

Solid Earth Discuss., referee comment RC1  
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## Comment on se-2020-215

Anonymous Referee #1

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Referee comment on "Four-dimensional tracer flow reconstruction in fractured rock through borehole ground-penetrating radar (GPR) monitoring" by Peter-Lasse Giertzuch et al., Solid Earth Discuss., <https://doi.org/10.5194/se-2020-215-RC1>, 2021

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Review for the manuscript: "4D Tracer Flow Reconstruction in Fractured Rock through Borehole GPR Monitoring"

In the manuscript, the authors describe a methodology to monitor fluid movement caused by a tracer test in granite geothermal reservoir. They apply a combination of reflection imaging and crosshole attenuation tomography to derive information on the temporal and spatial evolution of a flow field induced by a pumping experiment. Some paragraphs require language editing and should be rephrased by a native speaker. Nevertheless, the manuscript present a novel application that is of general interest to the audience and fit into the focus of this journal. Therefore, I recommend publishing this manuscript after answering to the following moderate revisions:

Page 1, line 15ff: "Our methodology proved to be successful for characterizing flow paths related with geothermal reservoirs in crystalline rocks, but it can be transferred in a straightforward manner to other applications, such as radioactive repository monitoring or civil engineering projects."

I think the authors did not proved, but moreover demonstrated the applicability of the method. Furthermore, the manuscript describes not the characterization of flow path, but of tracer flow (or fluid movement), please be more specific through the manuscript.

I believe the reader requires more background regarding the development of time-lapse GPR imaging, which is yet not well covered in the introduction. Here citing a Brewster and Annan (1994) and and a conference contribution by Allroggen et al., does not cover the state of the art research in time lapse GPR imaging. I suggest to including some of the references listed in the following more recent publications:

Mangel, A. R., Moysey, S. M. J., & Bradford, J. (2020). Reflection tomography of time-lapse GPR data for studying dynamic unsaturated flow phenomena. *Hydrology and Earth System Sciences*, 24(1), 159–167. <https://doi.org/10.5194/hess-24-159-2020>

Allroggen, N., Beiter, D., & Tronicke, J. (2020). Ground-penetrating radar monitoring of fast subsurface processes. *Geophysics*, 85(3), 1–19. <https://doi.org/10.1190/geo2019-0737.1>

Haarder, E. B., Binley, A., Looms, M. C., Doetsch, J., Nielsen, L., & Jensen, K. H. (2012). Comparing Plume Characteristics Inferred from Cross-Borehole Geophysical Data. *Vadose Zone Journal*, 11(4), 1539–1663. <https://doi.org/10.2136/vzj2012.0031>

Allroggen, N., Garambois, S., Sénéchal, G., Rousset, D., & Tronicke, J. (2020). Crosshole reflection imaging with ground-penetrating radar data: Applications in near-surface sedimentary settings. *GEOPHYSICS*, 85(4), H61–H69. <https://doi.org/10.1190/geo2019-0558.1>

Page 6, Line 120: “The formation water showed a conductivity of around 80  $\mu\text{S}/\text{cm}$ ”.

Do you have information on the density difference of the formation water and the infiltration water. Does it make a differences for the flow formation or can the density differences be neglected?

Page 6, line 131: “In total, we acquired three GPR data sets...”

Please make sure what you mean by data set and profile. Maybe add an overview table showing the recording times and the duration of each survey?

Page 7, line 170: “...(removal of eigenvectors associated with the largest eigenvalue).”

How much of the data variability was removed in this process? How many eigenvectors did you remove?

Page 7, line 173: “...that was confirmed by the tomography results, other GPR surveys at the test site..”

Something is missing in this sentence?

Page 9, line 198: "Despite the extensive correction procedures, the difference profiles still exhibited minor artifacts, resulting from improper canceling of static reflections and diffraction."

Similar observation have been analysed using time-lapse attributes by Allroggen et al 2016. I am not saying that you have to use such attributes, but you should at least cite this publication. Especially when presenting the SVD based filter approach.

Allroggen, N., & Tronicke, J. (2016). Attribute-based analysis of time-lapse ground-penetrating radar data. *Geophysics*, 81(1), H1–H8.  
<https://doi.org/10.1190/geo2015-0171.1>

Page 9, line 202: "As for the baseline reflection processing, a time-domain Kirchhoff-migration was then applied to the difference section."

Migration is an backpropagation of the wavefield. I do not understand how this backpropagation can be applied on the differences between two wavefields. Please add some theoretical background (or references). To my understanding the migration should be applied before subtracting the wavefields from each other, to not introduce additional artifacts (e.g., diffraction hyperbolas )?

Page 9, line 204: "we did not encounter significant sampling rate variations or drifts."

How did you the sampling rate shifts? Please add more details or remove this part from the manuscript. Furthermore, single sentences paragraphs should be merged.

Page 17, line 343: "Therefore, we combined the results from the two reflection surveys to at least partially overcome the radial ambiguity and confine the tracer localization:"

How do you partially overcome an ambiguity? Please rephrase.

Page 21, equation 6 and 7:

In think, you can remove the  $\mu$  from the equation as it is typically close to 1 for natural materials and therefore often ignored (low loss assumption)

Page 21, line 421: "However, the tomography resolution and the necessary regularization makes it impossible to visualize small fractures in the results"

But the aim is to image fluid pathways, why to mention fractures? To my experience changes in the conductivity are images very differently than small constant features. Please rephrase.

Page 21, line 435 : "...but the apertures obtained are realistic. This is an indication that our attenuation tomograms are also realistic."

Can you provide a reference for a realistic fracture width? What does a realistic fracture width at a single position has to do with the spatial distribution shown in the tomograms?

Page 2 line 35: "...waves in MHz to GHz frequency ranges." Should read range and not ranges

Page 2 line 26ff: usually the permittivity uses  $\epsilon$  as a symbol

Page 6, line 149: "In total, 38 usable reflection profiles were recorded"

Please add the averaged recording time of a profile.

Page 7, line 164: "With the subsequently applied difference processing, temporal changes between the individual measurements can be analyzed."

This sentence requires rephrasing.