs to get an idea of the procedure, esp. to know what approach and parameters were used in this work. Currently this occupies just 3 lines (p5,ln20-23).

a) First part is correct, seismic was not explicitly mentioned in the inversion section, thank you. For the joint inversion explanation we thought it would be nice not to go to much into detail and explain this more figuratively.

b) We will rewrite explanations for the flow chart diagram in a more demonstrative way and put in the basic equations for seismic inversion.

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3) The authors use the word "coverage" to describe the resolution of the inverted areas. Although I understand the purpose of using the word "coverage" I am not sure if this is the best term to describe the model resolution since I am not aware of the word "coverage" being used as a technical term (maybe is used in seismic imaging). Why not using the word resolution instead? If you decide to use the term "coverage"

you need to make a clear definition of it prior to its use as it is different for the case of electrical images (sensitivity norm) and the seismic images (seismic ray density). No definition of it.

a) The coverage is explained in the text and is not really a resolution in terms of data/model resolution as it is the sum of the sensitivities, although it is widely used as such. The seismic coverage is a standardized coverage, which is either 0 or 1, depending if the ray travels through a cell or not.

b) An explanation for seismic coverage is needed. In general we will add a subsection (or paragraph) concerning resolution and coverage with a new figure (see figure below for ERT) that shows resolution radii and the coverage for a final Äspö model. Here a real measure based on the calculated model resolution can be compared with the coverage and also justify that the easy-to-retrieve coverage can be used as a rough estimator for model reliability. According to this we modify the alpha shading using 3 values (1: reliable; 0.5: less reliable 0: not reliable). Alternatively, we define several lines with resolution radii that are plotted in the final result. We also generate such a plot with coverage and resolution radius for seismics. This will enhance the methodology impact of the paper.

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4) In continuation to the above I consider that the use of the sensitivity matrix norm (not just a summation ! as mentioned in line 2 pg6) to get a metric of the resolution of the geoelectrical inversion cells is interesting however its direct use into the inverted geoelectrical results generates some problems:

4.1) Shading generates complicated figures that non-expert readers are not easy to follow. In particular, strictly speaking, the colour scale in ERT images is not fully correct as the presented rainbow colour scale does not incorporate the overlaid alpha shading. For example, the reader cannot easily distinguish between highly shaded light green and yellow parameters so cannot really appreciate the actual resistivities behind the

highly shaded (almost colourless) areas. In any case I would think that the inverted images somehow need to be presented as any resolution metric related image could be an additional one.

4.2) As said the authors choose to use a binary (0,1) masking for the seismic data but a shaded one for the ERT images. Apparently they could have used the same approach for both: why not using seismic ray density, or seismic model resolution for alpha shading also to the seismic data? Or conversely why not using a 0,1 approach for the geoelectrical images: use a threshold sensitivity norm value below which all inverted resistivity values are blanked.

a) Good point. A gradual alpha shading for seismic would give a wrong impression, as the seismic wave either travels through a cell or not. Thus, a cell is covered (1) or not (0).

b) We will change the ERT figures by using only three values for the alpha shading as described in answer 3b).

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4.3) A further consideration is that I have doubts if the sensitivity matrix norm is an indicative proxy for deciding the reliability of the inversion result of a particular parameter. Sensitivity norm values are also dependent on the size of the parameters. In this work, parameters have uneven sizes (coinciding with triangular elements) so small sized parameters may exhibit small sensitivity norm values also because of their size and thus they may be appearing as partly shaded. However, the geoelectrical images are the product of an inversion procedure which is being subjected also to structural regularization (smoothness). This regularization is an important factor of the inversion and effectively it operates in a way that increases the reliability of smaller parameters. This fact is not taken into account into the alpha shading which is solely based on the parameter sensitivity matrix values. In this context, I would think that the diagonal of the model resolution matrix would be a more reliable indicator for accessing the reliability of the inversion as it also takes into account the inversion procedure. Overall, I agree with your idea to include a metric for evaluating the inversion results but this need to be done in a way that is more reliable and easier for potential readership (i.e. engineers) to follow. I have mentioned some possible suggestions of how this could be done, and I am sure that the authors can come with even better ways to address this issue in the revised manuscript.

a) We think that here a normalization by the cell size is meant. Right now this is done. Also the resolution radii are naturally normalized by the cell size. See also previous points.

b) Additional explanation of normalization by the cell size will be included.

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5) I find the forward modelling very interesting and important as it helps evaluating the data in a much better way. However forward modelling is restricted only to ERT data and is not extended to reproducing a seismic model (with a geometry identical to the one used in the field) which could then be jointly inverted with the synthetic ERT data. This joined inversion synthetic model could demonstrate the superiority of the approach (or maybe also some limitations) under the given field conditions and measurement geometry. Note that this suggested addition is not meant to serve as a general synthetic model study, but as a unique model tailored to the actual survey conditions which will really help to better evaluate the actual real data results.

a) Refraction data are not much effected by 3D effects. Due to the first arrival picking, only signals are taken into account that took shortest way or travelled in the fastest medium. The small island next to the profile consists of the same bedrock as directly in profile line. Assuming the same velocity, the first arrival is still from the signal traveling in profile line, because the way is shorter. The small bay (water body) north of the profile would be a low velocity anomaly, which can be ignored, because this will not give a refraction, as an increasing velocity is needed for that.

b) We will add a reference for this.

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6) Joined inversion Results: the geoelectrical joined inversion result are at parts difficult to justify. The joined inversion result clearly constrains the thickness of the sediments and also helps identify a fracture zone. The geoelectrical image however also depicts very high resistivity values with high “coverage” at the bottom parameters of the image esp. at the left bottom part of the image. This is very different compared to the independent inversion results. More importantly why now the bottom left part of the inverted space (e.g. see parameter at x=100m, z=-125) is more reliable? How this is justified given that the seismic image information is inexistent for this region and generally this part of the model is well established that it has an inherently low resolution in geoelectrical surveys? I believe that the high ‘coverage’ of this part of the model is due to the size of the parameters in combination of their extremely high resistivity values which however are not reliable. I believe that the points made in previous remark hold also for this case so again I feel that it strengthens that argument that authors need to reconsider the way they present the results.

a) The alpha shading is based on the sensitivity distribution of the final model. If the final resistivity distribution is different, the sensitivity based coverage will be as well. Sensitivity doesn’t take the electrode contact into account. That means as a low resistive zone channels the current and the signals, a high resistive anomaly will do the opposite and leads to larger penetration depth. The seismic does not cover the onshore part, but it delivers the bedrock interface towards the ERT result, which also affects the onshore part of the ERT result.

b) This comment is solved updating the figures to binary alpha-shading.

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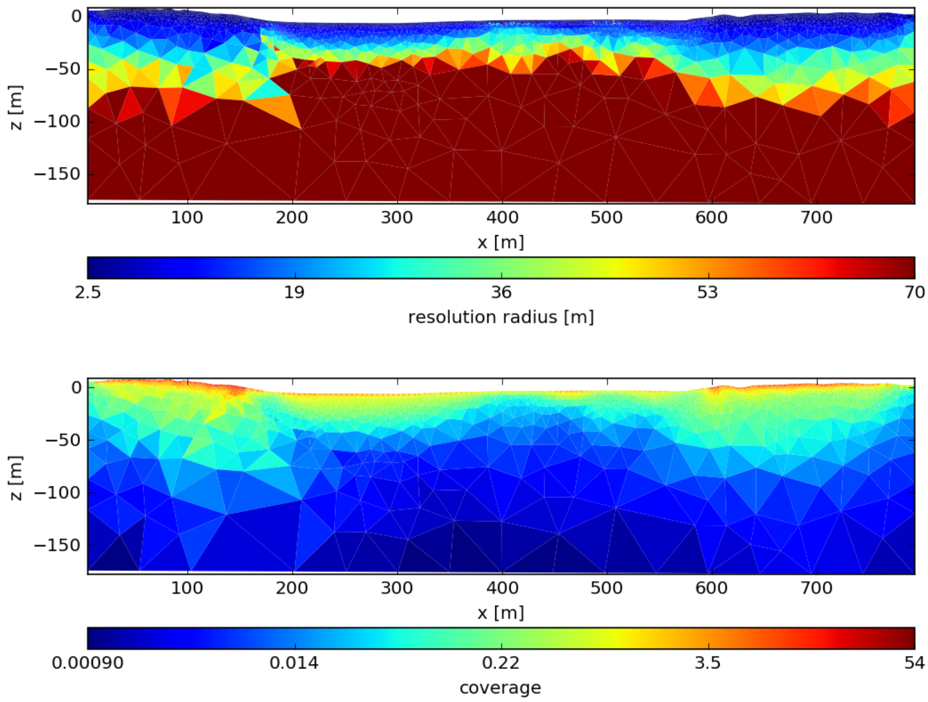

Fig. 1. For comment 3) - Calculated resolution radii distribution and coverage for the final ERT model