PROCEEDINGS, 43rd Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 12-14, 2018
SGP-TR-213

Sorption, matrix diffusion, … need not make a major difference for frac characterization from short-term tracer signals

Julia Ghergut, Horst Behrens, Jac Bensabat*, Martin Sauter, Bianca Wagner, Bettina Wiegand

University of Göttingen, Geoscience Centre, Goldschmidtstr. 3, 37077, Germany; *also with: EWRE Haifa, Israel

iulia.ghergut@geo.uni-goettingen.de

Keywords: artificial tracers, tracer test, single-well, flow-through, monopole-divergent, equilibrium adsorption-desorption, kinetic exchange, matrix diffusion, fracture-matrix, EGS, unconventional reservoir, reservoir stimulation, hydraulic fracturing, hydrofracturing, proppant-free, pure water frac, aseismic, N-German Basin.

ABSTRACT

The use of equilibrium adsorptive-desorptive or ion-exchanging (alongside with conservative, including contrasting-diffusivity) liquid-phase tracers for characterizing a single, large-area hydrofrac created at a pilot unconventional-reservoir site in the NW-German Sedimentary Basin is examined prospectively by numerical simulations. The purpose of the exercise is twofold: (I) to assist in the process of tracer species selection for upcoming tests at this particular site, and (II) to derive more general recommendations for the early-stage use of tracers in unconventional-reservoir development, from the '*Source*' and '*Pathway*' characterization perspective adopted within the EU-H2020 project "FracRisk" (grant no. 636811). In terms of S and P compartments (cf. fig. 5 in McDermott et al. 2014), the take-away from our scoping simulations can be summarized qualitatively: (i) overall tracer recovery ratios correlate with transmissivity ratios between hydraulically competing P, S compartments; (ii) tracer arrival times correlate with the effective aperture or porosity of the critical (spill-controlling) P compartment; (iii) mid-/late-time tracer signal slope changes may indicate geomechanical effects within P or S compartments. The pilot unconventional-reservoir site in the NW-German Sedimentary Basin offers the unique advantage of well-steerable forced-gradient flow conditions, thereby enabling to more reliably estimate in-situ adsorption-desorption properties for a number of tracer species currently regarded as promising candidates for reservoir stimulation applications. On the other hand, processes like tracer adsorption-desorption and/or matrix diffusion need not make a major difference for frac characterization from short-term tracer signals.

1. INTRODUCTION

According to a popular belief, sorptive species (amongst the liquid-phase tracers) should provide the privileged 'tool of choice' for quantifying fluid-rock interface areas in hydrogeological systems. Mostly, this belief is not accompanied by a precise definition of 'interface areas', whether in terms of total surface area, or surface-area density (area per volume, either bulk matrix or mobile-fluid volume), for which four different meanings have been examined in more detail by Ghergut et al. (2011). With a single-well push-pull (SWPP) test set-up, relying on a very small chaser injection volume (about half of the expected frac volume) to make the physical (pressure-drop related) limitations on liquid flowback volumes tractable, Karmakar et al. (2016) discussed some advantages but also significant limitations to using tracers with different sorptivity on proppant coatings and matrix rock surfaces, for gel-proppant fractures, and tracers with contrasting diffusivity or sorptivity, for hydrofracs. Given the small chaser volume, the fractures are perceived like 'infinitely-extended' for the whole duration of simulated SWPP tests (though being implemented as finite-extension in the numerical model that was used by Karmakar et al. 2016). Most recently, Hawkins (2017) finds organic compounds in guise of sorptive tracers to pose such severe problems in real-life field-size applications (with a multitude of in-situ physico-chemical influences whose variability in space and time or by their coupling with other dependent variables is hardly tractable by solute transport models), that anorganic cations (subject to ion exchange at rock surfaces) appear to him as a much more handy (and, as we believe, very promising) alternative; the process of ion exchange being formally analogous to adsorption-desorption at equilibrium, with the added bonus of lesser dependence on temperature, redox potential, etc. (though a pH dependence may still be significant).

In the present study, new scoping simulations are conducted w. r. to the use of equilibrium sorptive or ion-exchanging (alongside with conservative, including contrasting-diffusivity) liquid-phase tracers for characterizing a single, large (however finite) area hydrofrac created at the unconventional-reservoir pilot site in the Südheide (NW-German Sedimentary Basin) described by Tischner et al. (2004, 2010), Ghergut and Sauter (2015). The purpose of these scoping simulations is twofold: (I) assist in the process of tracer species selection for upcoming tests (2017/2018) at this particular site, and (II) derive more general recommendations for the early-stage use of tracers in unconventional-reservoir development, from the '*Source*' and '*Pathway*' characterization perspective adopted within the EU-H2020 project "FracRisk" (cf. fig. 5 of McDermott et al. 2014). Last not least, solute transport predictions implied by the present study can also become relevant from the mid- and late-stage perspective of hazard assessment and reservoir monitoring.

For ease of writing, in the sequel we use the term 'sorptive' to denote both adsorption-desorption (either 'weak' van-der-Waals-, or 'strong' covalent-type), as well as ion-exchange processes.

2. TECHNICAL BACKGROUND, AND SITE-RELATED MOTIVATION FOR THIS STUDY

At a 4-km deep well in the Südheide (NW-German Sedimentary Basin), formerly used for gas exploration below 4 km and now partly refilled, the BGR and LIAG Institutes (Federal Agency for Geosciences and Natural Resources, and Leibniz Institute for Applied Geophysics, based in Hannover, Germany) are evaluating the performance of innovative technologies for enabling and maintaining *high-rate fluid turnover in tight sedimentary* rock, using a single deviated wellbore that is screened in two disjoint intervals in different sandstone layers (some 100-150 m apart, with alternating thick claystone layers and thin sandstone horizons in-between). A special wellbore completion (with packers between tubing and casing to hydraulically uncouple the target screens from each other) enables to simultaneously inject and retrieve/produce fluids ("two wells in one borehole"). Several variations of this technique had originally been proposed and analyzed by Jung et al. (2005, 2006), Tischner et al. (2004, 2010), Wessling et al. (2009). These mainly comprised: (A) the option of inter-layer vertical push ('circulation') through a large-area, hydraulically-induced fracture (hydrofrac), (B) the option of establishing a large-scale fluid circulation system comprising both this artificially-induced hydrofrac and a nearby natural fault zone, and (C) small-scale, single-screen injection-withdrawal ('huff-puff') operation schemes, in suitable layers, all being seated in sedimentary formations in 3 – 5 km depth, with in-situ pore fluid pressure well exceeding hydrostatic levels, and temperatures exceeding 160 °C. Remarkably, option (B) could never be realized in practice – which at least indirectly bears testimony on the geological safety of artificial fracturing operations.

Within the large-scale interdisciplinary research project "gebo" ("Geothermal Energy and High-Performance Drilling", 2009 – 2014, funded by the government of Lower Saxony jointly with Baker Hughes, Celle), so-called 'gebo benchmark models' (GBM) were developed for eight reservoir candidate locations in the N-German Basin, each site posing a distinct challenge (Philipp and Reyer 2010, Philipp et al. 2011, Reyer et al. 2010, 2011) in terms of either drilling or of reservoir development technologies. The 8 sites were selected (Hördt et al. 2011) after screening a wealth of geo-exploration databases. Ongoing GBM development is aiming to

• provide a 'living repository' of geophysical, hydrogeological, geomechanical, thermal and hydrogeochemical data for economically-interesting sedimentary and volcanics layers in 3 – 6 km depth, from which the most promising reservoir exploitation paradigms for the N-German Basin were to be identified;

• make this knowledge accessible and understandable to all shareholders engaging in public debates on the environmental footprint of (especially unconventional) georeservoir technologies, and on hazards associated with these;

• enable knowledge and technology transfer from the past (conventional) hydrocarbon industry to the emerging (unconventional) geothermal, and from the latter 'back to' the (unconventional) hydrocarbon exploration.

Sustained work with the Südheide GBM beyond the scope of "gebo" (e. g., within the EU-H2020 project "MUSTANG") has repeatedly revealed the need to re-size model domains and re-design model geometries depending on the physical processes addressed and/or the particular field experiment setting used to interrogate those processes. For the purposes of the EU-H2020 "FracRisk" project, we again need to re-size and re-design the geometry of the model domain.

Whereas the georeservoir development and operation practices currently being tested in the Südheide are obviously very different from fracking and depleting a shale-gas reservoir, the special wellbore completion and the fully-instrumented fluid turnover and monitoring facilities at this site, alongside with the wealth of data already available from past experiments (2004ff.), offer some unique advantages worth exploiting within the "FracRisk" project, namely:

• opportunity to interrogate the fluid transport properties of hydrofrac and adjacent tight-rock matrix by tracer tests in a *flow-through* mode (which would not be technically feasible in the shale-gas realm),

• the large-area (~600 m height, up to 2 km length), nearly vertical hydrofrac of microseismically mute propagation in supra-salinary claystone/sandstone layers in the Südheide may also be regarded as a field-scale analogue of 'uncommon' (whether natural and induced) fluid migration pathways,

• opportunity to improve on public awareness and shareholder involvement.

The present study focuses on multi-tracer test design

• with the aim of quantifying frac area (viz.: frac length; with frac height being largely prescribed by lithostratigraphy) and frac aperture,

• under the constraint of a prescribed maximum rate of monitorable fluid turnover (viz., 20 L/s) and maximum duration (viz., two weeks) for fluid withdrawal; as to liquid-borne tracer signals during fracking operations in shale-gas reservoirs, the amount and thus the monitorable duration of HF liquid flowback is likely much shorter, therefore parameter sensitivity findings from the Südheide analysis shall provide the 'upper limit' of what can be expected from artificial tracers in HFF.

The 'multi-tracer' test endeavor is nourished by the expectation that "*interface areas can be quantified by using tracers with different diffusion and/or sorption coefficients*", and "*the higher the diffusion coefficient, the higher the sensitivity of a tracer signal w. r. to diffusion interface areas*", etc. Currently, such historically handed-down beliefs about the role of diffusion and/or sorption processes in 'metering' interface areas are still guiding the selection of tracer species for upcoming experiments in the Südheide (2017/2018) by third parties. Tracer signal simulations under the aforementioned constraints shall reveal some shortcomings to these beliefs.

3. TRACER TESTS AT THE UNCONVENTIONAL-RESERVOIR PILOT SITE; RE-DESIGNED MODEL GEOMETRY

Relying on past tracer test data (Behrens et al. 2006, 2009), alongside with data analyses (Ghergut et al. 2009, 2013[a], 2016) within "gebo" and the EU-H2020 project "MUSTANG", we once again adapt the GBM for the purposes of the EU-H2020 project "FracRisk". This comprises *enlarging the model vertically while reducing its lateral extension* (orthogonally to the frac plane). On the other hand, the hydrogeological parametrization of the model can greatly be simplified (fig. 1) for the purposes of short-term tracer test predictions (whereas for "FracRisk"'s aims of environmental hazard assessment certain lithostratigraphy details / variations shall later need to be considered). For a correct interpretation of tracer tests, from scoping simulations it proved of essential importance to consider the non-vertical well-path direction, i. e., the existence of a horizontal shift between its two screened intervals involved in tracer tests. Given the rather limited spatial scale of tracer tests, one can ignore the existence of a large-scale natural fault intersecting the former gas-well path (but no longer the current wellbore) in significantly greater depth. Therefore one may also assume symmetry w. r. to a vertical plane orthogonal to the hydrofrac, and containing the Detfurth and Solling well-screen intervals. Thus the lateral model size (along the frac plane) can be halved. The hydrofrac can be regarded as a planar (2-D) structure, coupled to a 3-D continuum (host rock matrix).

Flow and transport processes to consider comprise: rapid flow within hydrofrac (approximated by a 'cubic' law; allowing for variable hydraulic aperture, and for the transport-effective aperture to differ from the hydraulic one, cf. Tsang 1992), slow flow within host rock (approximated by Darcy's law; allowing for anisotropic permeability), advective-dispersive transport of (heat and) solute tracer within hydrofrac, exchange of (heat and) solute tracer between hydrofrac and host rock, diffusion-dominated transport of (heat and) solute tracer within host rock. Balance equations for fluid and solute mass, and for enthalpy (heat) are similar to those cited in Ghergut et al. (2013[b]), also allowing for the presence of a gas phase (which may become relevant later, at different field sites to be addressed within the EU-H2020 project "FracRisk"). However, for the purposes of the present study, we can ignore both the gas phase, and the temperature variability, given that long-term cold-water injections preceding the tracer tests ensure a roughly constant temperature, ~90 °C for the entire tracer test duration. On the other hand, fluid temperature cannot serve as an additional conservative tracer at this particular well, because temperature monitoring is not technically feasible downhole (room conflict with the somewhat intricate double-packer system), and uphole temperature values are altered by too many extraneous factors.

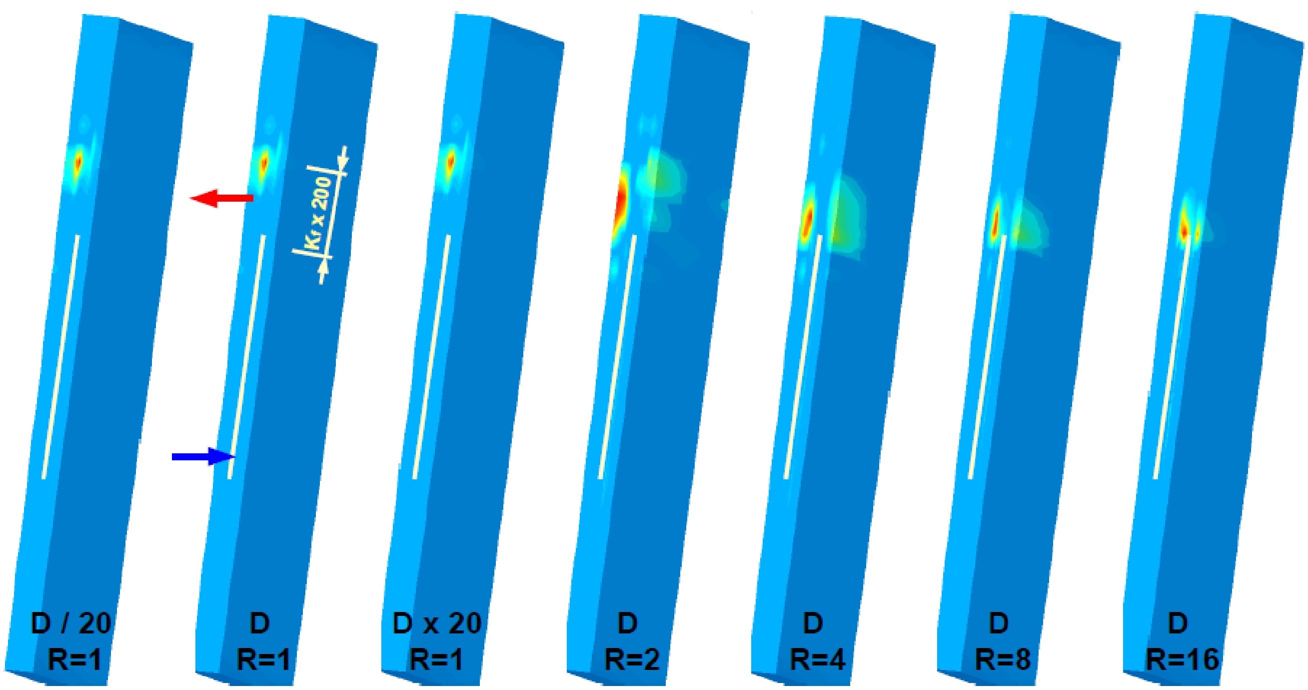

Figure 1: Model domain size reduction and simplified geometry for scoping simulations of a short-term field experiment. Also showing spreading patterns for the 7 different tracer species considered, by the end of the experiment (after constant fluid turnover at 20 L/s for 15 days). Fluid injection and production screens are indicated by arrows in blue and red, respectively. The nearly vertical hydrofrac and the arresting sandstone layer (permeability 200× higher than for the surrounding tight rock matrix) are indicated in light yellow.

At the lower and upper edges of the model domain, we assume impermeable boundaries for fluid and solute transport. At the lateral frac-parallel boundaries we assume free-outflow Robin-type conditions, whereas the frac-orthogonal edge containing the fluid injection and outflow screens (facing the viewer in fig. 1) must be treated as impermeable by way of the symmetry-based domain-size halving; the BC assumption for the opposite frac-orthogonal edge (hidden to the viewer in fig. 1), whether free-outflow or impermeable, was seen to have almost no influence on the results because the 'buffer' rock depth behind the frac was chosen large enough. Flow and solute transport equations are solved by the commercially-available finite-element software FEFLOW, version 5.4, taking advantage of its both physically intelligent and numerically efficient handling of fractures, embedded as 2-D features into the 3-D rock matrix volume (Diersch 2014, with contributions from Kolditz et al.). The model domain is discretized by ~10,000 elements (~15,500 nodes), and solute dispersivity parameters are chosen consistently with variable element sizes (ranging from ~centimetres close to frac and well-screen elements, to ~metres at remote boundaries); frac flow, however, is assumed to be more dispersive than matrix flow (twice as much, compared to the permeable sandstone layer arresting the frac in the upper section, and five-fold, compared to the adjacent tight rock).

Multi-tracer injection is supposed to be conducted at the lower well-screen, while tracer signal monitoring is performed uphole on the fluid produced from the upper well-screen. The finite duration of the tracer injection pulse at the lower screen is going to be so short (few minutes) in all versions of the planned experiments, that the injection pulse shape (or the improperly so-called 'initial dilution') is found to have no influence on tracer breakthrough curve (BTC) shapes in the upper-screen outflow. Seven tracer species with different diffusion or adsorption-desorption properties are considered:

• conservative (non-sorptive) tracers with diffusion coefficient ratios 1 : 20 : 400 (the lowest being 10^{-9} m^2/s),

• equilibrium-sorptive tracers with retardation factors $R = 2, 4, 8, 16$ (all assumed to have the same diffusion coefficient value, 2×10^{-8} m^2/s, which might be unrealistic but will be shown to be largely irrelevant).

Figure 1, apart from outlining the model geometry, also illustrates the different spreading patterns of these seven tracer species by the end of the experiment.

4. PARAMETER SENSITIVITY FINDINGS

Only an excerpt of simulation results is presented here, highlighting the major findings in terms of principles and comparing them with prior expectations. For each hydrogeologic scenario (i. e., a certain combination of frac area and aperture values), a set of seven, more or less different signals (BTCs) can be expected in the fluid produced from the upper screen, corresponding to the seven tracer species that were injected simultaneously at the lower screen. These seven-BTC sets are shown in fig. 2.1 – 2.9 for nine hydrogeologic scenarios, i. e. three values of the effective frac half-length: 900 m, 300 m, 100 m, and three values of frac aperture: 9 mm, 1 mm, 0.111 mm. By effective frac area or length we mean the 'flow-pervaded' part of the frac, i. e. the part hosting mobile fluid.

On the other hand, in order to assess parameter sensitivity one has to look at how tracer signals change, for a given species, when the hydrogeologic scenario is varied. This is shown in fig. 3.1 – 3.3 for only three of the seven tracer species considered, namely for the lowest-diffusive and highest-diffusive non-sorptive tracers, and for the moderately-diffusive, moderately-sorptive tracer; for the further four tracer species findings are not shown explicitly, being very much redundant to the three species shown. Each figure displays the same BTC information twice, in linear and logarithmic concentration scale, to improve the visibility of either peak or tailing details. In more general terms, it is seen that

• different diffusion properties (BTCs in black and gray tones in fig. 2) have little effect on tracer signals over the time and space scale of the planned experiment in the Südheide; diffusive effects increase slightly with increasing frac area or with decreasing frac aperture (as expectable), but the highest sensitivity to frac parameters is seen for the least-diffusive tracer (which seems surprising at a first glance);

• for a given frac area or length (a given color in fig. 3), tracer signal sensitivity to frac aperture is high at low aperture values (dense dotting in fig. 3); at high aperture values (sparse dashing in fig. 3), sensitivity is lost; this holds for sorptive and non-sorptive species alike;

• for a given aperture (given dotting/dashing pattern in fig. 3), tracer signal sensitivity to frac area (or length) is fairly good (different colors in fig. 3), but there is some interplay between aperture and length; this holds for sorptive and non-sorptive species alike;

• using at least one sorptive tracer alongside with the conservative (non-sorptive) tracer can in principle constrain the estimation of both frac area and length, and the higher the retardation of the sorptive tracer, the better constrained this estimation, except that ...

• ... the prescribed maximum duration or volume of fluid turnover bears an upper limit on the usable retardation factors; looking at concentration ranges for tracer signals (especially for large frac areas and/or low apertures), strongly-retarded tracers may stay below detection limits until the end of the experiment.

In terms of "Source"-"Pathway"-"Target" compartments, referring to fig. 5 from McDermott et al. (2014), the take-away from these scoping simulations can be summarized qualitatively – as a rule of thumb,

• the overall tracer recovery amount correlates with the transmissivity ratio between competing P, S compartments;

• tracer arrival times correlate with the effective aperture or porosity of the critical (spill-controlling) P compartment;

• mid-/late-time tracer signal slope changes may indicate geomechanical effects within P and/or S compartments.

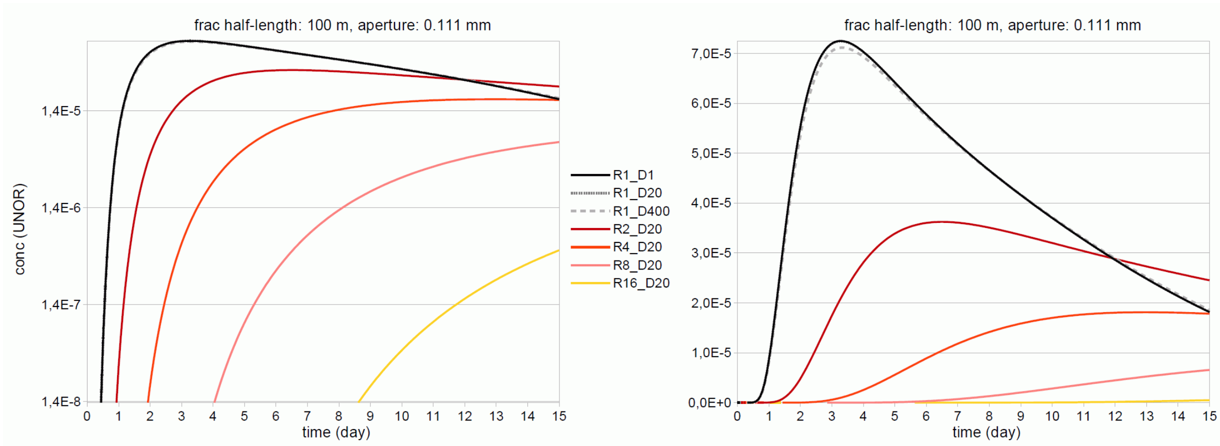

Figure 2.1: Simulated tracer BTCs for a small-area, low-aperture hydrofrac, with three non-sorptive (more or less diffusive) and four sorptive tracer species. BTCs are shown in logarithmic (l.-h.s.) and linear (r.-h.s.) concentration scale.

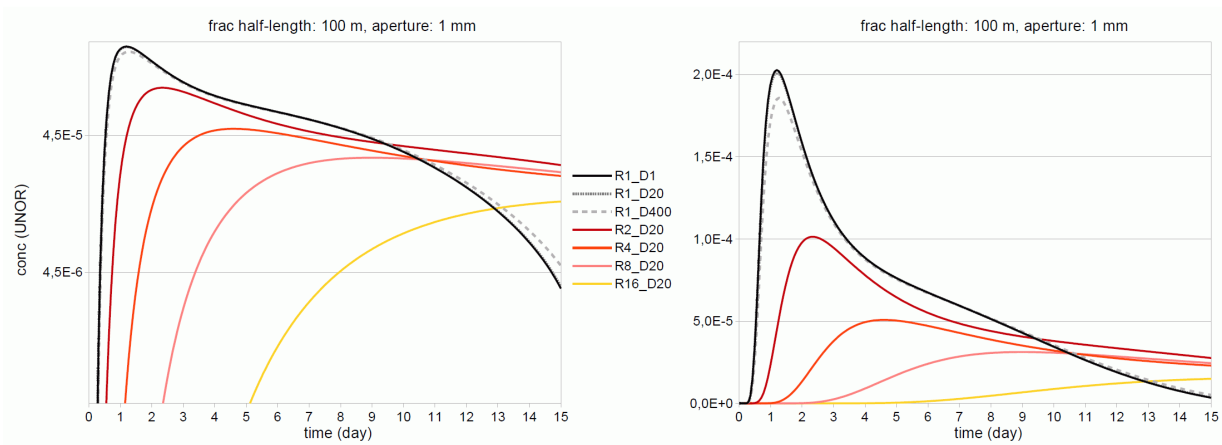

Figure 2.2: Simulated tracer BTCs for a small-area, mid-aperture hydrofrac, with (ibid., cf. fig. 2.1).

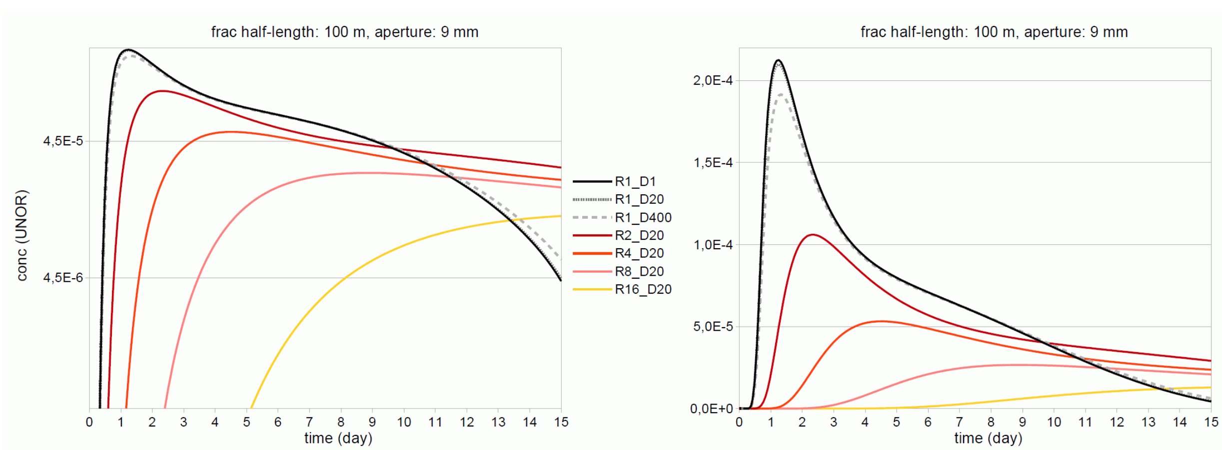

Figure 2.3: Simulated tracer BTCs for a small-area, large-aperture hydrofrac, with (ibid., cf. fig. 2.1).

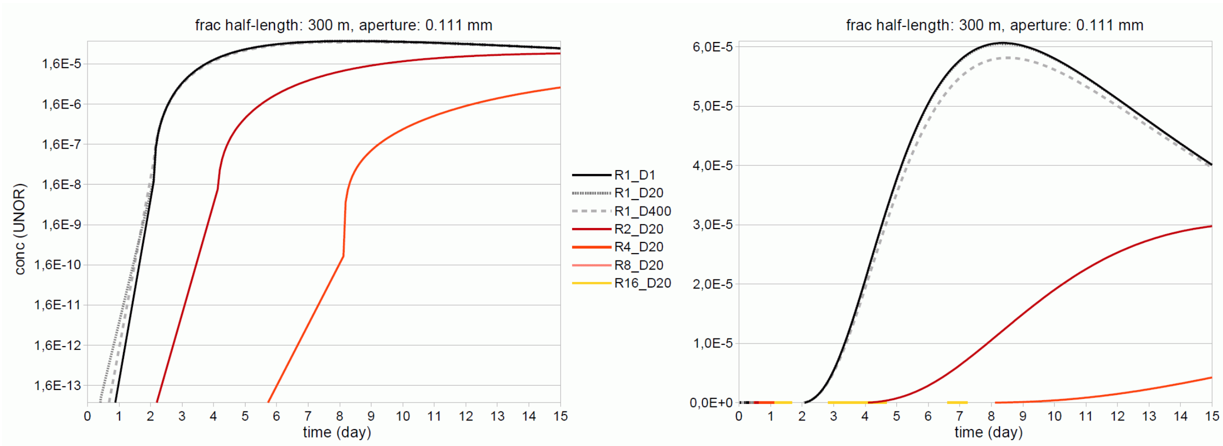

Figure 2.4: Simulated tracer BTCs for a mid-area, low-aperture hydrofrac, with (ibid., cf. fig. 2.1).

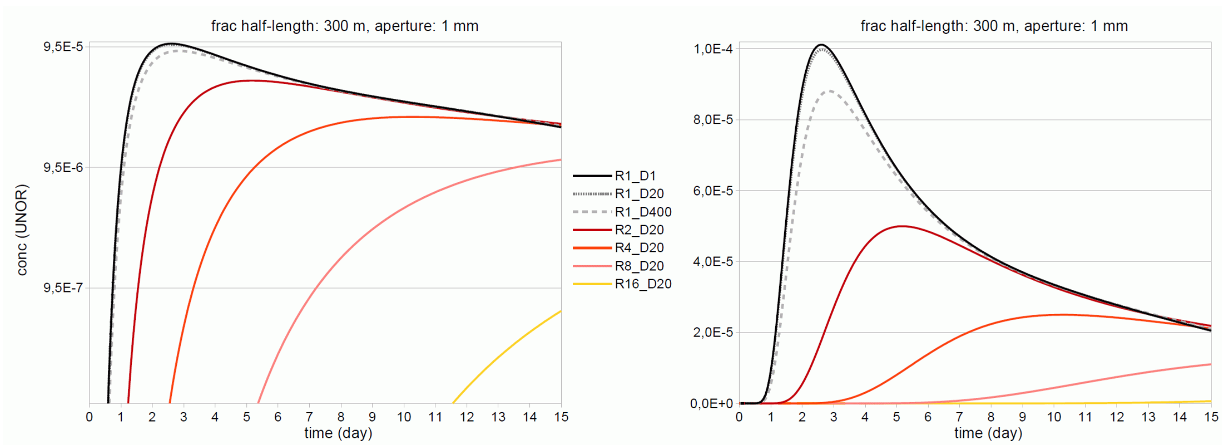

Figure 2.5: Simulated tracer BTCs for a mid-area, mid-aperture hydrofrac, with (ibid., cf. fig. 2.1)

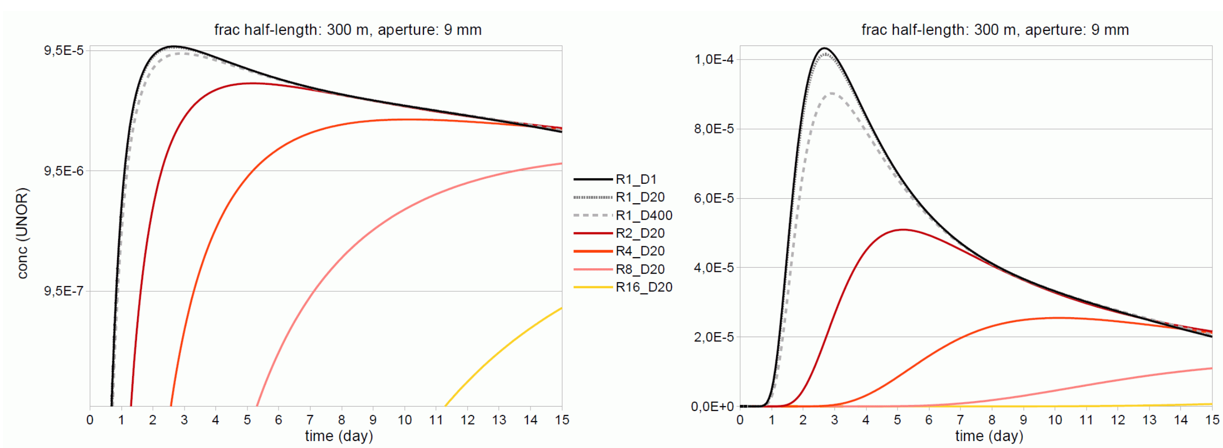

Figure 2.6: Simulated tracer BTCs for a mid-area, large-aperture hydrofrac, with (ibid., cf. fig. 2.1).

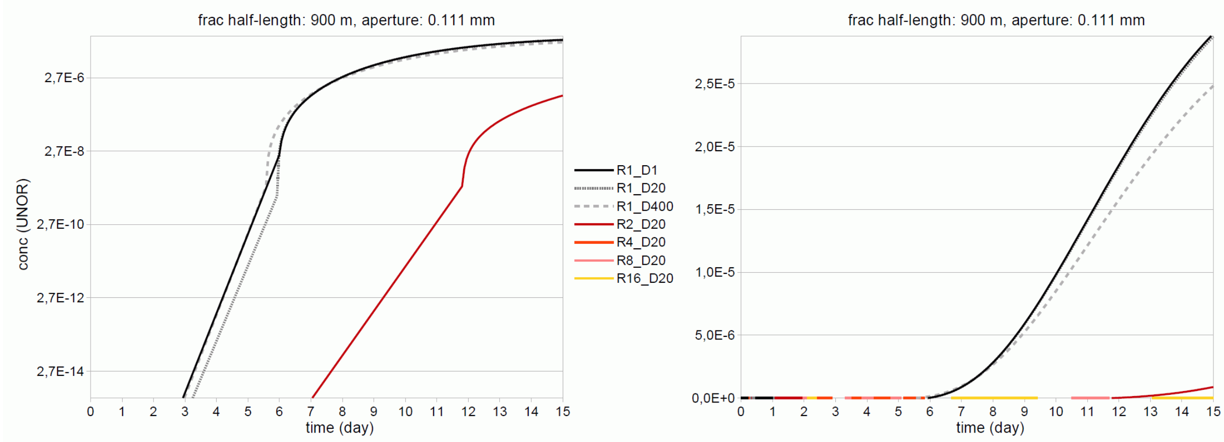

Figure 2.7: Simulated tracer BTCs for a large-area, low-aperture hydrofrac, with (ibid., cf. fig. 2.1).

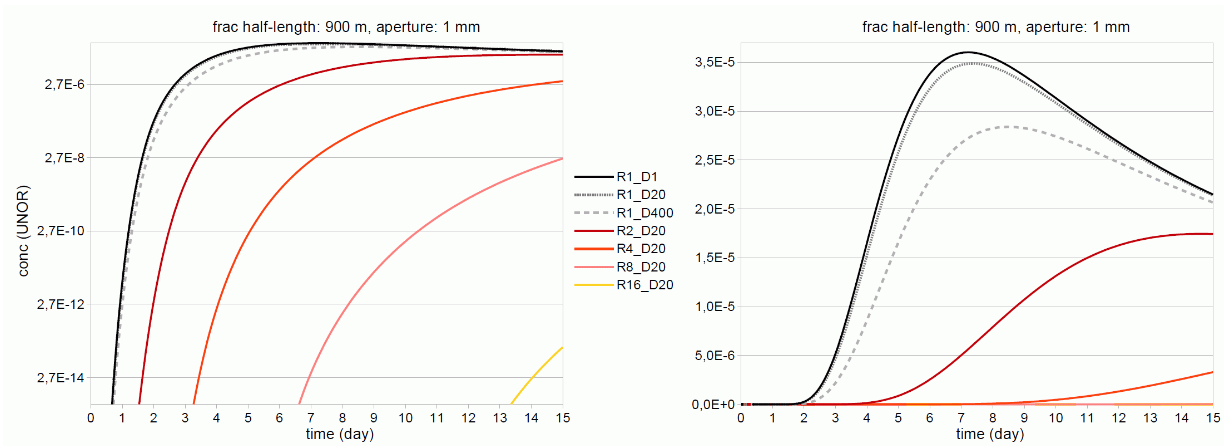

Figure 2.8: Simulated tracer BTCs for a large-area, mid-aperture hydrofrac, with (ibid., cf. fig. 2.1).

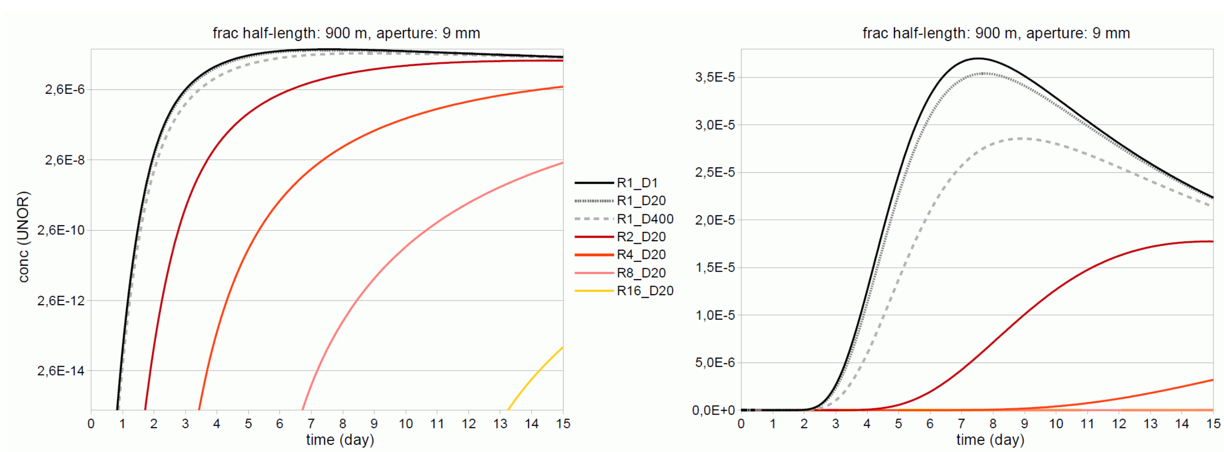

Figure 2.9: Simulated tracer BTCs for a large-area, large-aperture hydrofrac, with (ibid., cf. fig. 2.1).

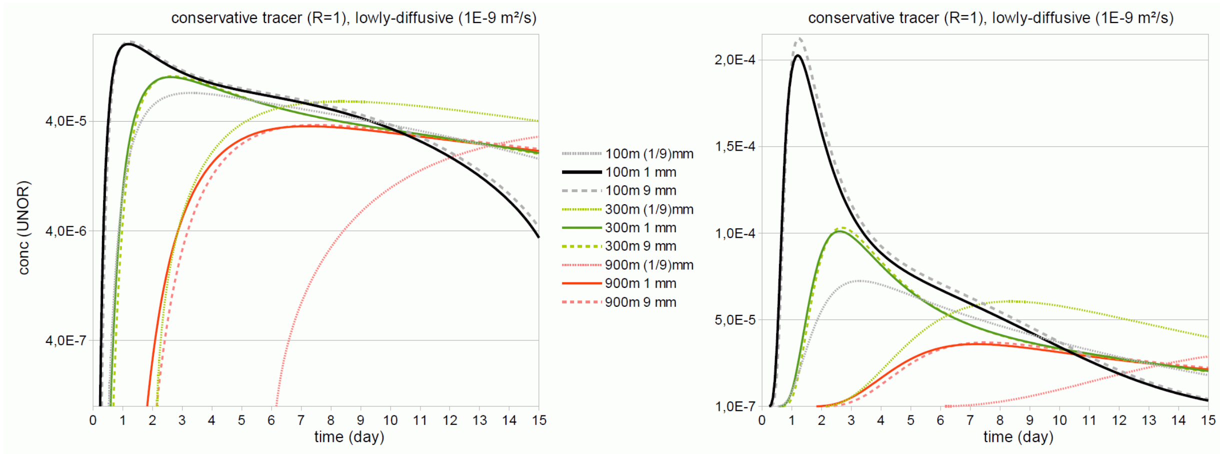

Figure 3.1: Simulated tracer BTCs for the lowly-diffusive, non-sorptive tracer, for nine different hydrogeologic scenarios, specified by frac half-length and aperture. BTCs are shown in logarithmic (l.-h.s.) and linear (r.-h.s.) concentration scale.

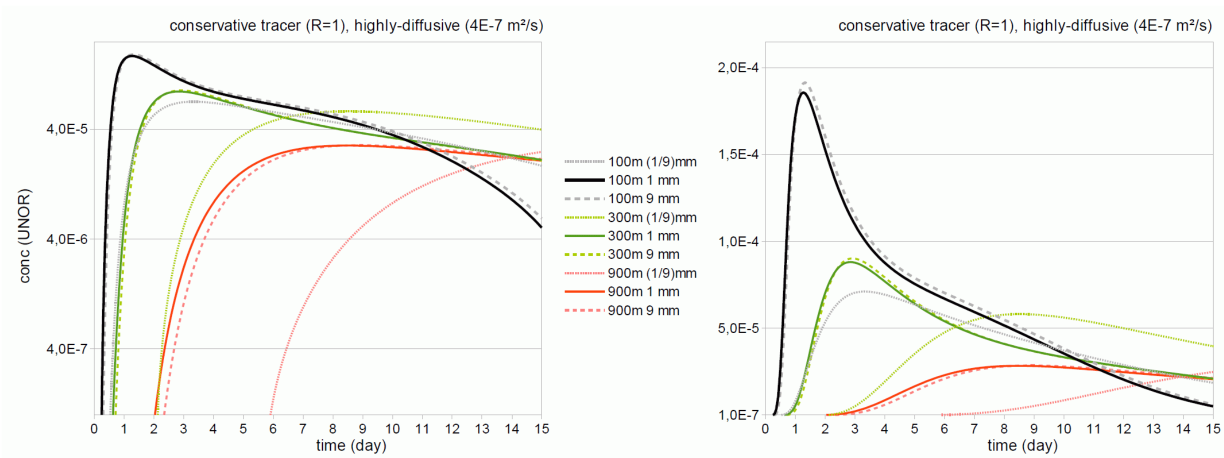

Figure 3.2: Simulated tracer BTCs for the highly-diffusive, non-sorptive tracer, for (ibid., cf. fig. 3.1).

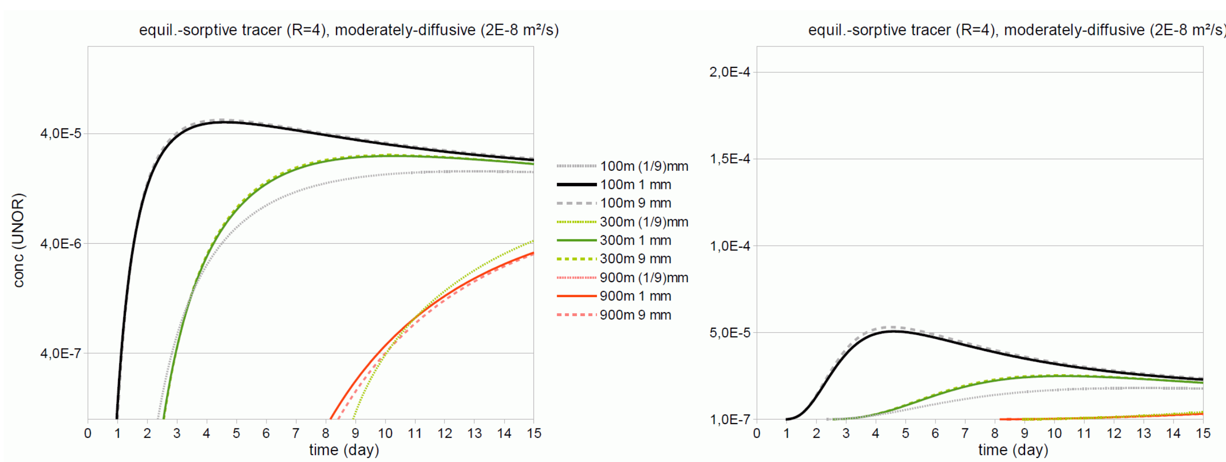

Figure 3.3: Simulated tracer BTCs for a moderately-diffusive, moderately-sorptive tracer, for (ibid., cf. fig. 3.1).

Last not least, it may be of interest to compare the late-time 'slope drop' seen in some of the signals in figures 2.2., 2.3, 3.1, 3.2 with the characteristic late-time slopes identified by Haggerty et al. (2000) within a different model approach, as shown explicitly in their figure 1. For details regarding their advective-dispersive multi-rate solute transfer (ADMT) models, the reader is encouraged to consult the original work of Haggerty et al. (2000).

5. REMARKS ON MULTI-TRACER SELECTION, SLUG SIZING, PREPARATIVE STEPS FOR SIGNAL METERING

From the scoping simulations, we may provisionally 'conclude' that

• It is not worth investing much effort into the accurate determination of molecular diffusion coefficients for each tracer species under the reservoir 'in-situ' conditions (which in fact requires extremely tedious laboratory work). In other words, even if it is impossible to specify what the reservoir 'in-situ' conditions actually are – it doesn't matter too much (in terms of molecular diffusion) for the two-week experiment now being planned in the Südheide.

• The least-diffusive tracer is the most prone to reveal the characteristic 'diffusive tailing' asymptotics (cf. fig. 1 of Haggerty et al. 2000) within the prescribed experiment duration.

• With sorptive retardation factors larger than ~3, *potential sensitivity gains no longer come into effect*, because of the limited duration of the experiment. Strongly sorptive or ion-exchanging cations (like Sr, Cs) are likely not very useful for the planned experiment; the more so as adding them as artificial tracers in the short-term frac flow might impede their mid- and long-term use as valuable natural tracers (cf. Wiegand and Sauter 2016), though a careful choice of isotope species may help to avoid this problem. Since the value of R depends on the (a priori unknown) aperture value, a preliminary guess of frac aperture is needed in order to select tracer species with suitable R values. We recommend using at least one ion-exchanging species alongside with a conservative species.

From SWPP or injection-flowback simulations, as well, we know that tracer sorptivity will not always enhance the sensitivity of tracer flowback signals to 'stimulation target' parameters like the porosity increase factor (ω) in matrix treatments. This is illustrated in fig. 4 for a mono-continuum matrix model where, unlike in past simulations (Ghergut et al. 2013[bc]), we also consider some possible effects of sorptivity as well as dispersivity changes between the injection and the flowback stages of the treatment. As outlined in fig. 4, all 'stimulation target' parameters of the mono-continuum model can in principle be 'inverted' from the measured tracer flowback signal:

• porosity increase factor (ω) alone from the dispersion-independent 'half-life', and

• dispersivity change factor ($1/\delta$) and final dispersivity value from any two BTC points or, more generally, by 'curve fitting',

all with fairly good sensitivity, whereas tracer sorptivity (neither by itself, nor by changing its rates between push and pull stages) does not significantly improve (or may even reduce, cf. red highlights in fig. 4) the sensitivity of determination for any of the aforementioned parameters. For sorptive tracer species, a change in adsorption/desorption rates between push and pull stages is likely to occur due to pH changes as unavoidable during matrix treatment – and the more so, the more difficult it becomes, and less likely to achieve a reliable quantification of in-situ behaviour for that particular tracer species, as already pointed out by Hawkins (2017).

6. OPPORTUNITIES FOR KNOWLEDGE TRANSFER BETWEEN PROJECTS IN THE DEEP-GEORESERVOIR REALM

As a matter of principles, since the 'environmental footprint' by routine operations (especially for re-fracking) is significantly larger than by the so-called 'hazards' associated with shale-gas exploitation, any improvement in exploration success rates and/or in productivity (to which an improved characterization of reservoir candidates primarily aims to contribute) will ensue in reducing the overall 'environmental footprint' of shale-gas reservoir development and exploitation much more sensibly than measures taken for hazard mitigation.

The pilot unconventional-reservoir site in the Südheide in the NW-German sedimentary basin offers the unique advantage of well-steerable forced-gradient flow conditions, thereby enabling to more reliably estimate in-situ adsorption-desorption properties of a number of tracer species currently regarded as 'promising candidates' for monitoring and evaluating (stimulated-)reservoir performance. Yet the opportunities for knowledge transfer between various EU as well as German projects in the deep-georeservoir realm extend definitely beyond this particular aspect, as summarized by the table at this section's end.

At this site, on the other hand, we are facing the physico-chemical challenges of a highly-saline brine, alongside with economically insignificant, but analytically 'very noisy' hydrocarbon contents, significant organic contents in aqueous phase, and a rock composition (clay-rich, also with significant amounts of quartzite) affine to that of shale formations. Whereas for gaseous tracers a real-time on-site detection may still be feasible with reasonable effort, liquid-phase organic tracer signal metering in such brines requires advanced laboratory-instrumental (including rather tedious sample preparatory) work. A possible workaround could consist in *over-sizing the added tracer quantity by a sufficient factor F, thereby allowing to dilute the liquid samples by the same factor F before tracer metering*, in order to reach the desired (optimum) tracer concentration range for a less-tedious instrumental detection while having the 'organic noise' and salinity levels in the liquid samples reduced by the same factor F. This might, for instance, spare the need for tedious solid-phase extraction (SPE) as a preparatory step before conducting HPLC. In the experiments now being planned at the Südheide site, for most organic tracer species under consideration, one would be using, say, 1 kilogram instead of 30 grams of a species; accordingly, with $F \sim 30$, the 'salt' (and other 'noise') in the brine could be diluted from 300 g/L to 10 g/L.

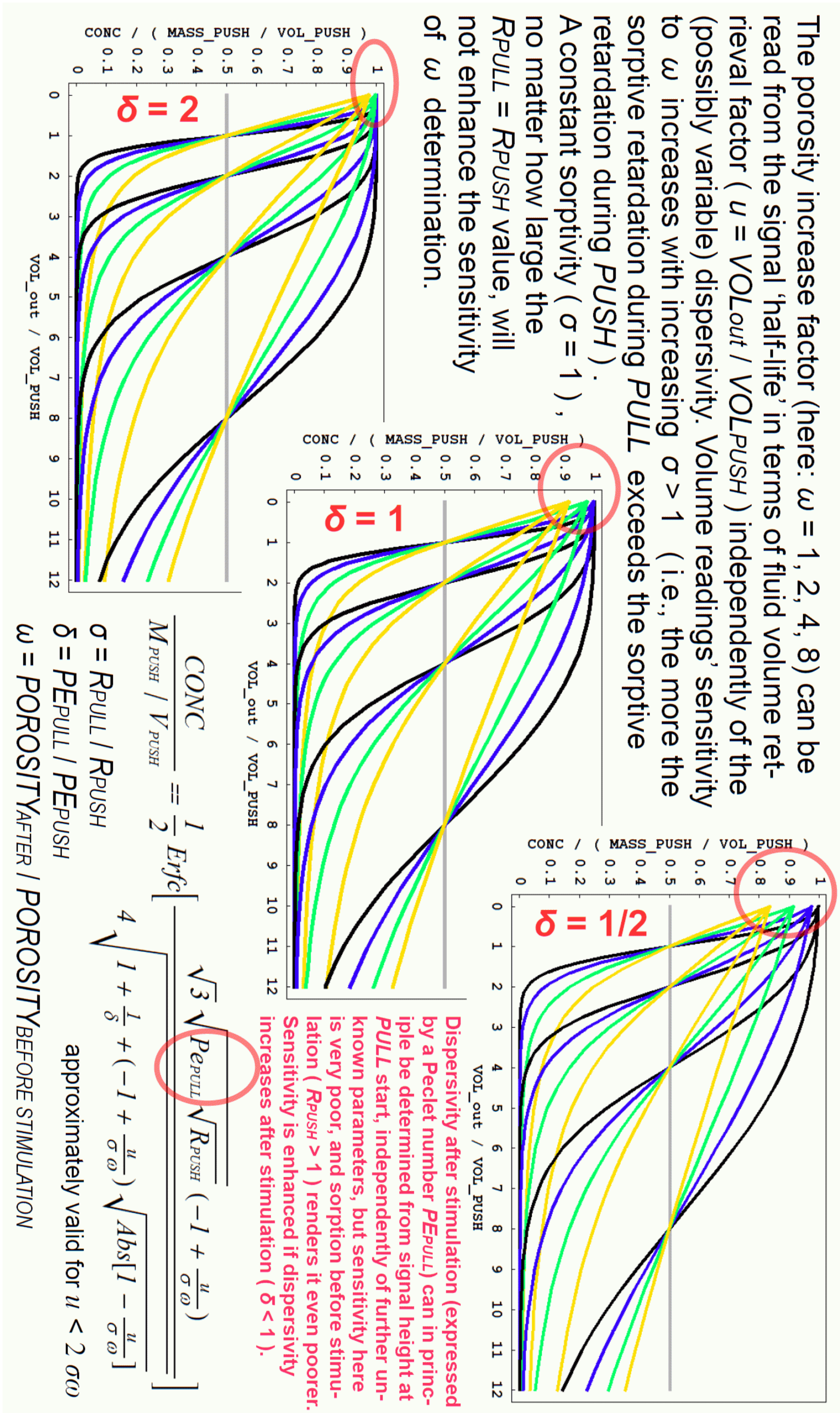

Figure 4: Tracer sorptivity does not enhance the sensitivity of tracer flowback signals to stimulation target parameters like the porosity increase factor.

Opportunities for knowledge transfer between various European projects in the deep-georeservoir realm			
item \ region	EGS in the N-German basin (various EU and German projects like “MEET”, “gebo”, “LOGRO”, “SmartTracers”)	tight-matrix stimulation (EU project “FracRisk”)	geothermally-exploited Malm aquifers (BMWi project “TRENDS”)
reservoir pervasion constraints	stimulated-zone *height* is confined by geostratigraphy (overburden spill hazards can occur from various above-ground operations, or from near-surface wellbore cementation/casing failures, but not from the stimulated reservoir zone)		geological formation (Malm aquifer) *height* is prescribed by ‘mother nature’ (max. 600 m for the study area) and cannot be increased by technical measures
stimulation aims	increase the effective ‘cross section’ for flow (for ‘aquifer’-like EGS), increase the heat transfer area (for petrothermal-type EGS) and delay ‘thermal breakthrough’ either by mainly advective (‘aquifer’-like EGS) or by mainly conductive (petrothermal EGS) mechanisms	create a volume of significantly increased permeability (desirably of elongated shape, whenever geologically possible and technically feasible)	increase the effective wellbore radius
conceptual model approximations suitable for tracer signal evaluation	dual-porosity, smtm. also dual-permeability	multiple-porosity	dual-permeability ***and*** dual- or multiple-porosity
parameter inversion approach relying on dual-continuum models (figs. 2 and 3, for flow-through experiments)	primarily relevant for petrothermal-type EGS, both for initial and for repeated treatments	relevant for 1) spill hazard assessment 2) quantification of certain tracers’ physico-chemical properties in laboratory experiments	relevant rather exceptionally, when large-aperture conduits or large-area fracture planes within the bedded facies make a notable contribution to overall transmissivity (cf. ‘cubic law’)
parameter inversion approach relying on single-continuum model (fig. 4, for SWPP experiments)	primarily relevant for ‘aquifer’-like EGS, especially for the repeated treatment of poor-quality reservoir intervals	more relevant for repeated than for initial treatments	primarily relevant for – repeated as well as initial – matrix stimulation treatments
“*augment-then-dilute*” strategy for facilitating the laboratory-instrumental metering of tracer signals	very useful in SWPP or injection-flowback experiments (e. g., associated with stimulation treatments)		not tenable for inter-well fluid tracings at reservoir scale

Whereas some of the present study’s findings on tracer flow-through signal sensitivity to ‘fracture’ (i. e., rapid-flow feature) geometry and sizes can sensibly be transferred to the project “TRENDS” dealing with porous-fissured-fractured aquifers in the Malm carbonate formation underneath the Molasse basin (especially as regards those ‘elusive’, discrete flow features within the bedded facies, as opposed to the ‘continuum-like’ flow within the reef facies), the aforementioned *strategy of ‘augment – then – dilute’ is not tenable* for the latter, since (with the typical Malm reservoir sizes) it would require tracer quantities in the order of hundreds of tons, even for the ‘best’ of tracer species available to date (i. e., those with the lowest detection limits, say, in the sub-ppb or tens-of-ppt range). Instead, tracer signals will need to be ‘magnified’ by solute enrichment from ‘volume-augmented’ liquid samples; for most species, SPE is going to be a *must-do*.

Tracer information needs to be combined with hydraulic information (pressure monitoring) in order to constrain the characterization of mobile- and stagnant-fluid compartments, and the estimation of their interface and volume-distributed parameters. In real-world applications, this is a sometimes feasible, but not trivial task. Not much surprisingly, the ‘best’ (i. e., the fastest) and ‘smallest’ flow-path feature, as well as the largest and ‘slowest’ void-space compartment (the one with the highest storage capacity, hosting most of the stagnant-fluid volume) remain the most refractory to parameter inversion from both hydraulic and tracer signals.

7. ACKNOWLEDGMENTS

The authors are grateful to Dr. Torsten Tischner (BGR Hannover) and Dr.-Ing. Christian Pletl (Stadtwerke München) for their decade-long open-mindedness towards ‘experimenting with tracer experiments’.

Tracer transport simulations shown in figures 2 and 3 were performed for the EU-H2020 project “FracRisk” (grant no. 636811).

SWPP simulations shown in figure 4 were performed within the German project “TRENDS” (cf. infra). The research underlying this paper also benefited from laboratory studies on the physico-chemical behavior of a number of organic tracers species interacting with various solid phases used in original or modified POCIS devices (courtesy: H. Behrens, Dr. Sebastian Schmidt, Hydrogeology Dept. and Steffen Fischer, Electromechanical Laboratories, University of Göttingen), within the research project “TRENDS” funded by the German Federal Ministry for Economic Affairs and Energy (BMWi, FKZ 0325515).

REFERENCES

Behrens, H., Ghergut, I., Lodemann, M., Licha, T., Orzol, J., Sauter, M.: Reactive behaviour of uranine (fluorescein) in a deep geothermal-reservoir tracer test. *Geophys. Res. Abstr.*, **8** (2006), 10448.

Behrens, H., Ghergut, I., Sauter, M., Licha, T.: Tracer properties, and spiking results (from geothermal reservoirs). *Proceedings*, 34th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, SGP-TR-187 (2009), 57-63.

Carrera, J., Sanchez-Vila, X., Benet, I., Medina, A., Galarza, G., Guimera, J.: On matrix diffusion: formulations, solution methods and qualitative effects. *Hydrogeology J.*, **6** (1998), 178-190.

Diersch, H.-J.G.: *FEFLOW − Finite element modeling of flow, mass and heat transport in porous and fractured media*. Springer, Berlin Heidelberg, XXXV (2014), 996 pp.

Ghergut, I., Sauter, M., Behrens, H., Licha, T., Tischner, T., Jung, R.: Single-well dual-tracer spikings during EGS creation in N-German sedimentary layers. *Proceedings*, 34th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, SGP-TR-187 (2009), 64-70.

Ghergut, I., Behrens, H., Maier, F., Karmakar, S., Sauter, M.: A note on ‘heat exchange areas’ as a target parameter for SWIW tracer tests. *Proceedings*, 36th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, SGP-TR-191 (2011), 303-312.

Ghergut, J., Herold, M., Sauter, M.: Geothermal Art in the N-German Sedimentary Basin: Grafting EGS with Aquifers. *Geotherm. Res. Counc. Transact.*, **37** (2013a), 949-955.

Ghergut, I., Bensabat, J., Niemi, A., Licha, T., Ptak, T., Sauter, M.: CCS site characterization by inter-well and single-well tracer tests. *Proceedings*, 38th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, SGP-TR-198 (2013b), 316-325.

Ghergut, J., Behrens, H., Wolfgramm, M., Sauter, M., Zimmermann, G., Wiegand, B., Herold, M., Licha, T., Ptak, T.: Tracer-push-pull bei Matrixstimulation in Sandstein und in Karbonat: sinnvoll auch ohne in-situ-Tracerdetektion? *Proceedings*, Der Geothermiekongress (Essen, Germany), ed. by: GtV-BVG (ISBN: 978-3-932570-68-1), Berlin (2013c), 6 pp.

Ghergut, J., and Sauter, M.: Hydraulic, thermal and tracer tests at wellbore and reservoir scale. In: Final Report of Geothermal Energy and High-Performance Drilling Collaborative Research Program (‘gebo’). *Schriftenreihe des EFZN / Energie-Forschungszentrum Niedersachsen*, Band **30-1** (2015), Cuvillier-Verlag Göttingen (ISBN: 978-3-7369-9080-7), pp. 203-225.

Ghergut, J., Behrens, H., Sauter, M.: Petrothermal and aquifer-based EGS in the N-German Sedimentary Basin, investigated by conservative tracers during single-well injection-flowback and production tests. *Geothermics*, **63** (2016), 225-241.

Haggerty, R., McKenna, S.A., Meigs, L.C.: On the late-time behaviour of tracer test breakthrough curves. *Water Resour. Res.*, **36**(12), (2000), 3467-3479.

Hawkins, A.J.: *Reactive tracers for characterizing fractured geothermal reservoirs*. Ph. D. Dissertation, Cornell University, Ithaca, NY (2017).

Hördt, A., Beilecke, T., Ghergut, I., Holzbecher, E., Löhken, I., Löhken, J., Philipp, S., Sauter, M., Reyer, D., Thomas, R.: Modelle geothermischer Reservoire als Grundlage interdisziplinärer Zusammenarbeit. *71. Jahrestagung Dt. Geophys. Ges.*, Köln (2011), Abstracts, GR-P04, 89.

Jung, R., Orzol, J., Jatho, R., Kehrer, P., Tischner, T.: The GeneSys Project: Extraction of Geothermal Heat From Tight Sediments. *Proceedings*, 30th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, SGP-TR-176 (2005).

Jung, R., Orzol, J., Kehrer, P., Jatho, R.: Verbundprojekt GeneSys, Vorstudie Erprobung der Wasserfrac-Technik und des Einsonden-Zweischichtverfahrens für die Direktwärmenutzung aus geringpermeablen Sedimentgesteinen. Abschlussbericht (70 pp.), GGA Hannover (2006).

Karmakar, S., Ghergut, J., Sauter, M.: Early-flowback tracer signals for fracture characterization in an EGS developed in deep crystalline and sedimentary formations: a parametric study. *Geothermics*, **63** (2016), 242-252.

McDermott, C.I., Sauter, M., et al.: *FracRisk: Furthering the knowledge base for reducing the environmental footprint of shale gas development*. Project proposal, www.fracrisk.eu (2014), figure 5.

Philipp, S.L., and Reyer, D.: Mechanical rock properties, fracture propagation and permeability development in deep geothermal reservoirs. *Geophys. Res. Abstr.*, **12** (2010), 11145.

Philipp, S.L., Lim, P.Y., Parchwitz, S., Reyer, D.: Numerical models of extension fracture propagation in mechanically layered rocks. *Geophys. Res. Abstr.*, **13** (2011), 2481.

Reyer, D., Bauer, J.F., Philipp, S.L.: Architektur und Permeabilität von Störungszonen in Sedimentgesteinen des Norddeutschen Beckens. *Der Geothermiekongress 2010* (Karlsruhe), CD-ROM publication, ISBN: 978-3-932570-65-0 (2010), 9 pp.

Reyer, D., Bauer, J.F., Philipp, S.L.: Fault zone architecture and fracture systems in sedimentary rocks of the North-German Basin. *Geophys. Res. Abstr.*, **13** (2011), 6403.

Tischner, T., Sulzbacher, H., Jung, R., Orzol, J., Jatho, R., Kehrer, P.: GeneSys: Hydraulische und thermische Charakterisierung des künstlich erzeugten Risses und Implikationen für dessen geothermische Nutzung. *Tagungsband*, *8. Geothermische Fachtagung*, Landau (2004), 131-139.

Tischner, T., Evers, H., Hauswirth, H., Jatho, R., Kosinowski, M., Sulzbacher, H.: New Concepts for Extracting Geothermal Energy From One Well: The GeneSys Project. *Proceedings*, *World Geothermal Congress*, Bali, Indonesia, paper 2272 (2010), 5 pp.

Tsang, Y.W.: Usage of 'Equivalent Apertures' for Rock Fractures as Derived From Hydraulic and Tracer Tests. *Water Resour. Res.*, **28**(5) (1992), 1451-1455.

Wessling, S., Junker, R., Rutqvist, J., Silin, D., Sulzbacher, H., Tischner, T., Tsang, C.-F.: Pressure Analysis of the Hydromechanical Fracture Behaviour in Stimulated Tight Sedimentary Geothermal Reservoirs. *Geothermics*, **38**(2) (2009), 211-226.

Wiegand, B., and Sauter, M.: Reservoir Characterization by Sr Isotopes – A Case Study from the Upper Rhine Valley. *Proceedings*, 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, SGP-TR-209 (2016).