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Comment on hess-2022-209

Anonymous Referee #2

Referee comment on "Characterization of the highly fractured zone at the Grimsel Test Site based on hydraulic tomography" by Lisa Maria Ringel et al., Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2022-209-RC2, 2022

Review comments on Ringel et al 2022 manuscript: Characterization of the highly fractured zone at the Grimsel test site based on hydraulic tomography (https://doi.org/10.519/hess-2022-209)

General Comments:

This manuscript presents the first use of a stochastic inversion method for estimating the location and hydraulic parameters of a 3D discrete fracture network (DFN) using hydraulic tomography (HT) field testing. The field application is a volume centered on 2 shear zones at the well-studied Grimsel test site, and substantial use is made of data and experience from prior testing at this site. The objective of this paper is "to reveal the feasibility and capability of 3D DFN inversion in practice under well-explored field conditions" (L65-66). Principal results are estimations of probable locations and parameterization of fracture connections between the 2 shear zones.

My overall assessment of the manuscript is strongly affected by the very limited application of HT (only 4 tests between a total of only 4 packed-off intervals in 2 boreholes) in a very limited volume of investigation that is modeled and interpreted with the use of a large amount of prior characterization and testing information, simplifications, and assumptions (L166-207). In this regard also, I question whether the issue of non-uniqueness is sufficiently addressed – and perhaps only can be for this type of study with prediction of field validation tests in different multi-well, multi-zone testing configurations, and/or which might include tracer tests that have multi-zone multi-well monitoring.

As currently presented, the combination of few HT tests with large amounts of prior data and assumptions (much of which restrict the range of possible fracture and fracture network occurrence - see Specific Comments below for L172-177 and what is shown in Fig 6 with particular relevance to this issue), and modeling the few tests within a small volume (i.e., close boundaries including 2 shear zones treated as having impermeable "cores"), raise questions about: (1) what the HT actually contributes to the results; (2) how sensitive the results are to the many individual and combined priors and assumptions; and (3) how feasible and capable the method is for application at other sites that may not have such abundant prior information or small volume of investigation and modeling.

Overall, my recommendation is either to recast the manuscript as a technical note or case study with revisions, or to rework the analysis with more of the available pressure data from some of the other 13 of 15 wells - and/or new tests and observation zones as suggested above - so a potentially more-realistic, alternative fracture network might be revealed and evaluated more clearly (i.e., with less reliance on constraining priors and assumptions).

Specific Comments:

L104-105 and L157-164: Why apply noisy data directly rather than use smoothed data (e.g., can be as simple as a moving average) and thereby reduce the error and uncertainty? See L232-234 where the text acknowledges the reduced quality and meaning of prediction uncertainty due, at least in part, to measurement noise.

L123-129: S3 shear zones are given impermeable cores but can be traversed by placing fractures across them. This makes sense as a strategy to manage realism with simplicity. Are any such fractures that cross S3 shear zones evident and placed in the modeling results? It is difficult to tell from Fig 6.

L133-139: Boundaries of specified pressure (at AU) and Robin type (at VE), and S3 shear zones with fixed impermeable cores, are so close to the HT test volume that they likely have effects on observed and modeled pressure changes (especially since rock matrix outside of modeled fractures is treated as impermeable). Commonly models move boundaries out far enough to have minimal effects, but that is not possible in this case. Some of the time-buildup curves in Fig 6 seem to under-match the observations suggesting perhaps "buffering" effect with boundaries? Perhaps this could be checked by modeling the HT tests with several very low to intermediate to actual injection rates to see if the build-up curves become affected progressively?

L169: For reference, since computing cost trade-off for accuracy (or for problem size?) is a stated consideration, it might be good to add what computing and time resources were used for the full set of realization runs. This type of information is commonly included in HT papers on new methods or applications.

L172-177 (and Fig 6): Important fixed modeling simplifications include 2 sets of fractures that have fixed orientations and that are surrounded by impermeable rock matrix. However, apparently contrary to these rules, Fig 6 shows several fractures at distinctly different angles than the 2 sets with fixed orientations - see panels for highly probable fracture locations and for highly probable large aperture occurrences at z=17m and z=16m in Fig 6. This occurrence of apparently disallowed fractures strongly suggests that modeling of all the test data with only the 2 fixed fracture sets does not fully compensate for additional fractures and fracture network structure. That is, it appears that there is a non-uniqueness issue that may be larger than just this Fig 6 non-allowed occurrence, and therefore should be acknowledged (in Section 4.3 and Section 5, L275-276), and should be somehow assessed.

L210: 27,000 DFN realizations are considered as posterior DFN realization. How many total realizations were run?

L284-287: The title suggests emphasis on HT, but future research recommendations here and description of other possible applications elsewhere (next comment) only consider more priors and prior treatments rather than more-capable HT designs and execution – such as greater testing and observation coverage to get more-definitive hydrologic evidence on the hydrologic heterogeneity of the main fracture system and its associated nearby fracture network. Cost and time are often raised as obstacles for HT, but it might be good to consider how much additional "direct" HT coverage could be attained for at least some of the cost and time of the many other "indirect" types of data and investigation that also have associated costs and time for collection, analysis, and efforts to relate data to hydrology as priors such as for this paper.

L290-294: This research at the Grimsel site may be focused on the connectivity of higher conductivity fractures between 2 shear zones, but other applications (e.g., repository leakage, directed circulation for in-situ remediation of contaminated source zones, multi-scale effects in critical zones…) may need quantitative understanding of less spatially restricted fracture occurrence, properties, connectivity, and network flow behavior – even in relatively small investigated volumes similar to this study. Can the method of this paper feasibly be adapted to get a full fracture network realization in a volume of a few 10s of meters in three dimensions, or scaled to larger volumes?

Technical Corrections:

Eqn 1 - T subscript for gradient operator needs to be explained.

Figure 4 - Shows only 2 gray and 1 orange data points for fracture set 2. Is this the full basis of support for this major fracture set? Unclear what the gray dots are vs what the colored (blue and orange) dots are.

Figure 5 – Recommend replotting on log-log axis scales to better assess the hydrologic responses in this common analytic frame of reference. Also it is difficult to distinguish between the two gray shades of prediction and posterior 95% limits. Perhaps add one generic axis label for pressure change on the left and one generic axis label for Elapsed time at the bottom, and change column labeling from caption letter codes to names of zones in wells at the top. Be explicit that plots of the injection zones per test are on the diagonal.

Figure 6 – It is difficult to relate the z positions to the model volume (no z axis or magnitudes shown in the very small cuboid reference diagram). Also it is difficult to read aperture magnitudes with the increment labeling on the shading scale. The text refers to east positioning (L255), so direction labels are needed here, and also in Fig 1. Enlarging the reference diagram would be helpful.