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When endo-tracers get into (reactivated) fault zones – what do they tell?

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Abstract

Scoping simulations of solute transport in a dozen ultra-conservative scenarios (all with an exaggerated worst-case propensity) of “fault reactivation during unconventional reservoir development” indicate (counter-intuitively at first glance) tracer signals, or spill freights to the overburden are highest in the hydrogeologically tightest scenario; yet in some scenarios solute ‘plumes’ in the overburden re-distribute between both sides of the fault zone.
Bearings on monitoring system design in the overburden, and prospects for a tracer-assisted characterization of highly-fractured fault-zone intervals at the KTB site are briefly addressed.

An extended summary in German (Zusammenfassung und Ausblick im BMWi-Vorhaben ‘TRENDS’, FKZ 0325515) is provided at the end of the document.

1. Introduction

Along with growing interest for the deeper subsurface as the host of ‘georeservoirs’ in terms of retrievable energy, storage capacity for mass / energy, or safe disposal options for various types of waste, concerns about environmental hazards associated with georeservoir development and operation are also intensifying, especially for systems involving forced-gradient flow and/or its artificial enhancement by means of (unconventional) reservoir stimulation techniques. A popular concern is that of an “overburden spill by natural / introduced contaminants migrating through [accidentally, not purportedly] *enhanced pathways*”, e. g., “large-scale fault zones that were reactivated” as a side-effect of, say, HF (hydraulic fracturing) operations in a deeper georeservoir formation. Overburden spill hazard assessments range from ‘alarming’ (Myers, 2012; Warner et al., 2012, 2013; Reagan et al., 2015; Sherwood et al., 2016) to ‘cautiously optimistic’ (Schwartz, 2015; Sauter et al., 2013; Lange et al., 2013; Taherdangkoo et al., 2017), or even the unreserved ‘all-clear’ signal (Kümpel, 2016; Pfunt et al., 2016). The hydrogeologist, though, will know that ‘*pathway enhancement*’ may have a twofold bearing:

(I) the larger the aperture, the higher the hydraulic transmissivity of the ‘enhanced pathway’, thus the higher the amount of fluid flow (and, potentially, spill freight) that will be redirected to it from competing-transmissivity compartments;

(II) the larger the aperture, or cross section area, or volume, and/or effective porosity of those ‘enhanced pathways’, the more retarded and diluted the ‘spill’ through them.

To a certain extent, mechanism (II) may, theoretically, alleviate the effects of mechanism (I) but, for real-world georeservoirs, irregular geometries and hydrogeological heterogeneity will prevent a rapid, rule-of-thumb assessment of their intermingled effects, from mere knowledge of aperture, porosity, etc. values; thus, in most cases, detailed site-specific models and simulations will be a must-do. Yet simplified, ‘scoping’ simulation on models half-way between generic and site-specific may contribute to ‘defusing’, and somewhat objectifying such controversies.

2. Materials and methods

The effect of permeability windows (PW) within a large-scale fault on the advective-dispersive, matrix-diffusive transport of a generic non-reactive solute (a conservative endo-tracer, cf. infra) from a neighboring, stimulated deep reservoir towards a shallow aquifer is explored by numerically simulating a set of ultra-conservative hydrogeological scenarios (i. e., with an exaggerated, yet still reasonable worst-case propensity, cf. infra).

A generic conceptual model comprising reservoir, basement, cap rock, aquifer layers, adjacent to or intersected by a sub-vertical normal fault underlies all scenarios (fig. 1, l.-h. s.). The large-scale fault is represented as a tight core flanked by relatively permeable damage zones. Within core and/or damage zones, PW (putatively associated with fault reactivation by pore pressure increase during unconventional reservoir stimulation) are assumed; their location, vertical extent and physical properties are varied between scenarios (table 1).

The term *endo-tracer* was coined within the German BMWi project ‘TRENDS’ (FKZ 0325515). It is always meant in conjunction with a *georeservoir-typical* (and well-defined) hydraulic operation sequence on a (more or less well-characterized, maybe still largely unexplored) georeservoir. Against this background, it flexibly denotes some either naturally-present, or artificially-introduced, or a combination of both kinds of tracer species, whose subsurface transport (within/to/from the georeservoir and its neighboring geological formations) is subject only to the forced gradients implied by that *georeservoir-typical* operation sequence. Thus, we are not referring to a purportedly conducted *tracer test* with its well-tailored design, usually involving some forced-gradients added, and its well-tailored sizing of tracer quantities, added such as to ensure optimum detection, metering, and inversion of tracer signals.

This might sound like a bit too much of sophistication; yet: the rationale emphasizing this distinction from a purportedly conducted *tracer test* is that the *endo-tracer* signals, as generated without further intervention, may (if at all detectable and quantifiable) be quite far-from-optimal for the purposes of georeservoir and/or process characterization; whereas the endeavor to optimize their use – like in *tracer tests’* best practice – might have required considerable hydraulic deviations, at odds with the georeservoir’s economic use.

By *georeservoir-typical* operation we mean, for instance, massive fluid injection for the purpose of georeservoir stimulation, followed by injection or production of a different kind of fluid; or fluid turnover by circulation within a geothermal-well doublet – which is certainly not the best-suited forced-gradient configuration for detecting and characterizing fluid transport in nearby fault zones (in some distance away from the actual reservoir).

Here, we simulate the signals of a conservative solute (‘the endo-tracer’) that entered the reservoir along with HF fluid (HFF) and may or not become detectable in the reservoir’s overburden (the latter including a shallow aquifer – where tracer signals could represent ‘HFF spill’).

To prevent confusion, it is recalled that *conservative tracer* stands, roughly, for a physico-chemically stable species, whereas *conservative scenario* (in the context of anthropogenic and/or georeservoir-related hazard assessment – Sauter et al., 2013, Lange et al. 2013) deems a set of worst-case assumptions (implying events that would need to be paid most attention – if they were to occur), which, may they even be ‘ultra-worst’, still sound ‘imaginable’ (not fully impossible) and ‘worth consideration’ (not fully unreasonable, like, e. g., continental-scale violence) by geoscientific and socioeconomic standards.

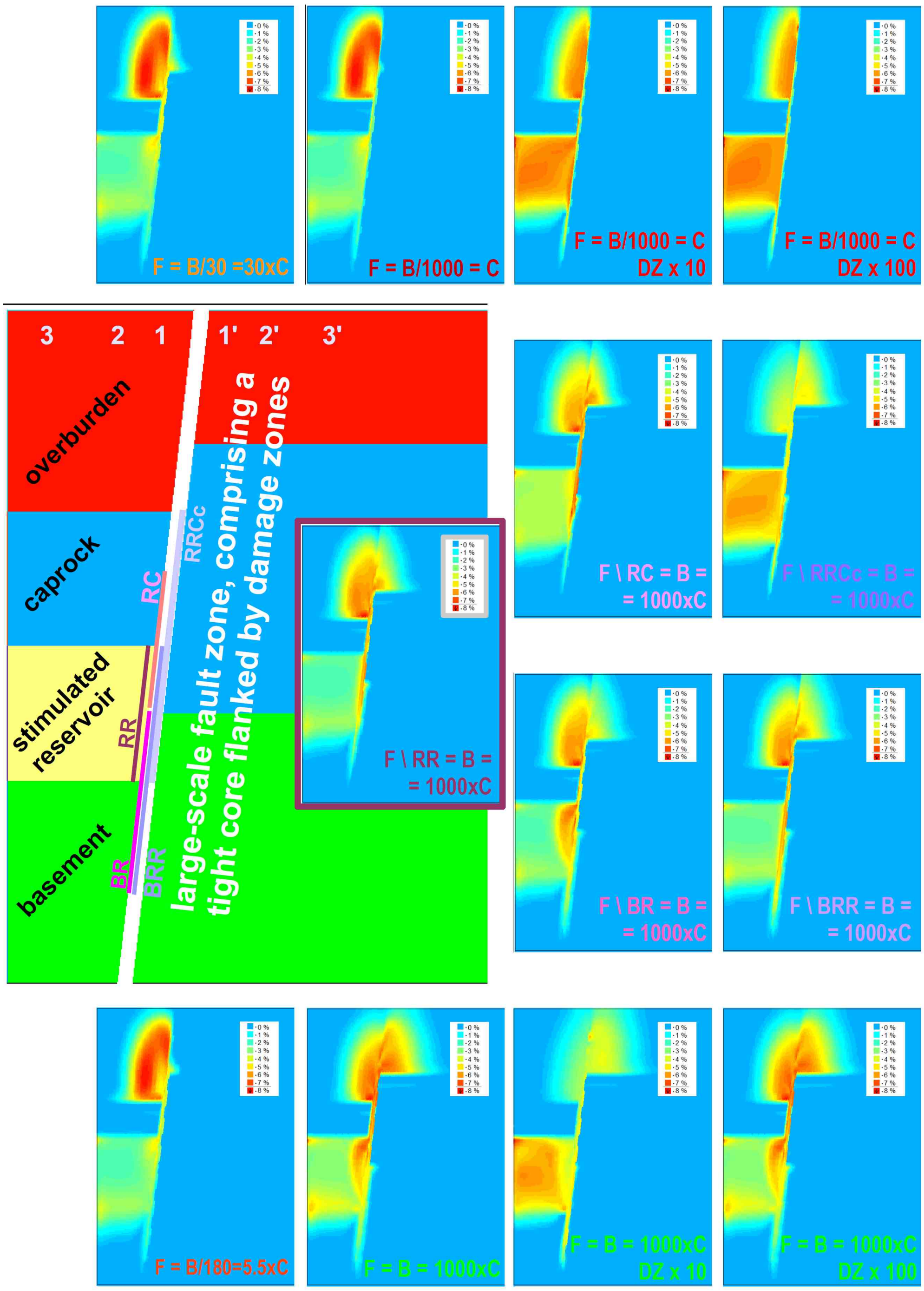


Fig. 1: Conceptual model, and illustrative pattern of solute plume shapes after 300 days since injection start (with injection stopping after 30 days), for the 12 “rupture” scenarios (plus reference scenario, shown second from left in the upper row).

Table 1: Hydrogeological parametrization of conceptual model, and of so-called “rupture” scenarios

scenario id	**key feature (brief characterization)**	fault core permeability [mD], compressibility [m^{-1}], and transport-eff. porosity [%]	damage zone transmissivity, expr. by effective ‘cubic law’ aperture [mm], compressibility [m^{-1}], and cross section area per model width unit [m² / m]
F = B/1000 = C	**entire fault core is kept similar to the caprock**	0.5 μD , 10^{-8}/m , 0.1%	1 mm, 10^{-4}/m, $5 \cdot 10^{-4}$ m
F = B/1000 = C DZ x 10	ibid.; damage zone eff. aperture 1 mm → 1 cm	0.5 μD , 10^{-8}/m , 0.1%	1 cm, 10^{-3}/m, $5 \cdot 10^{-3}$ m
F = B/1000 = C DZ x 100	ibid.; damage zone eff. aperture 1 mm → 10 cm	0.5 μD , 10^{-8}/m , 0.1%	10 cm, $2 \cdot 10^{-3}$/m, $5 \cdot 10^{-2}$ m
F= B/180=5.5xC	fault core resembles caprock rather than basement rock	2.75 μD , 10^{-7}/m , 0.2%	1 mm, 10^{-4}/m, $5 \cdot 10^{-4}$ m
F= B/30 =30xC	**fault core is intermediate (geom. ave.) between caprock and basement**	15 μD , 10^{-6}/m , 0.4%	1 mm, 10^{-4}/m, $5 \cdot 10^{-4}$ m
F \ RR = B = = 1000xC	**fault core is kept similar to caprock, except for the indicated \segment, which becomes similar to the basement rock**	outside the \segment: 0.5 μD , 10^{-8}/m , 0.1% and within the \segment: 0.5 mD , 10^{-6}/m , 2%	40 cm, $3 \cdot 10^{-3}$/m, 0.2 m
F \ BR = B = = 1000xC			
F \ RC = B = = 1000xC			
F \ BRR = B = = 1000xC			
F \ RRCc = B = = 1000xC			
F = B = 1000xC	**entire fault core becomes similar to basement rock**	0.5 mD , 10^{-6}/m , 2%	1 mm, 10^{-4}/m, $5 \cdot 10^{-4}$ m
F = B = 1000xC DZ x 10	ibid.; damage zone eff. aperture 1 mm → 1 cm	0.5 mD , 10-6/m , 2%	1 cm, 10^{-3}/m, $5 \cdot 10^{-3}$ m
F = B = 1000xC DZ x 100	ibid.; damage zone eff. aperture 1 mm → 10 cm	0.5 mD , 10^{-6}/m , 2%	10 cm, $2 \cdot 10^{-3}$/m, $5 \cdot 10^{-2}$ m
all scenarios	permeability, compressibility, and transport-eff. porosity:	5 D, 10^{-5}/m, 3.5% for the overburden 50 D, 10-6/m, 0.5% for a fully max.-stim. reservoir	

3. Results

Solute (endo-tracer) breakthrough signals in the shallow aquifer are shown in fig. 2 for six hypothetical observation points in 100 m depth, three on each side of the fault zone in ~20 to ~600 m horizontal distance (cf. numbering 1,2,3, 1´,2´,3´ in fig. 1), along with a full horizontal profile of solute concentration in this same (100 m) depth, after 300 days since injection start.

Solute signals in the overburden may reach values as high as 10% M_{inj} / (1000 m^3), which amounts to 10 ppm if M_{inj} was 100 kg; instrumental detection and metering sensitivity would need to be ensured accordingly, with a detection threshold below ~10 ppb to enable 'early warning' during the first 3 days of injection.

In the 'unsealing' scenario classes, the overall solute freight re-distributes between the reservoir-adjacent and the opposite side of the fault zone. Thus – however unlikely a reactivation of nearby faults by reservoir stimulation operations may be –, once a theoretical "overburden spill hazard" has come to be considered as 'relevant' (for whatever reason), then the fluid-based monitoring should not remain confined to fault-zone vicinity and the overburden region above the reservoir, but extend, on its 'remote' side (opposite to the reservoir), at distances amounting to at least the reservoir size.

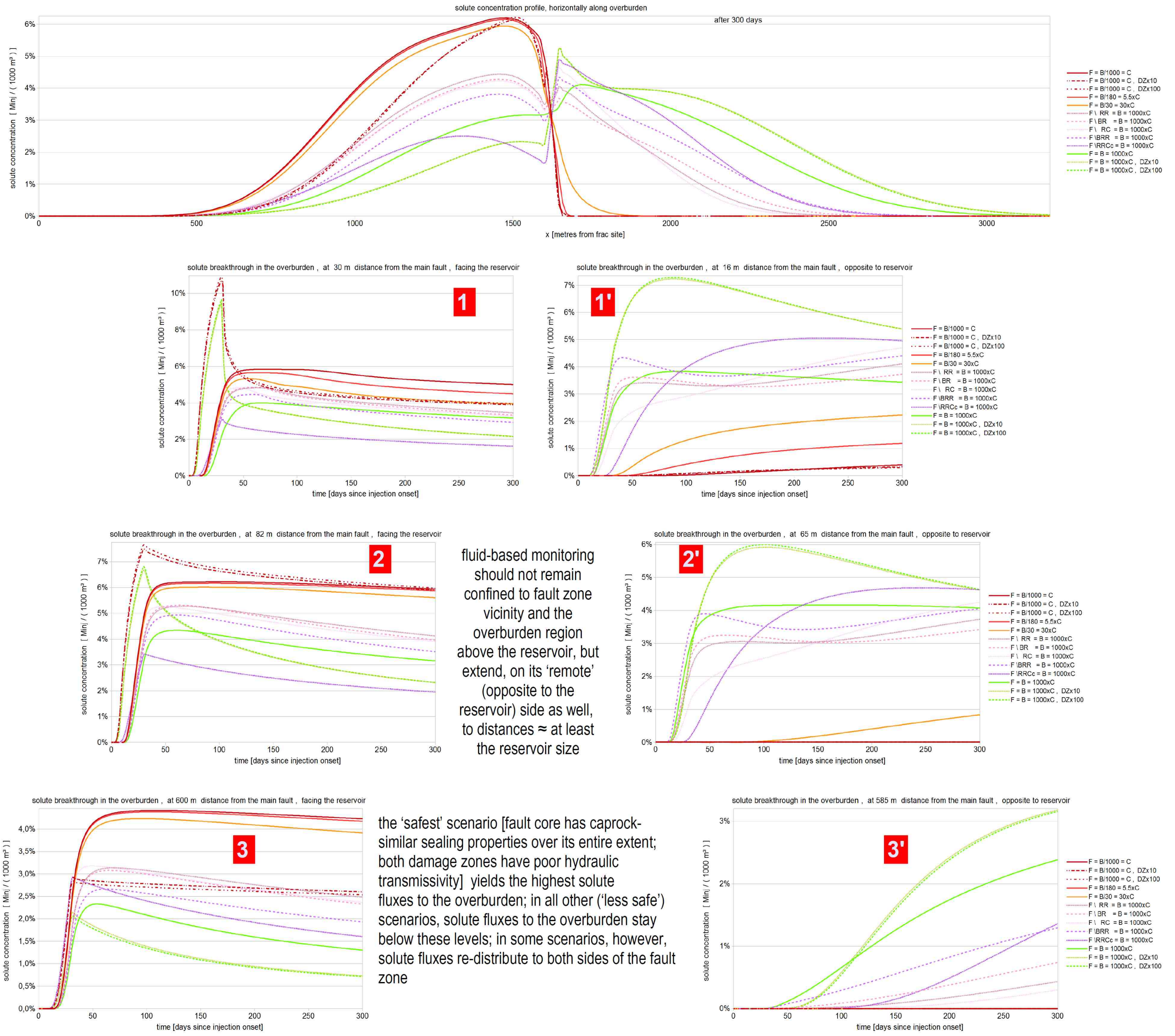
Further, if fluid sampling would be actively conducted by fluid extraction (rather than passively recording in-situ concentrations) from the overburden, then the predicted signals shown in fig. 2 would need to be converted to solute flux density (solute mass retrieved per per cross section area, per time) before comparing between predicted and measured signals, and total freight estimations should be based on these measured flux densities, rather than on predicted 'resident-type' concentrations.

4. Comment

Our simulation results should not be mistaken for a prediction of shallow aquifer contamination induced by HF operations. Rather, we are more interested to see whether tracer signals detectable by shallow sampling can be used for fault-zone characterization at depth, or for telling the transport properties of at least some of its compartments. This would nicely complement Shapiro's (2015) agenda of using induced (micro)seismicity to infer hydraulic properties of the subsurface (with a prominent example at the KTB site), since inverting hydraulic parameters from seismicity and/or from pressure signals (McDermott et al. 2006) leaves fluid transport parameters yet undetermined (Ghergut et al., 2007, 2016). This 'hidden agenda' has let us select and combine hydrostratigraphy, fault-zone and PW property ranges yielding non-zero (i. e., instrumentally detectable) tracer shallow signals for the scenarios' most part, for which we were willing to put up with unrealistically high upward fluxes (ultraconservative scenarios, in the sense of Sauter et al. 2013, Lange et al. 2013). Thus it's more about seeing the fault zones, than about seeing the tracers.

Last not least, it is worth recalling the large-scale fault-zone tracing test initiated at the KTB site back in 2005 (www.icdp-online.org/projects/world/europe/ktb/), funded by the German Research Foundation (DFG).

A tracer slug comprising uranine (disodium fluorescein) and 1,5-naphthalene disulfonate was pushed into the ~4 km deep, densely-fractured crystalline formation some decametres radially away from the pilot hole (KTB-VB), with the prospect of a tracer 'plume', retrievable during a future pumping test at the 9 km deep main hole (KTB-HB), to enable characterizing the fracture network in terms of fluid transport properties at several-kilometres scale (Ghergut et al., 2007).



fluid-based monitoring should not remain confined to fault zone vicinity and the overburden region above the reservoir, but extend, on its 'remote' (opposite to the reservoir) side as well, to distances ≈ at least the reservoir size

the 'safest' scenario [fault core has caprock-similar sealing properties over its entire extent; both damage zones have poor hydraulic transmissivity] yields the highest solute fluxes to the overburden; in all other ('less safe') scenarios, solute fluxes to the overburden stay below these levels; in some scenarios, however, solute fluxes re-distribute to both sides of the fault zone

Fig. 2: Solute concentration profiles, horizontally in 100 m aquifer depth, after 300 days since injection start (with injection stopping after 30 days), and solute breakthrough signals at six different locations in this same aquifer depth (cf. numbering shown in Fig. 1), for the 12 "rupture" scenarios besides the reference scenario (listed first in each legend, plotted in intense red).

At the time of tracer slug injection, the faulted / fractured rock formation around the KTB-VB was under moderate hydraulic stimulation (Kümpel et al., 2006; Shapiro, 2015: Ch. 3.1). If at least the second tracer species is physico-chemically stable (at in-situ 150–200°C, pH~6, ~70 g/L TDS), then tracer signals in the range of >ppb, or even ~1 ppm can be expected, even after 13 years of shut-in.

At such research sites where large-scale fault systems are not the undesired, hazardous feature, but the very target of a forced-gradient fluid-turnover based exploration (like the KTB site, targeting the crystalline basement, or the Horstberg site in the N-German sedimentary basin), tracers are expected to convey those fluid transport properties that could not be told from geophysical and hydraulic signals.

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An extended summary in German language is provided below.

Zusammenfassung und Ausblick im BMWi-Verbundvorhaben 'TRENDS' (FKZ 0325515)

Die theoretische Möglichkeit einer Kontamination oberflächennaher Aquifere durch Fremdstoffe, die von einem stimulierten tiefen Reservoir entlang theoretisch reaktivierbarer Störungszonen (putativ) nach oben migrieren, wird in einer Dutzend ultrakonservativer (übertrieben gefährdungsbetonter) Szenarien betrachtet, die in Anlehnung an aktuelle Debatten aufgestellt wurden.

Ausgehend vom Referenzfall einer über ihre gesamte Architektur (Störungskern und Alterationsbereiche) verhältnismäßig dichten Verwerfungszone, werden ihre hydraulische Transmissivität und transportwirksame Porosität abschnittsweise (im Kristallin, im Reservoir, im top seal bzw. caprock) um bis zu 3 Größenordnungen erhöht. Wie die Simulationen zeigen, führt keine dieser Erhöhungen zu einem nennenswerten Anstieg der Kontaminationsfracht im oberflächennahen Aquifer.

In einigen Szenarien ergibt sich eine Umverteilung der Stofffracht zwischen beiden Seiten der Störungszone, über Entfernungen in der Größenordnung der Reservoirlänge. Dies wäre bei einem etwaigen 'Vorratsdaten-' bzw. 'Verdachtsmonitoring' der Fluidinhaltsstoffe im oberflächennahen Aquifer zu berücksichtigen; d. h., Fluidmonitoring nur im unmittelbaren Umfeld der Störungszone ist nicht immer schlüssig. Andererseits enthalten solche Endotracersignale, sofern überhaupt detektierbar, wertvolle Auskunft über (geänderte) hydraulische Transmissivitätsverhältnisse zwischen target und non-target Geosystemkompartimenten, sowie ggf. über transportwirksame Hohlraumanteile der Störungszone – von besonderem Interesse dort, wo es sonst keinen theoretischen, prozessbasierten Ansatz gibt zur Korrelierung seismologisch erfassbarer Sliplängen mit hydraulischen und Fluidtransportparameteränderungen entlang/innerhalb einer (zeitweise reaktivierten) Störungszone.

Solche Simulationen dienen zugleich der Abschätzung unvermeidbarer (teils nützlicher, teils unerwünschter) Tracerfrachten von einem markierten (target) Thermalwasserkreislauf zu benachbarten (non-target, bzw. auch ohne direkt erkennbare Kopplung beeinflussten) Fluidzirkulationssystemen, wie sich diese Frage für Design, Dimensionierung und Auswertung multipler Tracertests im geothermisch genutzten Malm des Großraums München aktuell stellt (BMWi-Vorhaben "TRENDS: Tracertechniken zur Evaluierung der Nachhaltigkeit / Lebensdauer einer expansiven Nutzung geothermischer Ressourcen im Malm-Molassebecken", FKZ 0325515), und in diesem Sinne wurde ursprünglich der Begriff 'Endotracer' geprägt.

Die wachsende Nachfrage nach bezahlbaren konservativen und empfindlich nachweisbaren Fluidmarkierungsmitteln für konkrete (teils akute) Angelegenheiten geothermisch genutzter Malmreservoire im Großmünchner Raum bedingt zurzeit ein Umdenken in der Tracerentwickler-Gemeinschaft – und eine gestraffte Priorisierung unter der Vielzahl alter Phantomschmerzen und ungemachter Hausaufgaben. Für die im Rahmen des BMWi-Vorhabens "TRENDS" geplante Anwendung an der dreifach-Dublette des Heizkraftwerks Süd mit gekoppelter DAS- und DTS-Auswertung liegt bereits ein praktikables Fluidmarkierungsschema vor. Die ursprüngliche Tracertestplanung für die geothermische Triplette (Doppelmarkierung) bei Sauerlach sollte hingegen vorübergehend zurückgestellt werden, und erst nach Geosystemerweiterung (durch vierte Bohrung), mit entsprechend angepassten Tracerstoffmengen vorgenommen werden.

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