Dear Reviewer,

First of all, we want to thank you for your time that you have put into our contribution. We are happy to hear that you found our work interesting. Your detailed revision and constructive criticism will improve the quality of our manuscript.

Direct answers to your individual comments are found below in blue text color.

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:

We will try to improve the language quality of the manuscript in the revised version.

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.

We will address this in the revised version and phrase this differently. Yet, we also want to emphasize here that the flow path geometry could be delineated with the method described. While classical (e.g., dye) tracer tests can characterize flow and transport, they are mostly unable to delineate the flow path geometry. We intended to highlight this advantageous feature of GPR. The new sentence will read as:

"Our methodology was demonstrated to be applicable for monitoring tracer flow and transport and 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 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 timelapse 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

Thank you for your comment and suggested publications. We will address this in the revised version by adding the following sentences in line 46:

"Also, the infiltration of water in unsaturated soil was successfully monitored with GPR (e.g., Trinks et al., 2001; Klenk et al., 2015). One key prerequisite of time-lapse GPR surveys is a high reproducibility and thus data consistency between the individual time steps. To this end, automated acquisition setups have been employed, such as by Mangel et al. (2020), who successfully demonstrated time-lapse reflection tomography to be capable of resolving water infiltration in the vadose zone. To resolve changes in time-lapse GPR images with higher robustness towards perturbations in the GPR traces that were unrelated to the monitored hydrological process, image similarity attributes were successfully applied to resolve fluid propagation (Allroggen et al., 2016; Allroggen et al., 2020)."

Page 6, Line 120: "The formation water showed a conductivity of around 80 µS/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?

There is a difference in density. Formation water density was approximately 1000 g/L, while the saline tracer had an approximate density of 1030 g/L. How much difference it makes for the flow formation is uncertain, however we could not compensate for the density difference with ethanol (as described in Shakas et al. 2017) in these experiments, due to concerns about bacteria growth. We will mention this uncertainty in the revised version and make clear that comparisons with more conservative tracers need to be made with caution by adding the following in line 130:

"The salt-water-ethanol tracer that was used by Shakas et al. (2017) and Giertzuch et al. (2020) could compensate the increased density of the saline tracer in comparison with the formation water. However, in the experiments presented here, this mixture could not be used due to concerns about bacteria growth related to the ethanol. The results in Giertzuch et al. (2020) and the reflection results presented in this manuscript, do not diverge strongly, such that the effect due to the density difference is assumed to be little. However, comparisons with more conservative tracers need to be made with caution."

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?

We will make this clearer in the revised version by adding an overview table.

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?

We removed only the eigenvector related to the largest eigenvalue, which mainly relates to the direct wave. The line should read "…(removal of the eigenvector associated with the largest eigenvalue)."

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

Something is missing in this sentence?

Yes. Thank you for noticing. The line should read "...that was confirmed by the tomography results, and other GPR surveys at the test site..."

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

The general problem of improper cancellation is known for difference imaging and different approaches to respond to this have been considered. Most of the signal was properly cancelled from our previously applied processing routine. This additional filter enhanced image clarity by suppressing artifacts, but this was not a key step to overcome the problems of data compatibility issues in general. We are aware of the Allroggen and Tronicke publication, which successfully imaged soil irrigation this way. However, there is no SVD based filter mentioned in this publication. Therefore, we do not judge a comparison to their approach is necessary here. Nevertheless, we will mention their approach in the revised introduction, as stated above.

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 sime theoretical background (or references). To my understandung the migation should be applied before subtracting the wavefields from each other, to not introduce additional artifacts (e.g., diffraction hyperbolas)?

We have applied the migration after the wavefield difference calculation for multiple reasons. The data differences should to our understanding be calculated on data with as little processing as possible in order to not introduce additional processing artifacts. Diffraction hyperbolas are to our understanding not an artifact, but actual data, and should thus be treated as such to calculate data differences. Some processing is necessary to retrieve compatible data sets, however migration does not help with this regard. The general application of a migration on difference data has been justified in Dorn et al. (2011), due to the linearity of the Kirchhoff migration. It has been used successfully on difference data in several studies with borehole antennas in fractured rock, such as: Dorn et al. (2011), Dorn et al. (2012a), Dorn et al. (2012b), Shakas et al. (2017), Giertzuch et al. (2020). In the revised version, we will add to line 202:

"This is possible on difference data, due to the linearity of the migration routine and makes the resulting profiles comparable to migrated GPR sections (Dorn et al., 2011). Furthermore, it helps to reduce ambient noise in the difference data due to focusing of the energy."

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.

Strong sampling rate drifts can typically be observed in the raw data by trace comparisons. Additionally, Giertzuch et al. (2020) have described a method to quantify and correct for such drifts. In our experiments, such variations were not significant, and the procedure of Giertzuch et al. (2020) consequently could not improve the results. However, as the data processing routine in this manuscript closely follows that of Giertzuch et al. (2020), we judge it appropriate to mention that here we have diverged from this routine and that the reason for strong drifts is likely the control unit, rather than the antennas.

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.

We will rephrase this in the revised version as:

"Therefore, we combined the results from the two reflection surveys to reduce the radial ambiguity and confine the tracer localization."

Page 21, equation 6 and 7:

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

We agree that μ can be removed, but with regard to the comments of the second reviewer, we have decided to remove the back-of-the-envelope calculation on fracture apertures. Hence, this part will not be included in the revised version.

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.

Virtually all fluid flow in fractured crystalline rock occurs within the fracture network, hence fluid pathways are constrained and defined through the fractures. However, with regard to the comments of the second reviewer, this part will not be included in the revised version.

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?

The fracture aperture for the targeted fracture in the injection interval is on the order of 10^-4 m, according to Brixel et al. (2020). However, with regard to the comments of the second reviewer, this part will not be included in the revised version.

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

We will address this in the revised version as:

"GPR makes use of electromagnetic waves in the MHz to GHz frequency range."

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

We will address this in the revised version.

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

Please add the averaged recording time of a profile.

We will address this in the revised version, also within the suggested overview table.

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

We will rephrase this in the revised version as:

"Subsequently, we applied difference processing, such that temporal changes between the individual measurements can be analyzed."

Thank you for your time and review!

Mentioned publications in our answers:

Trinks, I., H. Stümpel, and D. Wachsmuth (2001), Monitoring water flow in the unsaturated zone using georadar, *First Break*, **19**(12), DOI: 10.1046/j.1365-2397.2001.00228.x.

Klenk, P., S. Jaumann, and K. Roth (2015), Quantitative high-resolution observations of soil water dynamics in a complicated architecture using time-lapse ground-penetrating radar, *Hydrology and Earth System Sciences*, **19**(3), 1125–1139, DOI: 10.5194/hess-19-1125-2015.

Shakas, A., N. Linde, L. Baron, J. Selker, M.-F. Gerard, N. Lavenant, O. Bour, and T. Le Borgne (2017), Neutrally buoyant tracers in hydrogeophysics: Field demonstration in fractured rock, *Geophysical Research Letters*, **44**(8), 3663–3671, DOI: 10.1002/2017GL073368.

Dorn, C., N. Linde, T. Le Borgne, O. Bour, and L. Baron (2011), Single-hole GPR reflection imaging of solute transport in a granitic aquifer, *Geophysical Research Letters*, **38**(8), DOI: 10.1029/2011GL047152.

Dorn, C., N. Linde, T. Le Borgne, O. Bour, and M. Klepikova (2012a), Inferring transport characteristics in a fractured rock aquifer by combining single-hole ground-penetrating radar reflection monitoring and tracer test data, *Water Resources Research*, **48**(11), DOI: 10.1029/2011WR011739.

Dorn, C., N. Linde, J. Doetsch, T. Le Borgne, and O. Bour (2012b), Fracture imaging within a granitic rock aquifer using multiple-offset single-hole and cross-hole GPR reflection data, *Journal of Applied Geophysics*, **78**, 123–132, DOI: 10.1016/j.jappgeo.2011.01.010.

Giertzuch, P.-L., J. Doetsch, M. Jalali, A. Shakas, C. Schmelzbach, and H. Maurer (2020), Time-lapse ground penetrating radar difference reflection imaging of saline tracer flow in fractured rock, *Geophysics*, **85**(3), H25–H37, DOI: 10.1190/geo2019-0481.1.

Brixel, B., M. Klepikova, Q. Lei, C. Roques, M. R. Jalali, H. Krietsch, and S. Loew (2020), Tracking Fluid Flow in Shallow Crustal Fault Zones: 2. Insights From Cross-Hole Forced Flow Experiments in Damage Zones, *Journal of Geophysical Research: Solid Earth*, **125**(4), e2019JB019,108, DOI: 10.1029/2019JB019108.