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On the Visibility of Non-Intersected 'Nearby' Fractures in Inter-Well Tracer Tests: Scoping Simulations, I

Julia Ghergut, Horst Behrens, Martin Sauter, Sebastian Schmidt, Bianca Wagner

Appl. Geosci. Dept., Goldschmidtstr. 3, University of Göttingen, 37077, Germany

iulia.ghergut@geo.uni-goettingen.de

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ABSTRACT

In past scoping simulations (2013a), we illustrated the parameter uncoupling between heat and solute (tracer) transport in a geothermal well doublet within a 'five-fracture reservoir' model, and the use of thermosensitive tracers to restore the correlation between thermal lifetime (as a prediction target) and tracer signals (as an early predictor). In the present technical note, we look into the effects of non-intersected fractures 'inside' or 'outside' the reservoir on inter-well tracer test signals. Unlike in the past study, where fracture parameters were varied uniformly for the whole set of fractures, we now 'switch' fractures on and off individually. Preliminary scoping simulations on this greatly simplified five-fracture geometry indicate that tracer signals before ~two 'reservoir turnover time' units exhibit slight influences from fracture presence or absence, yet not sufficient sensitivity to enable 'detecting' the presence of non-intersected fractures, neither 'outside' nor 'inside' the reservoir. Though the fracture sensitivity of tracer BTCs generally increases with observation time, late tailings of tracer signals still cannot provide a sensible 'method' for fracture detection. Nonetheless, it still seems worthwhile attempting to provide a tracer BTC 'type-curve' framework for such systems, given that the tracer-based 'inversion' of some of the matrix-fracture system parameters can sometimes be constrained by other methods.

1. INTRODUCTION

In Ghergut et al. (2013a) some scoping simulations were presented regarding tracer tests in a five-fracture system (fig. 1), mainly with the purpose of demonstrating the parameter uncoupling between heat and solute (tracer) transport: heat transport was seen to be more sensitive to fracture apertures, and rather insensitive to matrix porosity, whereas solute transport was seen to be highly sensitive to matrix porosity (as expected) but rather insensitive to fracture parameters (somewhat surprising); further, we illustrated how thermosensitive solute tracers with certain properties (cf. Nottebohm et al. 2012, Schaffer et al. 2016) can 'restore' the sensitivity of tracer signals w. r. to fracture apertures, and thus the predictability of thermal breakthrough from (early) tracer signals.

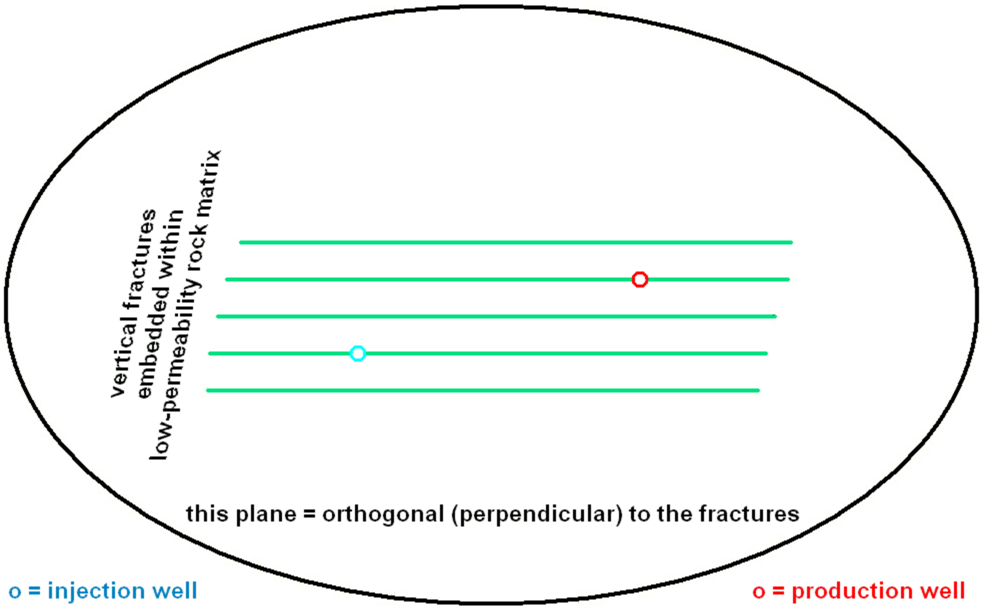

Figure 1: Top view of the 'five-fracture' pastiche model.

The present technical note addresses a different aspect, which was raised in the context of tracer test planning for some geothermally-exploited Malm aquifers below the Molasse basin in the Southern Munich area, Germany. Amongst other issues (cf. Dewi et al. 2016), one question raised was: how will the presence of 'nearby' fractures or fault zones (that are presumably not intersected by the geothermal wells, yet likely to occur within short distance) be perceived in the measured tracer test signals? can the latter serve to 'detect' or 'ascertain' the presence of those fractures? – facing the not uncommon situation that some fractures or faults that have been identified by the large-scale geophysical exploration remain 'invisible' in hydraulic tests, or, conversely, hydraulic tests sometimes indicate the 'effectiveness' of fractures or faults that could not be 'detected' by exploration methods. Beyond this context, the roughly-simplified caricature model (fig. 1) used in simulations here might also serve – depending on the modeling task – as a 'pastiche' for scoping simulations on tracer test sensitivity in different other geo-settings in the N-German basin.

2. A PASTICHE MODEL

Through its finite number of fractures as well as their finite longitudinal and lateral extension, this model (fig. 1) is essentially different from both the multiple single-fracture models dealt with by Karmakar et al. (2016), and from the parallel-fracture model considered in Ghergut et al. (2013b). It loosely resembles, or mimics certain features from geothermal reservoir settings in Southern Germany at which tracer tests are currently under consideration (cf. Dewi et al. 2016), or from geo-settings in Northern, central and Southern Germany at which tracer tests were conducted since 2003 (cf. Ghergut et al. 2013ab, 2016), comprising both natural and artificially-induced fractures, orthogonal and/or oblique to the inter-well 'axis', some intersected, some not intersected by the wells, some 'feared' to act as a hydraulic or and/or transport short-cut, some 'hoped' to act as lifetime-prolonging for the geothermal system under consideration.

3. NON-/ADVECTIVE TRANSPORT PARAMETERS OF ROCK MATRIX AND FRACTURES, AND THEIR INTERPLAY

Despite the seemingly extreme simplicity of this model geometry (fig. 1), flow and transport patterns within this geometry do not follow a universal scheme, and are also difficult to categorize into a finite number of distinct types. This is due to the competing (lifetime-prolonging and lifetime-shortening) effects of matrix and fracture parameters, most of which act (in sometimes opposite ways) on both the advective and non-advective contributions to solute transport:

– fracture aperture: controls the lateral transmissivity component;

– fracture aperture: controls the matrix diffusion rate, for both heat and solutes;

– fracture aperture: controls the longitudinal advection velocity;

– fracture aperture: controls the lateral advection velocity;

– matrix permeabilities (Kxx, Kyy): control both the lateral and longitudinal advective flux components;

– matrix porosity: controls both the lateral and longitudinal advective velocity components;

– matrix porosity: controls the solute diffusive fluxes;

– fracture height: controls the inter-well transmissivity component;

– fracture spacing, fracture length, fracture height: control the reservoir turnover volume; they also relate to the overall reservoir size; a re-scaling study is to be performed separately from parameter sensitivity analysis.

Moreover, one and the same process may have a lifetime-prolonging, or a lifetime-shortening effect depending on its location 'inside' or 'outside' the reservoir, and, in the latter case, on whether it is 'injection-outwards' or 'outwards-production'.

4. SCOPING SIMULATIONS (I), SWITCHING OFF INDIVIDUAL FRACTURES

While in the scoping simulations presented by Ghergut et al. (2013a) fracture parameters were varied uniformly (same way for all fractures simultaneously), here we are interested in probing the effects of fractures individually, i. e., by 'switching' fractures on/off one-by-one, and looking at how their effects differ depending on their location 'inside' or 'outside' the reservoir (and closer to injection or to production wells, respectively).

Figure 2 compares the hydraulic head distribution in the matrix-fractures system (top view) for the three cases, switching off, one-by-one, the inside fracture and the two outside fractures. To be noted, pressure signals at the injection and production wells do respond to such changes, yet we do not address them here, since the motivation for the present study was precisely the reported "persistent ambiguity of hydraulic test inversions". Before attempting to develop procedures for a joint inversion of pressure and tracer signals, some more scoping simulations on the 'tracer-only' side are needed. Furthermore, pressure signal inversion is in turn affected by a number of fracture-non-related factors, especially at early times, which require a separate analysis before attempting the 'causal' attribution of a certain signal feature to the presence of a certain fracture.

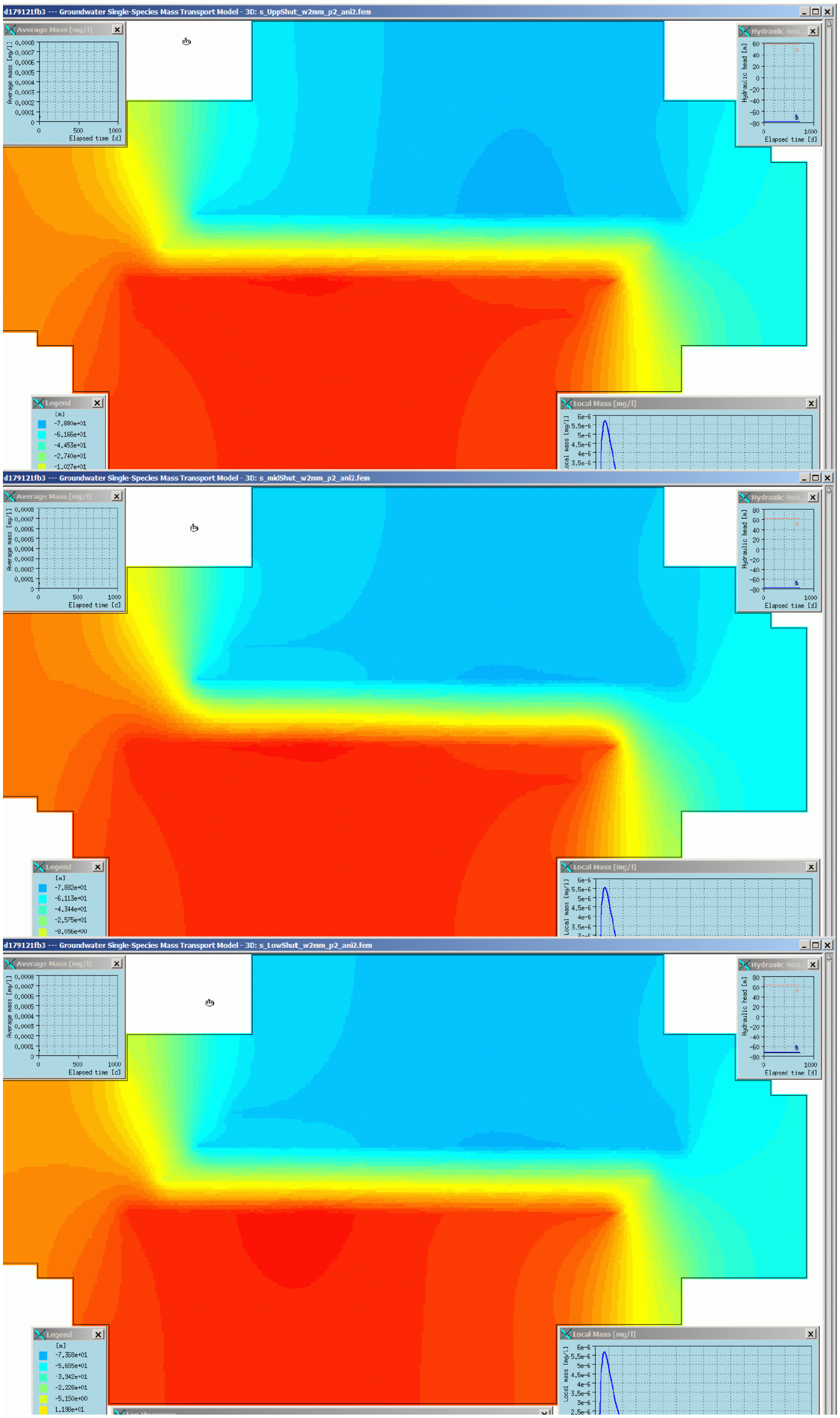

Figure 2: Hydraulic head distribution in the matrix-fractures system (top view) when switching off, one-by-one, the ‘outside’ fracture close to the production well, the ‘inside’ fracture, and the ‘outside’ fracture close to the injection well, respectively.

Figure 3 shows the predicted tracer signals for the three cases (one fracture missing 'inside' or 'outside' close to injection or production well), compared to the reference (all-fractures-present) case.

The time axis in fig. 3 is 'scaled' by a reservoir turnover time 'unit' T1, defined by dividing the matrix pore volume V1 comprised in-between all fractures by the fluid turnover rate (injection and production rate). One should not interpret T1 or V1 as 'reservoir turnover time' or 'reservoir turnover volume'; the latter shall always be larger than T1 and V1, respectively, however in roughly this order of magnitude. The tracer signal axis is scaled by a flux concentration 'unit' defined by dividing the total quantity of tracer added at the injection well (as a finite pulse of duration much shorter than T1) by the reference volume V1. This is only a pseudo-scaling, since the simulated tracer BTCs will not remain invariant to changes of the overall system size (invariance holds only as long as the matrix porosity is kept fixed, and matrix diffusion effects remain negligible).

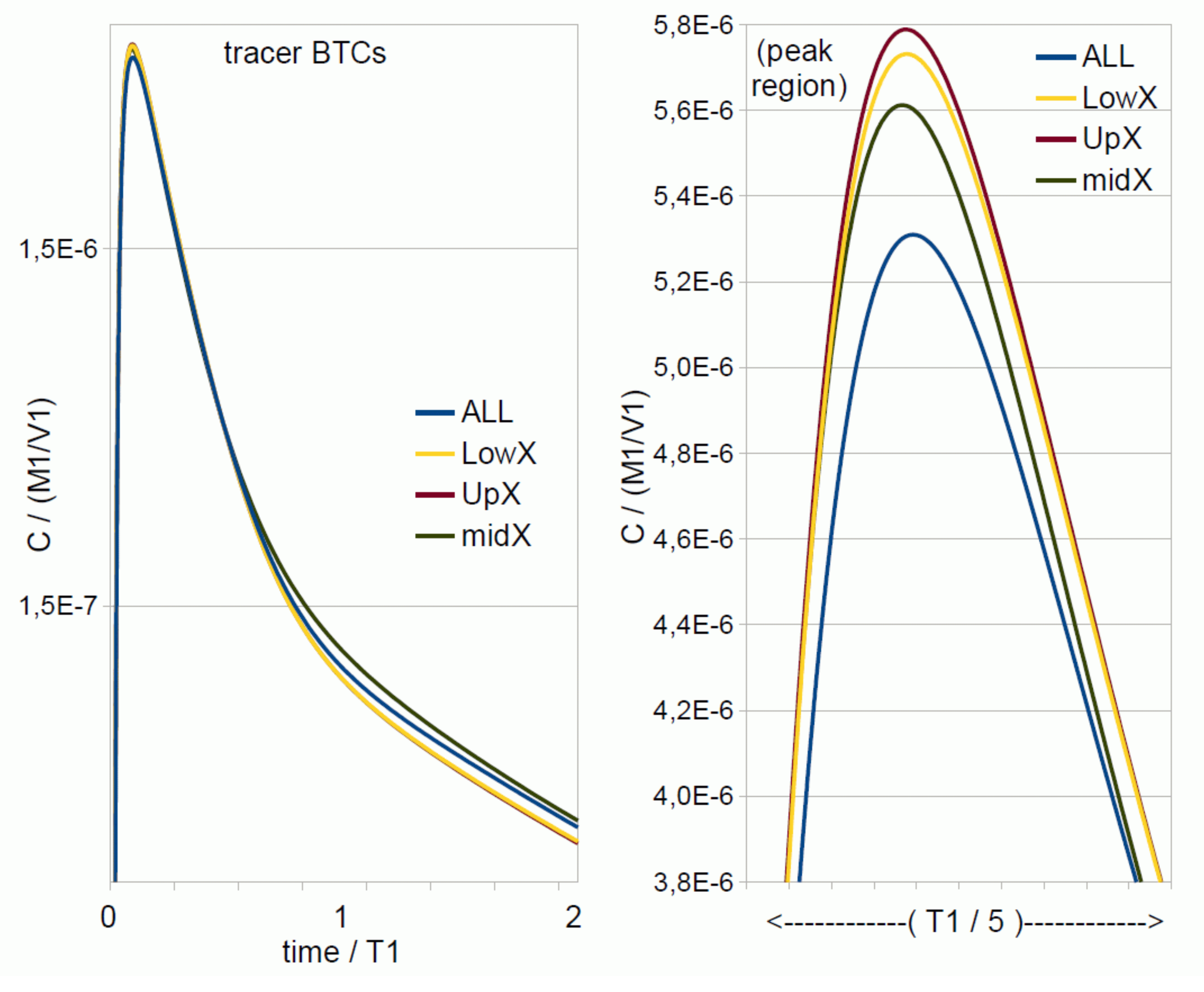

Figure 3: Tracer signals in the all-fractures-present case, compared to the one-fracture-missing cases.

Figure 4 compares the spreading of the remnant tracer plume after twice T1 for the three cases. By 'remnant' we mean tracer that has not yet been retrieved at the production well (to be noted, the model does not consider tracer recirculation by way of re-injection; in other words, the model simulations yield tracer BTCs 'already de-convolved'). In all cases, by the end of twice T1, most of the remnant tracer has left the fractures, and is now concentrated around fracture edges.

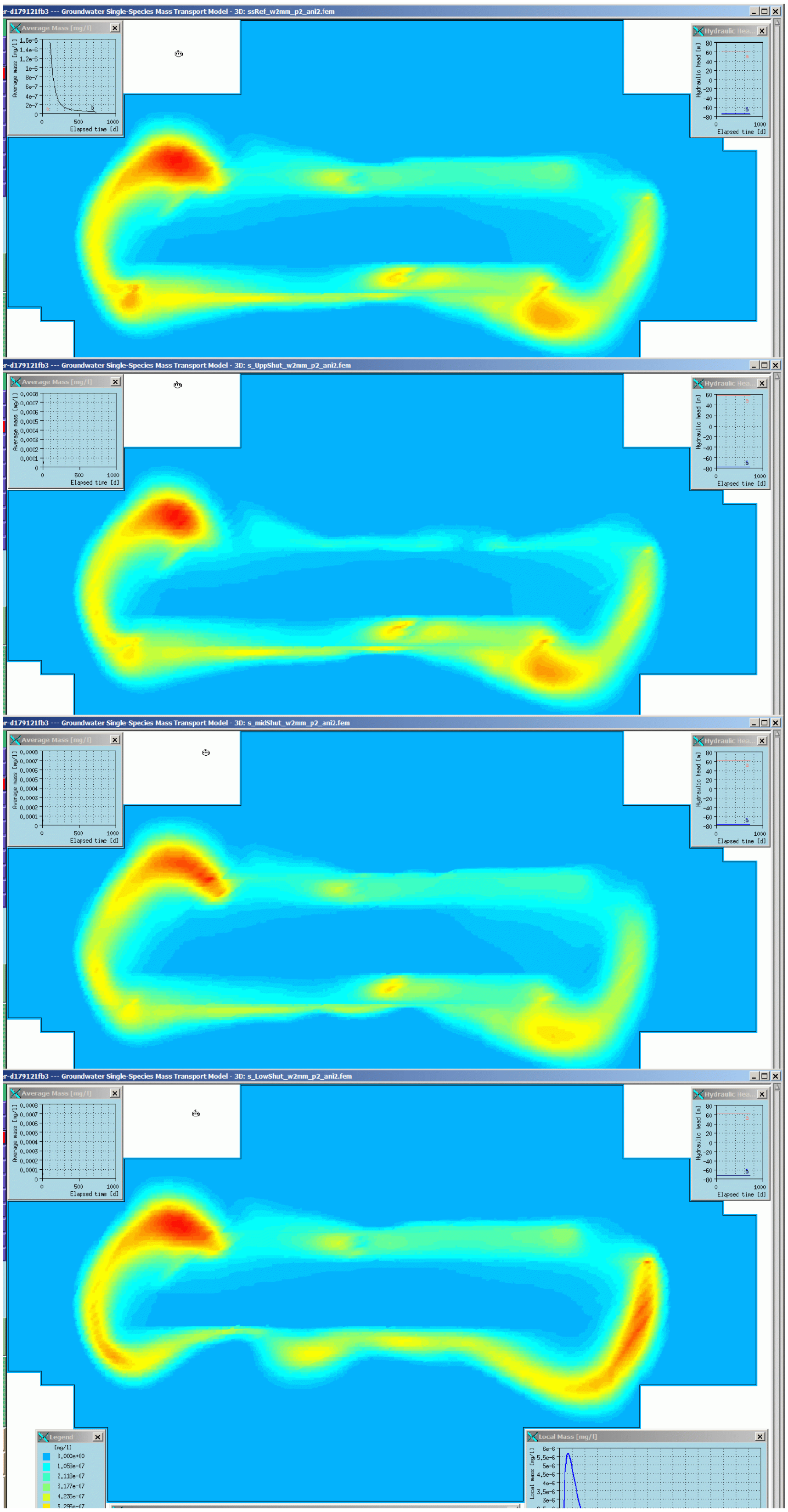

Figure 4: Remnant tracer plume spreading in the all-fractures-present case, compared to the one-fracture-missing cases, after twice T1.

5. PRELIMINARY FINDINGS FROM SCOPING SIMULATIONS, AND NEED FOR FUTURE STUDIES

From fig. 3 it can be recognized that the fracture sensitivity of early tracer signals is insufficient to enable ‘detecting’ the presence of non-intersected fractures (neither ‘between’ injection and production wells, nor ‘injection-well-outwards’, nor ‘outwards-production-well’). Tracer signals for the different cases differ by less than 10% from each other (which is below measurement errors and overall uncertainty even in the ‘best world possible’). Late tailings, available if monitoring were continued for about 10 T1 (which amounts to about one decade even for the physically ‘very small’ system of Ghergut et al. 2013a) show more significant differences between the cases with/without each fracture individually, and become fairly sensitive also to fracture parameters, but with such long durations of monitoring one can no longer speak of a ‘detection capability’. Furthermore, late tailing levels and slopes are influenced by a multitude of other factors (fault-zone heterogeneity and especially the multi-porous character of the rock matrix, not considered by this model), which, again, impede the unambiguous causal attribution required by a so-called ‘fracture detection’.

Further, one has to consider that the hydraulically-effective aperture of fractures may differ from their transport-effective aperture, and changing the hydraulic aperture will lead to a different distribution of fluid (and tracer) fluxes between matrix and fractures, thereby also influencing tracer signals; this aspect shall be explored in M. Sc. theses by N. Khaleefah and S. Mohandas Surekha (University of Göttingen, in prep.), who shall also show the effects of individual fractures on heat transport and thermal breakthrough at the production well.

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