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First-Order Discontinuity in Cumulative Tracer Recovery: Need for Endo-Tracer Push-Pull

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ABSTRACT

Forced-gradient flow sustained by a geothermal well doublet in a porous-fissured reservoir is subject to a tracer test anew, following a significant augmentation of fluid turnover rates. The distinct aromatic sulfonates (N2S, P4S) serving as a tracer in the first (lower-rate) and the second (higher-rate) test, respectively, are supposed to be transported conservatively, an thus similarly to each other under this reservoir's in-situ conditions. Cumulative mass recovery for each tracer can be calculated based on its theoretical 'single-passage' signal, deconvolved from its measured signal (eliminating 'redundant' contributions from fluid recirculation; to account for flow-rate variability, we set up an ad-hoc deconvolution algorithm). From tracer sampling to date, CMR amounts to ~28% for P4S, and ~70(!)% for N2S – whose first 20-30(!)% mass amounts were swept through the reservoir under the lower-rate flow regime, and its subsequent amounts under the higher-rate regime, reaching 60-65(!)% by the time P4S was added. CMR values for N2S marked by an (!) cannot be told accurately due to short-term flow-meter (instrumental) failures during precisely this transition; not only these particular values for N2S, but its entire subsequent CMR calculation is impeded by the flow-meter data gap. (As a substitute, one may attempt to reconstruct the missing flow-rate values from geothermal power generation data, but here operator-provided records proved insufficient.)

CMR for P4S exhibits a significantly lower growth rate than for N2S, even when plotted against cumulative fluid turnover, which should have compensated for flow-rate disparities. More strikingly yet, it shows a marked first-order discontinuity (tangent drop) after reaching ~20% (which would correspond to ~30% N2S after the same cumulative fluid turnover volume, counted since tracer injection). Since P4S was injected much later after the flow-meter failure, its tangent discontinuity in CMR stays independent upon those missing flow rate data.

Four hypotheses which might explain P4S CMR findings are proposed: (i) P4S loss by some physico-chemical processes (maybe related to borehole cleaning / acidizing treatments), i. e., non-conservative tracer behavior? (ii) evidence for large induced fracture(s), or reservoir stimulation, thus stronger P4S dilution? (iii) reservoir compartmentalizing, thus P4S loss into some non-pay zone? (iv) last not least, might flow-rate records be flawed over a time interval significantly larger than originally believed?

Accordingly, we consider and evaluate a couple of more specialized monitoring options that would allow to disambiguate (or refute) some induced-fracture / activated-fault / karst 'narrow window' scenarios. To validate or infirm (i), we suggest conducting endo-tracer push-pull (single-well dilution) tests during late-tailing stages of both N2S and P4S (at the geothermal production well), which would allow for a direct quantitative comparison as to their possibly non-/conservative behavior in-situ. To corroborate or refute either (ii) or (iii), complementary knowledge from geophysical exploration, in-situ stress field characterization, additional (hydraulic, thermal) data are needed. If all of (i) – (iv) can be excluded, one can still attempt to 'reconstruct' the correct flow-rate values based on holomorphicity requirements for the second tracer's CMR curve.

In any case, signal monitoring for both tracers would need to be extended by at least 16 months, counting from the second tracer's CMR tangent drop (i. e., few months from today), and assuming the higher flow rate were kept approximately constant over the entire duration until conducting the endo-tracer push-pull test, for which, then, a much slower rate is recommendable.

1. TRACER TEST CONTEXT, AIMS, AND EXPECTATIONS BY PRIOR STUDY

This is an update to our prior study concerning the forced-gradient flow sustained by a geothermal well doublet in a porous-fissured, more or less karstified (and maybe faulted and fractured) Jurassic 'Malm' formation in 2 – 2.5 miles depth in Southern Germany, for which a conceptual-hydrogeologic model was outlined in Behrens et al. (2020), along with some competing hypotheses as to what role fractures might play for heat and solute transport at reservoir scale (cf. especially fig. 2 of ibid.; details not repeated here).

Inter-well flow in this reservoir is subject to a tracer test anew, following a significant augmentation of fluid turnover rates (from ~9,000 to ~12,000 m³/day). The distinct aromatic sulfonates (N2S and P4S) used as a tracer in the first (lower-rate) and the second (higher-rate) test, respectively, are supposed to be transported conservatively, an thus similarly to each other under this reservoir's in-situ conditions.

Tracer tests at this site are ongoing, with long-term signal monitoring to be continued until at least the end of 2021. Originally, the (first) tracer test was supposed to yield an 'explanation' for the anomalous evolution of production temperature seen at this site (cf. fig. 3 of ibid.). This had been attempted in terms of a flow-path 'short-circuiting' feature, i. e., rapid inter-well drainage by a transmissivity 'window' of either natural origin (falling below detection limits of prior geophysical exploration), or induced by wellbore operations at very early stages of reservoir development (unintended 'stimulation' resulting in 'misaligned' increase of permeability).

2. MAJOR FINDINGS BY 2020 THIRD QUARTER

Tracer signals recorded to date (fig. 1 here) add some, yet unspecific evidence to the simulations ('predictions') shown in fig. 4 of Behrens et al. (2020), but they also raise a new issue, not quite expectable by prior scenarios. Cumulative mass recovery (fig. 2 here) for each tracer can be calculated based on its theoretical 'single-passage' signal, deconvolved from its measured signal (i. e., eliminating 'redundant' contributions from fluid recirculation). To account for flow-rate variability, we set up an ad-hoc deconvolution algorithm (cf. next section for more details, and caveats).

Flow-storage distribution for each tracer is renormalized (fig. 3 here) according to Behrens et al. (2010). In the context of geothermal reservoir characterization, FSD diagrams have originally been proposed by Shook (2003) as a way of describing 'reservoir geometry' (metaphorically speaking). This concept had been illustrated by Shook mostly using data from field tests of rather short duration (typical for a 'pilot' project scale). The renormalizing proposed by Behrens et al. (2010) allows to more adequately account for matrix diffusion processes (generically: slow kinetic exchange of solute tracer between mobile- and immobile-fluid compartments of heterogeneous void space in reservoir rocks), with tracer tests whose signals need to be recorded on a longer term (which is to say: in larger, real-world reservoirs).

From tracer sampling to date, CMR amounts to ~28% for the P4S signal, and to ~70(!)% for the N2S signal – whose first 20-30(!)% mass amounts were swept through the reservoir under the lower-rate flow regime, and its subsequent amounts under the higher-rate regime, reaching 60-65(!)% by the time P4S was added. CMR values for N2S marked by an '(!)' sign cannot be told accurately due to short-term flow-meter (instrumental) failures during precisely this flow regime transition; not only these particular values for N2S, but its entire subsequent CMR calculation is impeded by the flow-meter data gap. (As a work-around, one may attempt to reconstruct the missing flow-rate values from geothermal power generation data, but here operator-provided records proved insufficient.)

CMR for P4S exhibits a significantly lower growth rate than for N2S, even when plotted against cumulative fluid turnover, which should have compensated for flow-rate disparities. More strikingly yet, it shows a marked first-order discontinuity (tangent drop) after reaching ~20% (which would correspond to ~30% N2S after the same cumulative fluid turnover volume, counted since tracer injection). Since P4S was injected much later after the flow-meter failure, its tangent discontinuity in CMR stays independent upon those missing flow rate data.

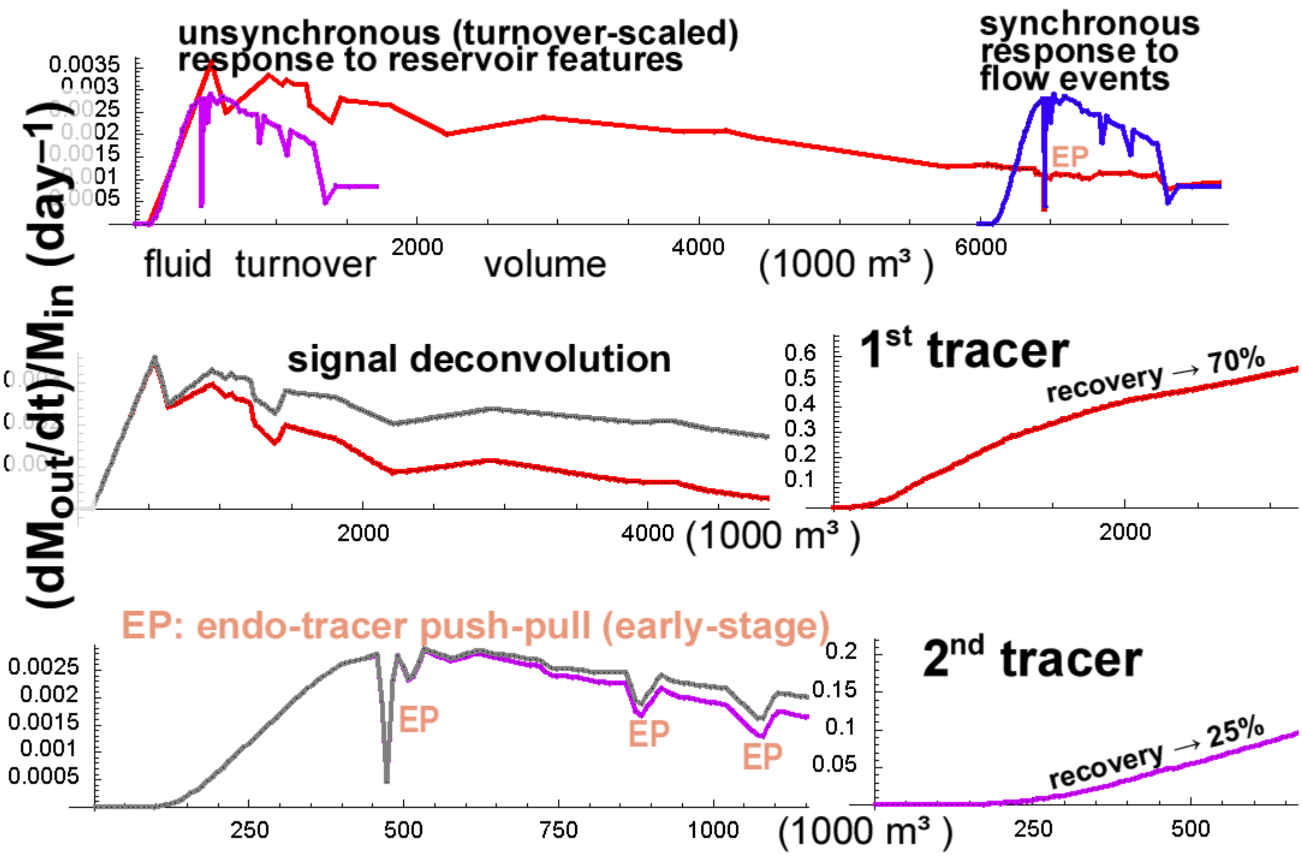

Figure 1: Solute tracer BTCs, deconvolved signals, early recovery rates and cumulative recovery ratio

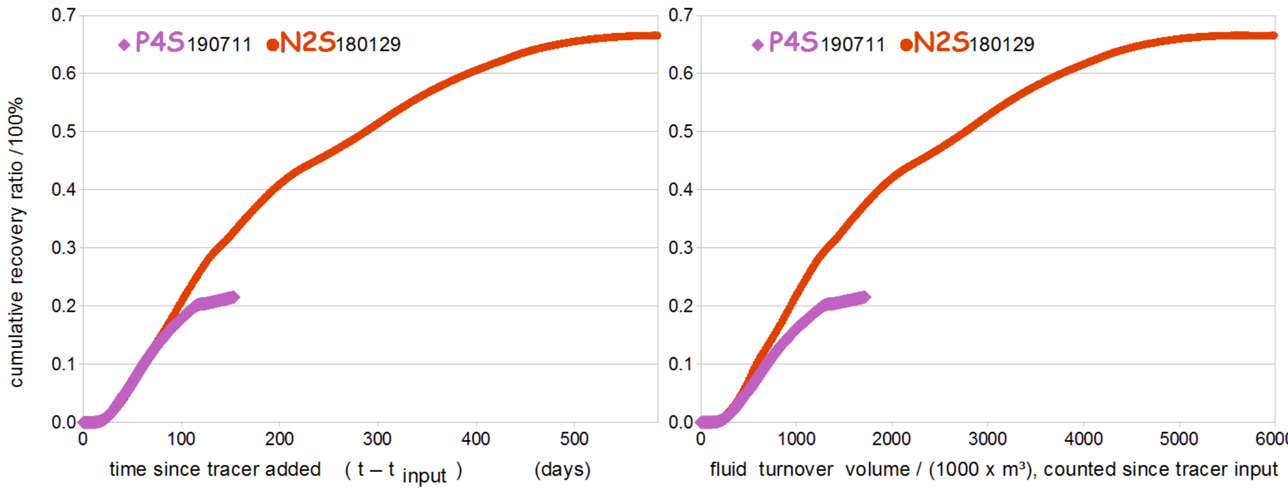

Figure 2: Cumulative recovery of each tracer to date (2020, third quarter)

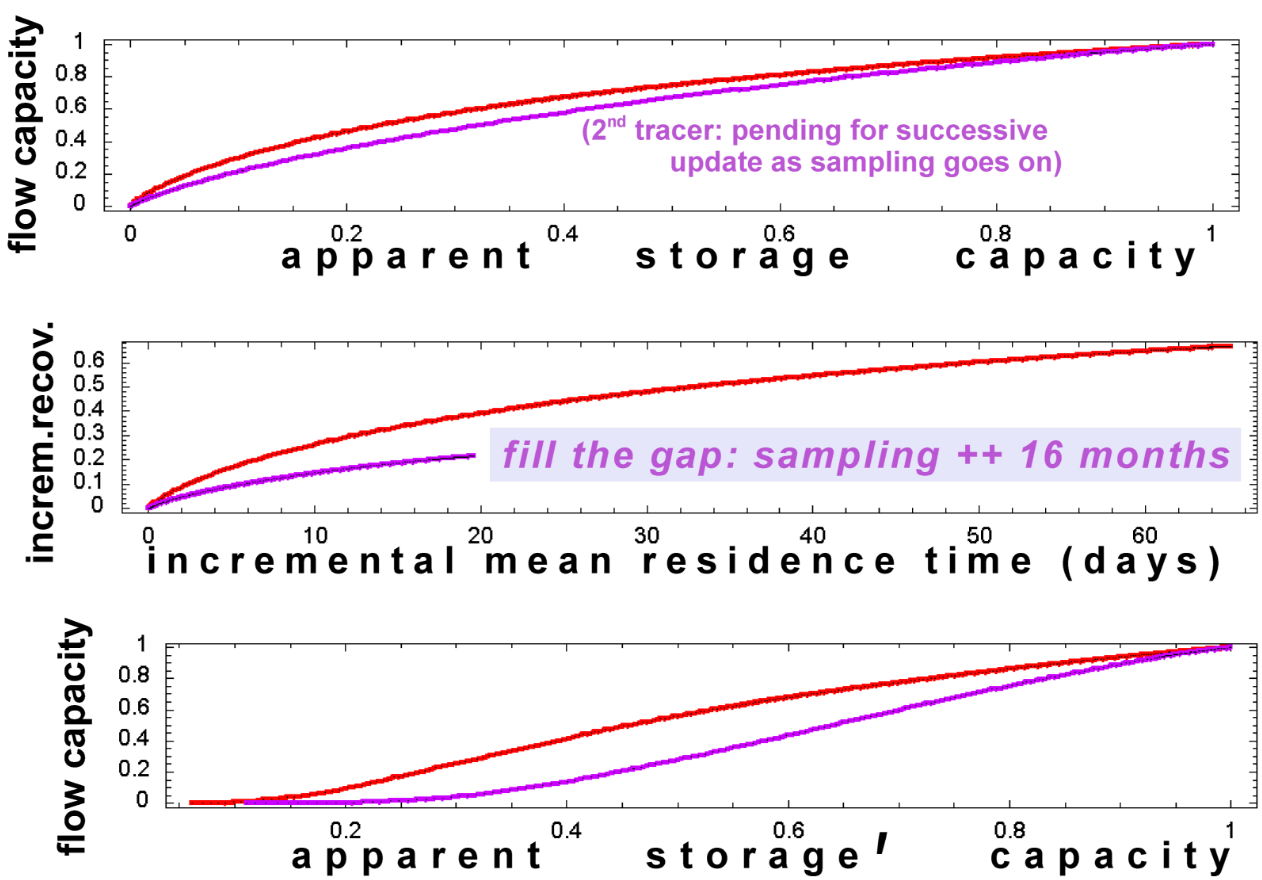

Figure 3: Approximate FSD shapes derived from solute tracer BTCs by 2020 third quarter

Pore velocity estimations lie in the range of 25 m/day as a median value (with ~50 m/day as a modal value), based on the reservoir volume swept by the tracers to date; thus, the median velocity value is over-estimated, and is expected to decrease as new tracer signal data are fed in, i. e., as the tracers sweep a growing reservoir volume. – Here, we use the 'swept reservoir' notion with the same meaning as given to it by Rose et al. (2004), i. e., irrespective of FSD shape uncertainties, relying merely on CMR calculation.

3. DISCUSSION

With (more than just slightly) varying flow rates, Green's solution kernel for the solute transport IBVP also changes with time, in at least three of several possible ways:

[linear] : global 'rescaling' by ac-/decelerated dilution,

[non-linear] : advective front shift (shift of 'peak arrival'),

[non-linear] : pore-velocity effect on hydrodynamic dispersion at pore scale,

[non-linear] : pore-velocity 'scale' effect on 'macro-dispersion',

[non-linear] : pore-velocity 'structural' effect on FSD (flow-storage *re*distributing) at reservoir scale,

to list just some generic mechanisms.

Thus, with a time-varying convolution kernel, deconvolving a 'recirculated' tracer signal (fig. 4) is not quite a trivial endeavor any more, and it takes a (markedly) model-dependent character. As our conceptual model improves, the deconvolved signals, their CMR, and FSD shapes (as previously shown in figs. 1–3) are also likely to change.

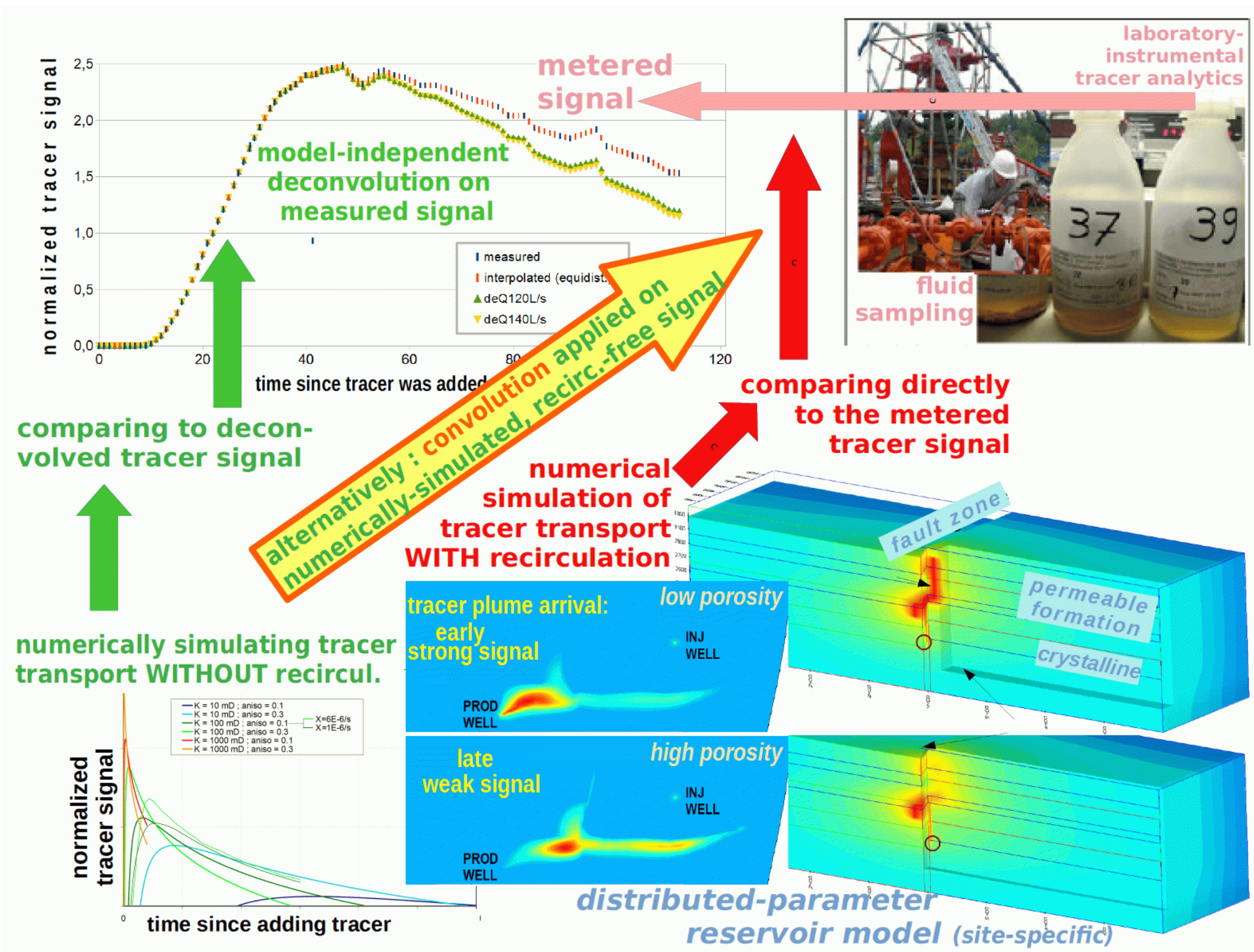

Figure 4: Three alternative workflow schemes for deconvolving a tracer signal recorded at the production well in doublet 'circuit' flow, with their more or less model-dependent elements, ensuing primarily from flow-rate variability – and, indirectly, from reservoir heterogeneity, especially in reservoirs with strong fluid mobility contrast between features like

fault zones or large-scale fractures and adjacent tight rock, where even moderate flow-rate variations may significantly alter the assumed 'convolution kernel' function

Four hypotheses which might explain the CMR tangent drop for the P4S tracer are proposed:

(i) P4S loss by some physico-chemical processes (maybe related to borehole cleaning / acidizing treatments), i. e., a non-conservative tracer behavior?

(ii) evidence for large induced fracture(s), or unintended (misaligned) reservoir 'stimulation', thus stronger P4S dilution?

(iii) reservoir compartmentalizing, thus P4S loss into some 'non-pay' zone?

(iv) last not least, might flow-rate records be flawed over a time interval significantly larger than originally believed?

Accordingly, we consider and evaluate a couple of more specialized monitoring options that would allow to disambiguate (or refute) some induced-fracture / activated-fault / karst 'narrow window' scenarios. To validate or infirm (i), we suggest conducting endo-tracer push-pull (single-well dilution) tests during late-tailing stages of both N2S and P4S (at the geothermal production well), which would allow for a direct quantitative comparison as to their possibly non-/conservative behavior in-situ. The term 'endo-tracer' (Ghergut et al. 2019) describes tracers whose (more or less remote-)past input into georeservoir fluid had been like that of an artificial tracer (i. e., well-defined and narrowly localized in space and time), but whose current spreading in the circulating fluid resembles more the natural-tracer pattern (i. e., quasi-uniform spreading over sufficiently large space and/or time intervals – 'sufficiently' w. r. to the desired application scale). To corroborate or refute either (ii) or (iii), complementary knowledge from geophysical exploration, in-situ stress field characterization, additional (hydraulic, thermal) data are needed; (ii) and (iii) would essentially resemble the scenarios illustrated in figs. 1, 2, 5 of our prior study (Behrens et al. 2020), but they would need to occur at a much later time than could still be explained by those early-stage poroelastic effects described in figs. 8–12 of ibid.; in other words, some kind of 'long-term reservoir dynamics', maybe as a cumulative effect of fluid turnover and/or pore pressure buildup, would still be awaiting explanation.

In any case, signal monitoring for both tracers would need to be extended by at least 16 months, counting from the second tracer's CMR tangent drop, and assuming the higher flow rate were kept approximately constant over the entire duration until conducting the endo-tracer push-pull test, for which, then, a much slower rate (in the order of 10–30 L/s) appears recommendable, relying on the scaled 'type-curve' families for conservative-tracer push-pull tests derived by Ghergut et al. (2013), against which the signal variations marked by 'EP' in fig. 1 can be evaluated in a half-quantitative manner and regarded as 'involuntary rehearsal' for the endo-tracer push-pull test to be purportedly conducted at a much later stage.

As a work-around for (iv), one may attempt to reconstruct the missing flow-rate values from geothermal power generation data, but here operator-provided records proved insufficient; on the other hand, can we, at all, attempt to 'reconstruct' the correct flow-rate values based on holomorphicity requirements for a tracer's CMR curve shape? this, in turn, would implicitly exclude hypothesizing structural reasons like (ii) or (iii) that would indeed violate holomorphicity (circular argument!).

As new tracer signal data are fed in, the gap between FSD shapes seen in fig. 3 may decrease or increase, and the meaning of this gap will depend on how corroboration / refutal progresses among hypotheses (i) – (iv). The late-tailing regime accessible, within affordable 'waiting time', synchronously for both tracers (in guise of endo-tracers) provides the opportunity of a comparative in-situ push-pull (single-well dilution) test, to verify that rate sensitivity and FSD shift (which would be beneficial for the reservoir's thermal lifetime) is not an 'artifact' reflecting physico-chemical deviations between two aromatic sulfonates, but a genuine hydrogeological feature or 'dynamic response' of the Malm reservoir. Such opportunity of a 'new tracer test without adding new tracer' is going to occur within few months from now (the flip side of the coin to premature decline of production temperatures). Indeed a pretty rare occasion in the realm of deep-geothermal reservoirs, and of particular value for a production well, whose unnecessary 'spoiling' by added tracers is to be avoided by any means.

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Abbreviations:

BTC : 'breakthrough' curve (a rather inappropriate, but historically naturalized name for an artificial tracer signal)

CMR : cumulative mass recovery

FSD : flow-storage distribution

IBVP : initial and boundary value problem

N2S : a naphthalene-disulfonic acid salt isomer

P4S : a pyrene-tetrasulfonic acid salt (the stable isomer)

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