EGU22-6133
https://doi.org/10.5194/egusphere-egu22-6133
EGU General Assembly 2022

Do tracer tests enable model-independent predictions of georeservoir output? two examples from Southern Germany, involving thermal drawdown and solute co-production

Horst Behrens, Julia Ghergut, Bettina Wiegand, Bianca Wagner, and Martin Sauter

Applied Geoscience Dept., University of Göttingen, Germany (iulia.ghergut@geo.uni-goettingen.de)

For geothermal reservoirs operated by production and re-injection wells, thermal lifetime is usually defined in terms of a temperature drop threshold, and estimated as a function of fluid turnover time T_{fluid} and heat exchange surface-area density σ (area per volume),

$$T_{heat} = R \cdot T_{fluid} + D \cdot \sigma^2 \cdot T_{fluid}^2 ,$$

with T_{fluid} supposed to be measurable by means of a tracer test, whereas σ is rather difficult to infer from tracer signals alone; D aggregates thermal diffusivity properties which are not very well known in advance, but whose natural variability in deep georeservoirs spans less than one magnitude order, unlike σ whose uncertainty may span many orders of magnitude.

For 'aquifer'-like reservoirs, the linear term prevails:

$$R > (>>) 1 , \quad D \cdot \sigma^2 \cdot T_{fluid} << 1$$

For fracture-dominated ('petrothermal') reservoirs, the quadratic term prevails:

$$R \approx 1 , \qquad D \cdot \sigma^2 \cdot T_{fluid} >> 1$$

Deriving T_{fluid} from artificial-tracer signals looks 'model-independent', but is subject to large-time signal extrapolation uncertainty (which 'restores' model-dependence).

Unlike thermal forecasting, tracer-based prognosis of solute co-production (more precisely, of its lower-bound level, assuming conservative transport by fluid turnover only, non-'replenished' from adjacent rocks) is not impeded by large-time extrapolation uncertainty, nor by reservoir model and/or parameter ambiguity, since mass output prediction as a function of time,

$$M_{out}(t) = (C_{ini} - C_{resid}) \left[VOL_{out}(t) - \int_o^t \int_o^{t'} Q(t') Q(t'') g(t'') dt'' dt' \right]$$

requires just knowledge of conservative-tracer fluxes within the forecasting time horizon.

Once a tracer test was conducted in accordance with the rules of the art (which usually includes approximate observance of flux-type fluid sampling and tracer input B.C.s, cf. *Kreft and Zuber 1978*), the reservoir can be treated like a 'black box' with 'response function' (Green's kernel surrogate) g.

If solute 'replenishment' (say, by ion exchange or de-sorption processes) from adjacent rock remains negligible, the solute contents of the mobile-fluid turnover volume ($V_{fluid} = Q\, T_{fluid}$, when Q is steady) represents an upper bound on the maximum extractable solute mass; whereas the maximum amount of the latter can stay well below the former, for the chosen duration of reservoir operation. Normalizing the cumulatively co-produced solute mass by this upper bound, when Q is steady we get

$$\left[(C_{ini} - C_{resid})\, V_{fluid} \right]^{-1} M_{out}(\tau) \equiv \mu(\tau) = \tau - \int_o^{\tau} R(\tau') d\tau'$$

as a function of dimensionless time $\tau \equiv t / T_{fluid}$, where R denotes the cumulative tracer recovery, normalized by the tracer input mass, and expressed as a function of dimensionless time τ. Thus, at early times ($t << T_{fluid}$) , the extracted mass fraction grows proportionally (1:1 like τ) with time; in physical units, the early growth rate equals $Q\,(C_{ini} - C_{resid})$. Extrapolating this early growth rate to later times would tremendously *over*-estimate M_{out} , because the growth rate drops significantly when $t > T_{fluid}$. Such solute depletion behavior was analyzed in detail, based on actual tracer signal data from tests conducted in 2004/2005, by Behrens et al. (2022) for the pilot-geothermal site Horstberg in the N-German sedimentary basin, and for Soultz-sous-Forêts in the Upper Rhine Rift Valley, showing that the 'final' solute mass output is less than ⅓ of what early extraction rates would have 'predicted'.

Here, a broader view is obtained in dimensionless 'type-curve' format, enabling to compare between reservoirs of different sizes ($V_{fluid} = Q\, T_{fluid}$) , operated at different rates Q, by assuming a single Peclet number can at least roughly quantify their heterogeneity at reservoir scale, $Pe \equiv V_{fluid} / (S\ \alpha_{longit})$ with S the average cross-section area available for fluid flow, and α_{longit} a "longitudinal dispersivity" value characterizing reservoir heterogeneity. The stronger the heterogeneity, the lower the Pe value; for uniform (piston-like) flow, $Pe \rightarrow \infty$. Whereas the advective-dispersive model for conservative solute transport would forbid Pe values lower than 1, one may use values "$Pe \leq 1$" to roughly reproduce the effects of matrix diffusion processes (which are not included in the advective-dispersive model, but are likely to play a most significant part in tracer transport through the consolidated-rock formations of the deeper subsurface). Roughly speaking, the lower the Peclet number's value, the more pronounced the 'fractured' or 'petrothermal' character of the reservoir – irrespective of its geological classification as 'sedimentary' rather than 'crystalline'.

Allowing Pe to span three orders of magnitude (from 100 to $1/\sqrt{10}$), we obtain the normalized tracer signals of fig. 1, with cumulative recovery curves as shown in fig. 2, and with their corresponding time "deficit" amount (the second term in μ (τ), cf. supra) growing with time as shown in fig. 3; these "deficit" values are used to estimate μ (τ) as shown in fig. 4, as well as the variable co-extraction rate μ (τ) / τ as shown in fig. 5, for early and for late times, respectively.

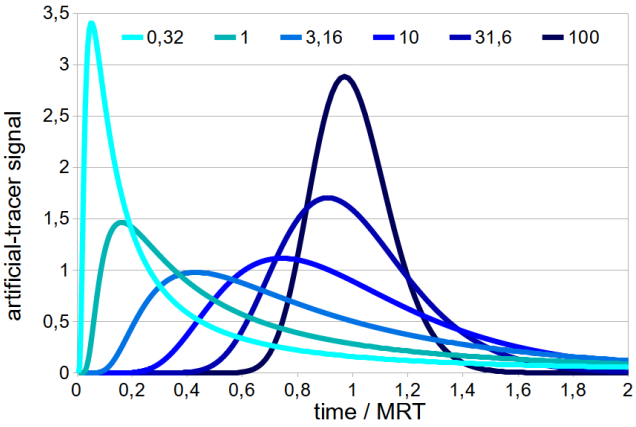


Fig. 1: Normalized tracer-signal type curves with Pe between 100 and 1/√10

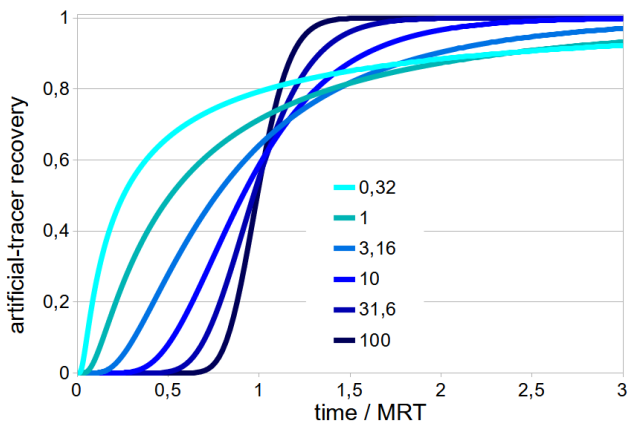
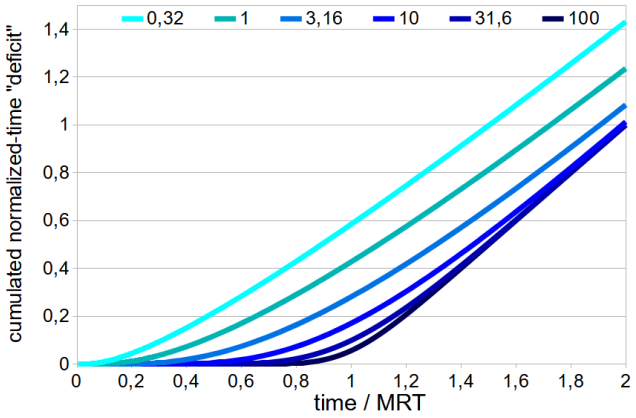


Fig. 2: Cumulative recovery ratios corresponding to the tracer-signal type curves of fig. 1



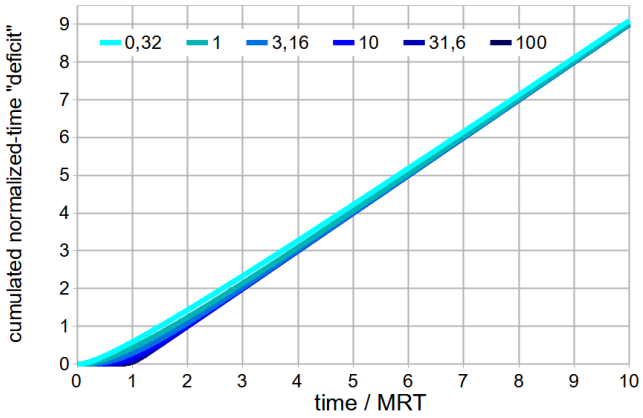
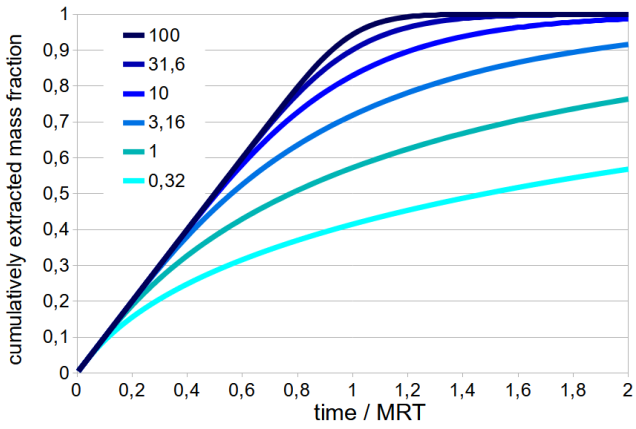


Fig. 3: Cumulative dimensionless time “deficit” corresponding to the tracer-signal type curves of fig. 1 (Peclet-number sensitivity of early vs. late increase)



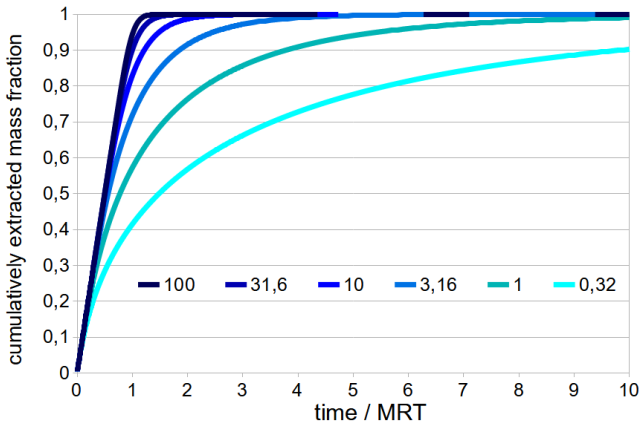


Fig. 4: Co-produced solute mass output corresponding to the tracer-signal type curves of fig. 1 (early growth vs. late plateau)

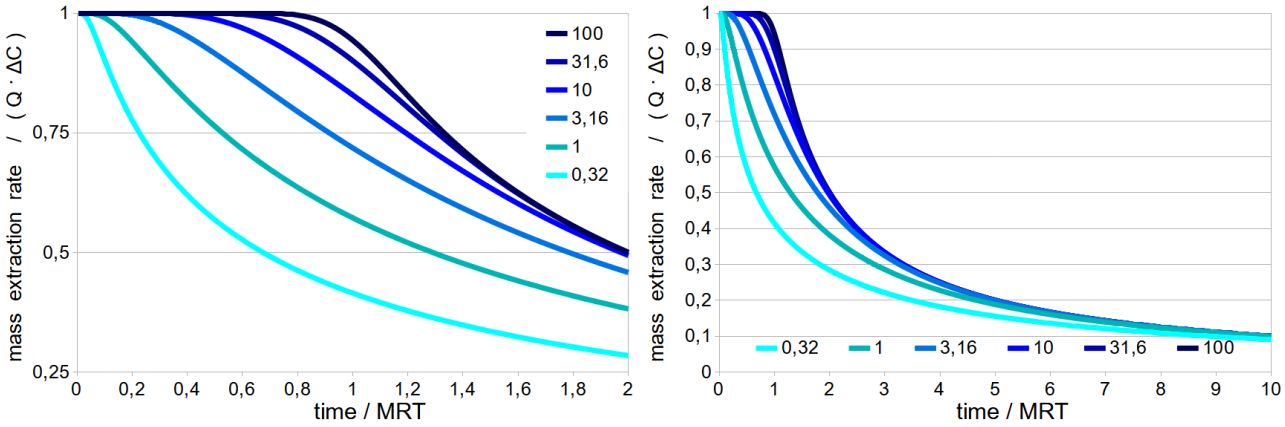


Fig. 5: Mass extraction rate drop corresponding to the tracer-signal type curves of fig. 1 (early rate stability vs. late rate drop)

In abscissa-axis labels, MRT stands for “mean residence time” which is identical with the “fluid turnover time” T_{fluid} in the relationships above. In the ordinate-axis labels of fig. 5, ΔC abbreviates the solute concentration difference $C_{ini}–C_{resid}$ (for the co-produced solute only, not for the artificial tracer), in which C_{resid} was assumed as time-independent for simplicity (C_{resid} is a technical parameter of the solute extraction technology, say, by means of ion exchange, as implemented in some uphole facility; C_{resid} will depend on the column size used, retention times, etc.; it is essentially unrelated to solute transport processes within the georeservoir in question).

This approach is adequate for (conservative) solute co-production, but not for heat transport in the same georeservoir. Tracer test results from a particular Upper-Jurassic (“Malm”) carbonate aquifer near Munich illustrate (fig. 6) the issue with T_{heat} as a multivoque ‘function’ of T_{fluid} values inferrable from tracer tests.

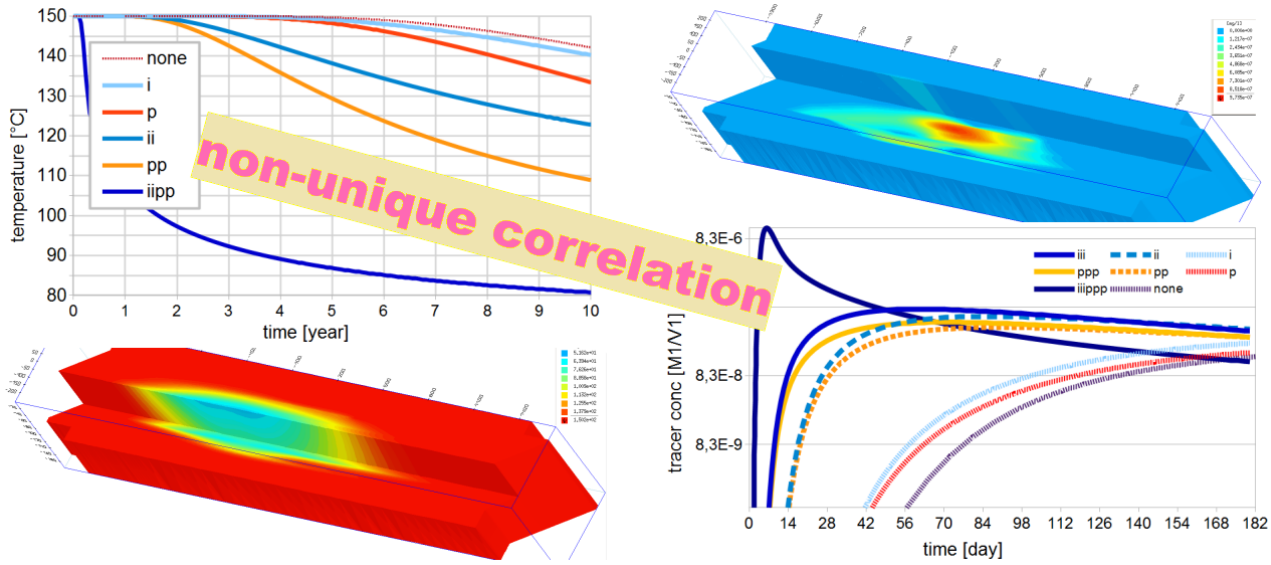


Fig. 6: Theoretical uncoupling between production temperature and solute tracer signal predictions for a fissured (and possibly fractured) Upper-Jurasic (“Malm”) carbonate reservoir

Tracer signals available to date yield T_{fluid} in the range of months (still subject to extrapolation uncertainty), and are compatible with both fracture-dominated and 'aquifer'-like representations of reservoir structure; 'compatible' values of σ span four(!) orders of magnitude.

By contrast, even the only-incipient signals from a tracer test in a fractured-porous reservoir, Eastern side of the Upper Rhine rift, though yet incomplete, could already be used to predict lower bounds on "geothermal lithium" output and its expected evolution during fluid turnover, irrespective of the availability of a reservoir model and the uncertainty of its parametrizing (Behrens et al. 2022).

Interestingly, the time "deficit" (μ(τ)–τ)'s dependence on Pe (i. e., on reservoir heterogeneity, or its 'occult petrothermal' character) seems to vanish (fig. 3, r.-h.s.) with increasing time; notwithstanding, co-produced solute output (fig. 4) as well as production rates (fig. 5) still show a strong dependence on Pe, most strikingly for the curves in light cyan, corresponding to "Pe<1" which actually means violating the advective-dispersive model and forcibly bringing in matrix diffusion; the curves in sea-foam green (Pe=1) delineate between advective-dispersive and 'matrix-diffusive' regimes of solute transport.

Roughly speaking, *the stronger the heterogeneity* or permeability contrast a.k.a. *discontinuity* (or 'petro-thermal') features, *the longer it will take* (in terms of normalized time) to 'pull' the maximum-possible solute contents 'out' of the reservoir. Conversely, *the more homogeneous the reservoir, the more efficient the solute co-production*. This is the take-away message from such simplistic type-curve calculations.

The non-trivial challenge, however, is to foresee and quantify overall water-rock interaction effects of 'spent fluid' re-injection, the latter being depleted of its particular micro-constituent, albeit at trace levels only, while being likely acidized or 'unreliably' buffered at major-ion levels. Water-rock interactions cannot be told from conservative-tracer signals; hydrogeochemical modeling (*Kölbel et al. 2020*, *Maier et al. 2021*) becomes indispensable.

Acknowledgments

We gratefully acknowledge long-term support from Germany's Federal Ministry for Economic Affairs & Energy (BMWi) within the applied-research projects "LOGRO", "TRENDS", "UnLimiteD", funded under grant nos. 0325111B, 0325515, 03EE4023E (https://sites.google.com/view/bmwi-0325515-trends, https://sites.google.com/site/goetracerhydro/research-projects, www.geothermal-lithium.org).

References

Behrens H, Ghergut J, Sauter M, Wagner B, Wiegand B (2022) Solute co-production from small geothermal reservoirs – how little is too little? Stanford Geothermal Program, Stanford University, SGP-TR-223, 200–210

Kölbel L, Kölbel T, Maier U, Sauter M, Schäfer T, Wiegand B (2020) Water-rock interactions in the Bruchsal geothermal system by U-Th series radionuclides. GeoThermalEnergy (GTE), 8, 24

Kreft A, Zuber A (1978) On the physical meaning of the dispersion equation and its solutions for different initial and boundary conditions. Chem Eng Sci, 33,1471–1480

Maier U, Tatomir A, Sauter M (2021) Hydrogeochemical modeling of mineral alterations following CO2 injection. Appl Geochem, 136, 10515