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(Endo-)Tracer-Aided Visibility of 'Nearby' Fault Reactivation: Scoping Simulations, II

Julia Ghergut, Diego A. Bedoya González, Jacob Bensabat, Chris I. McDermott,
Bianca Wagner, Bettina Wiegand, Martin Sauter

University of Göttingen, Applied Geoscience Dept., Goldschmidtstr. 3, 37077 Göttingen, Germany

iulia.ghergut@geo.uni-goettingen.de

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ABSTRACT

The effect of permeability windows (PW) within a large-scale fault on the advective-dispersive, matrix-diffusive transport of a generic non-reactive solute (conservative endo-tracer) from a neighboring, stimulated deep reservoir towards a shallow aquifer is explored by numerically simulating a set of worst-case hydrogeological scenarios. A generic conceptual model comprising reservoir, basement, cap rock, aquifer layers, adjacent to or intersected by a sub-vertical normal fault underlies all scenarios. 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. Somewhat counter-intuitively, PW augmenting is not found to increase the overall solute freight to the aquifer, but, in some cases, solute plumes are found to redistribute from the reservoir-adjacent to the opposite side of the fault zone. Bearings on aquifer monitoring system design, and on some current research projects in the 'georeservoirs' realm are briefly discussed. 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 (endo-)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). 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 ('ultra-conservative' scenarios, in the sense of Sauter and Lange 2012). Thus it's more about 'seeing' the fault zones, than about 'seeing' the tracers. Furthermore, at 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 and Horstberg sites in Germany, and certain spots beneath the Molasse basin), tracers are expected to convey the fluid transport properties that could not be told from geophysical and hydraulic signals. On the other hand, we coined the term 'endo-tracers' – always in conjunction with a georeservoir-typical hydraulic operation sequence on a (more or less well-characterized, maybe still largely unexplored) georeservoir – in order to flexibly denote 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 (e. g., massive fluid injection for the purpose of georeservoir stimulation, followed by injection and/or production of a possibly different kind of fluid). – I. e., 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. Thus 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 – would have required considerable hydraulic deviations, at odds with the georeservoir's economic use.

1. ENDO-TRACERS INTO LARGE-SCALE FAULT ZONES: SHALL WE SEE THEM? (PURPOSE OF THIS STUDY)

Hydraulic fracturing (HF) has been practiced for many decades – in various, more or less similar forms, depending on georeservoir play type. Concerns about environmental hazards associated with what is nowadays deemed 'unconventional' reservoir development technologies (i. e., HF in its various technical formulations) only became acute over the past decade, with an almost exclusive focus on shale-gas reservoir development – from where the same concerns are sometimes simply replicated to the 'enhanced geothermal systems' (EGS) realm, implicitly assuming a kind of natural equivalence between 'enhanced' or 'stimulated', and 'unconventional'. Most concerns (Myers 2012; Warner et al. 2012; Vengosh et al. 2014; Reagan et al. 2015; Sherwood et al. 2016) revolve around the prospect of shallow aquifers suffering from contamination by HF fluid (HFF) constituents, and/or by reservoir gas, or brine, possibly enriched in some undesired minerals etc., mobilized (Schwartz 2015) from the reservoir matrix along with its permeability stimulation. This (more or less theoretical) prospect may further be aggravated by assuming HF-related processes – putatively, fault reactivation by virtue of pore pressure increase – can induce new, or augment pre-existing migration pathways, e. g., permeability 'windows' (PW) between the stimulated reservoir and a shallow aquifer. Interestingly, concerns about enhanced fluid and solute migration following fault reactivation (cf. ExxonMobil 2012) appear to be disproportionately strong in Germany, compared to world regions naturally more prone to such hazards – likely nourished by vivid memory (Zoback and Gorelick 2012; Scheer et al. 2017; Kissinger et al. 2017) of controversies on CCS in the years preceding the 'fracking' debate, and/or of the Preese Hall (Bowland shale) 2011 'incident' (Clarke et al. 2014).

A wealth of evidence and knowledge about the hydrogeology and hydrotectonics of sedimentary basins renders it reasonable to assume that the very mechanisms that bestowed us with drinking water resources in the (shallow) subsurface will continue to keep them protected, reliably enough, against 'threats from below', whether natural or anthropogenic – including the above-cited hazards associated with 'unconventional' reservoir development; or, as Flewelling and Sharma (2014) put it, "*upward head gradients and high bedrock permeabilities* [*are*] *mutually-exclusive*". Even without explicitly sharing (like Kümpel 2016) this credo to start with, numerous modeling exercises (e. g., Kissinger et al. 2013; Lange et al. 2013; Sauter et al. 2013; Pfunt et al. 2016; Taherdangkoo et al. 2017) finally re-attain it as a conclusion from numerically simulating the vertical reach distance of HFF- or reservoir-derived contaminants across the caprock matrix and/or along fractures and fault zones, under various hydrogeomechanical scenario assumptions ranging from moderately-optimistic to worst-case.

Nonetheless, a case can be made for the opposite party as well: "*Creation of new springs following earthquakes has been observed for millennia*" (Fischer et al. 2017); "*rising fluid pressure induces fault slip, creating a temporary fracture permeability which allows partial draining of the reservoir*" (Sibson 1981); "*the intrinsic roughness of natural fault surfaces* [*implies*] *that freshly ruptured faults should become highly permeable* [...] *channel-ways post-failure*" (Sibson 1994). Long before HF-related hazards became a matter of concern, Sibson (1981) described a naturally-occurring behavior he first deemed "*cyclic hydro-fracturing* [*along*] *an intermittently slipping fault*" – what later became his 'fault-valve' model, a simplistic, yet powerful concept enabling to explain a variety of observations on natural phenomena, e. g., associated with earthquake swarms (Fischer et al. 2014). Specialized (site-specific) 'natural evidence' of this kind nourishes a diffuse, but strong 'public feeling' (ExxonMobil 2012) that generic-evidence arguments like those of Flewelling and Sharma (2014) are 'not reassuring enough'. Fischer et al. (2017) remarkably manage to match long-term records of intermittently degassing mantle CO_2 in West Bohemia by a generic model of utmost simplicity (rectangular fault valve, with hydraulic diffusivity as its sole fitting parameter). By contrast, in the artificial HF realm, for hazard assessment purposes, a non-negotiable need for detailed site-specific models has been recognized, even by the most prominent generic-model advocates.

On the other hand, fault zones are known to be complex structures, of intricate architecture (Reyer et al. 2010; Bense et al. 2013: fig. 5), mid-scale sharp contrasts (Tsang and Doughty 2003: fig. 1), strong anisotropy in permeability (Bense et al. 2013: fig. 9; Shapiro 2015: fig. 3.2 and 3.3), and somewhat elusive hydraulic/hydrogeomechanical 'memory' (Shapiro 2015: fig. 5.10). For any fault-zone model one may think of: it will never be site-specific and detailed 'enough'. Conversely, the more detailed the model (by an ever growing number of compartments and hydrogeophysical parameters), the higher the uncertainty associated with parameter value ranges. Thus, for predicting the behavior of fault-zones especially, finding the appropriate balance between 'site-specific' and 'generic' remains a non-trivial endeavor.

By the present scoping simulations, we look into the effects of PW within a large-scale sub-vertical fault (PW being possibly or putatively associated with fault reactivation, if not already pre-existing within the fault's damage zones) on the advective-dispersive and matrix-diffusive transport of a generic non-reactive solute (conservative endo-tracer) from a neighboring stimulated deep reservoir towards a shallow aquifer. We vary the size and location of PW within the fault in line with observations and/or arguments (Edlmann et al. 2018; Shapiro 2015; Tatomir et al. 2016; Wiener et al. 2016) that fault slip may also occur below and above the reservoir depth. Our simulation results should not be mistaken for a prediction (prognosis) of shallow aquifer contamination induced by HF operations. Rather, we are more interested to see whether (endo-)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, 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). This 'hidden agenda' has let us select and combine hydrostratigraphy and fault-zone 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, cf. section 2.2). Thus it's more about 'seeing' the fault zones, than about 'seeing' the tracers. Furthermore, at research sites (cf. examples in the last section) where fault systems are not the 'undesired, hazardous' feature, but the very target of a forced-gradient fluid-turnover based exploration, tracers are expected to convey the fluid transport properties that cannot be told from geophysical and hydraulic signals.

2. MATERIAL AND METHOD

The first ingredient hereto is a basic understanding of how artificial tracers perform in subsurface flow applications. Tracer tests in deep-subsurface flow usually yield fluid residence time distributions (RTD) for a sparse selection of fluid spiking and fluid sampling points. Such RTD can be explained (more or less adequately) assuming a fractured-porous void-space structure in which advective-dispersive, matrix-diffusive transport and possibly partitioning/reactions at interfaces take place, along with well-defined boundary conditions (BC) for flow and transport; flux-based BC allow to directly equate RTD with normalized tracer signals. Yet RTD do not by themselves enable to tell 'where' a flow process is taking place. So to say, "to trace is not to track", and 'tracking' would require some complementary kind of mapping, imaging, or monitoring – additionally to the metering of tracer fluxes at the few accessible places (deep boreholes) at which fluids can be sampled. We do not feel the need for such 'tracking' capability, when tracer-based RTD are used to predict the thermal lifetime of, say, a geothermal well doublet. However, the ability to 'locate' flow and transport processes (in both space and time) may become critical when facing environmental impacts of deep-georeservoir operation, and liabilities associated with these.

The term **endo-tracer** was coined within the German project 'TRENDS' (funded by the Federal Ministry for Economic Affairs and Energy). 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 – would 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 and/or production of (a possibly different kind of) fluid; or fluid turnover by forced-gradient circulation within a geothermal-well doublet – which is certainly not the best-suited hydraulic configuration for detecting and characterizing fluid transport in (presumed) 'nearby' fault zones (in some distance away from the actual reservoir).

One major difference from artificial tracers' best practice is that endo-tracer signals are *not* equivalent to the fluid's inlet – outlet *residence time distribution* (cf. Kreft and Zuber 1978), nor are they convertible to such RTD by elementary calculus (differentiation and/or integration). What this implies when interpreting endo-tracer signals from single-well multiple-passage injection-flowback operations during georeservoir development is discussed in the parallel paper by Tintoretto et al. (2019).

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'). Suitable tracer species have been identified (and their ultra-low level, high-sensitivity metering developed to a certain extent) by Warner et al. (2013), Vengosh et al. (2014) for the purpose of pinpointing HFF additives (distinguishing them from similar chemicals of a different source, once an allegedly typical 'spill' has occurred in the reservoir's overburden), or by Wiegand and Sauter (2016) for the broader aims of georeservoir characterization in terms of 'tracking' the fluids' origin, and fluid mixing across reservoir compartments and time scales (geological, historical, recent). As to methane itself as a 'tracer' from (shale-, tight- or conventional) gas reservoir operations, distinguishing between shallow anthropogenic and deep fossil sources is not always trivial, despite their distinct isotopic signatures – especially in the presence of abundant cattle stock at the surface (e. g., Yacovitch et al. for the Groningen field).

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.

2.1 Conceptual Model Hydrogeology

To simulate the signals of a conservative solute (endo-tracer) that entered the reservoir along with 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'), we set up a hydrogeologic ten-unit model (shown as a vertical section in fig. 1), comprising reservoir **R**, basement **B**, cap rock **C**, shallow aquifer (overburden) layers, treated like single continua, adjacent to or intersected by a large-scale sub-vertical fault. The latter is represented as a (initially tight) 'fault core' **F** of finite width, flanked by relatively permeable 'damage' zones **DZ** (able to drain significant fluid fluxes from adjacent layers; yet hydraulically infinitesimally 'thin', compared to their geological width, if treated like planar fractures), one **DZ** facing the reservoir, the other **DZ** opposite to it (l.-h. s. and r.-h. s., respectively, in all sections of fig. 1). In order to account for alleged "fault reactivation" to a certain extent over a certain 'length' (which may well exceed geomechanical 'rupture' sizes as quantified by seismologists – e. g., Wells and Coppersmith 1994), we allow for different parametrization of **F** and **DZ** in up to three variable-depth segments (table 1). Within **F** and/or **DZ**, the location, vertical extent and hydraulic properties of PW (putatively induced by reservoir operations) are to be varied between scenarios (section 2.2). Whatever mechanisms produce such changes to fault-zone hydrogeology, they stay beyond the model's scope. Fluid flow in all model units is approximated like single-phase Darcian, except for **DZ**, where planar fracture-like, cubic-law flow is allowed. The conservative tracer is transported by advection-dispersion, and experiences 'matrix diffusion' by virtue of strong permeability contrasts at inter-layer and layer-fault interfaces.

Model domain sizing is vertically prescribed by stratigraphy; based on data collected within EU projects FracRisk and MEET (cf. section 3.2). A depth range of ~3.5 km is assumed from the overburden to the basement, with reservoir layer thickness ~500 m. Horizontally, besides the ~1 km distance between reservoir injection site and fault, some ~4 km distance are added between the fault and the opposite (r.-h. s. in fig. 1) edge of the model, the rationale being to have this edge remote enough to render the effects of inadequate BC negligible. One cannot over-emphasize it: BC assumptions, often inadequate to some degree, may considerably influence the overall solution to flow and transport equations – and, in particular, the sought 'HFF spill' patterns across the entire model domain. The bearings of impermeable ('repelling') and free-outflow ('attracting') BC at certain domain edges are detailed in section 2.2, as they intermingle with the very scenario definitions. However, an impermeable BC can be assumed, without significant loss of generality, at the vertical edge on the reservoir side (implying symmetry w. r. to this edge, i. e., a second, identical (!) fault zone, frac jobs, injection rate, etc. in the missing l.-h. s. half-domain – which may not be found in real-world reservoirs, but does not impede the pertinence of simulation findings; to spare computational effort, Zbinden et al. (2017) resorted to a similar model-domain 'halving').

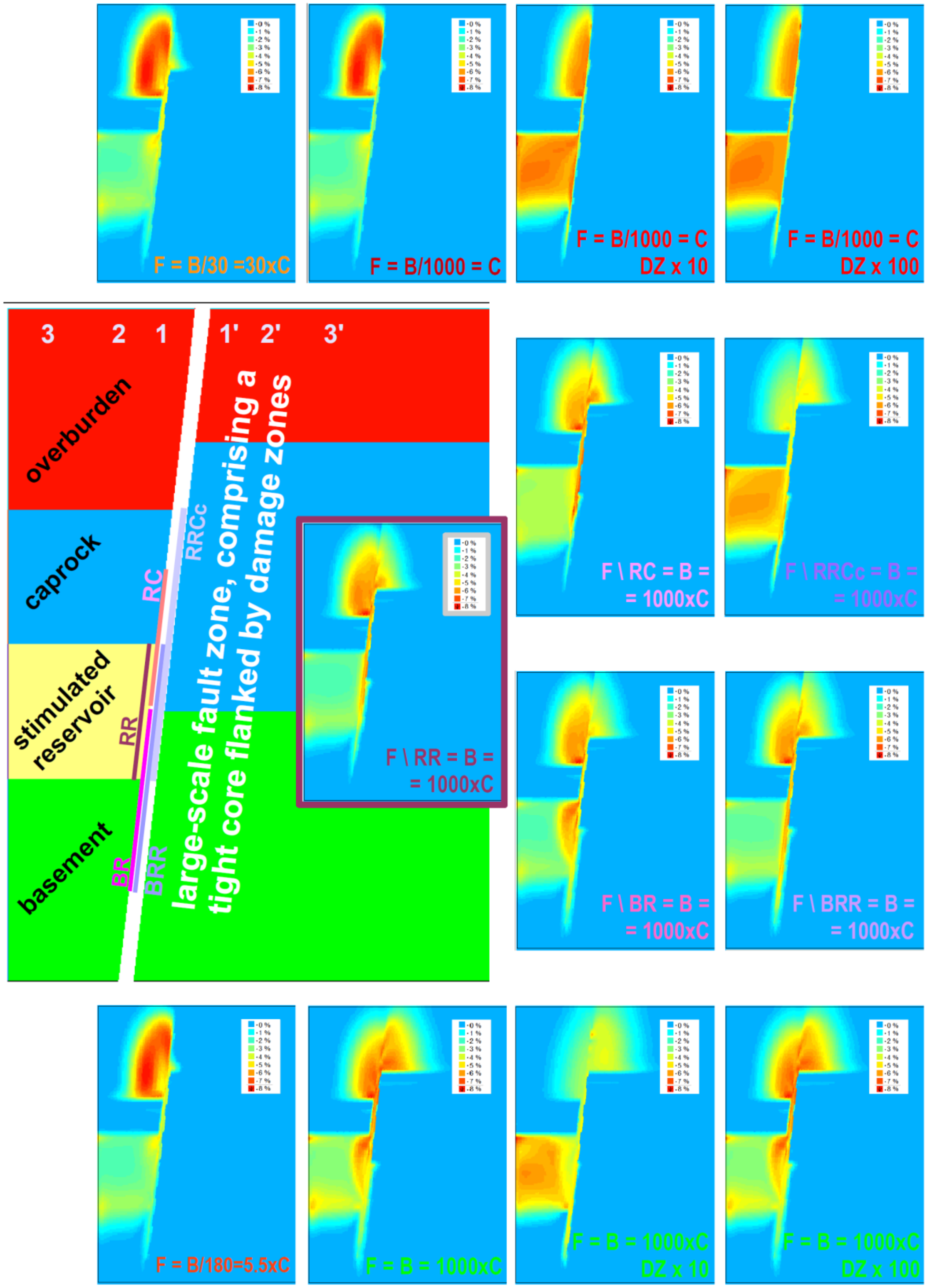

Figure 1: Conceptual model, and illustrative shapes of endo-tracer plumes after 300 days since injection start (with injection stopping after 30 days), for the 12 "rupture" scenarios (plus reference scenario, shown 2nd from left in the upper row).

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	

2.2 'Pathway Enhancement' or PW Scenario Set-Up, and Solute Transport Simulation

Reservoir stimulation operations are of limited duration and localized 'reach' in operative terms, whereas the diffusion of pore pressure, and of associated changes to effective stresses, is less limited in space and time. Fluid flow, driven by pore-pressure gradients (persisting, after injection stop, for shorter or longer, with free-outflow or impermeable BC respectively), and thereby the advective-dispersive transport of conservative endo-tracers, will not stop when stimulation operations cease. In a series of 'pre-scoping' simulations, a scenario duration of ~300 days (which incidentally amounts to ~10× the duration of stimulation operations) was found adequate to identify, demonstrate and sufficiently characterize the sought pattern of solute 'plume' shapes – whose spreading, horizontally and vertically, may continue with similar concentration ranges for further >~1000 days. In hydrogeological terms, PW scenarios were set up as detailed in table 1, ranging between two extremes: in the 'safest', reference scenario, the **F**[ault core] has **C**[aprock]-similar sealing properties over its entire depth extent, and both **D**[amage]**Z**[ones] have modest drainage ability; in the 'most dangerous' scenario, **F** looses sealing ability over its entire depth range, becoming similar to the **B**[asement] rock, and **DZ** drainage ability is augmented considerably (e. g., aperture increase by 100× translates into × 1 million for transmissivity, by virtue of the 'cubic law'). With 'PW' standing for various ways of change to fault-zone hydrogeology, the 13 scenarios can be grouped into four PW classes:

– entire **F** is kept similar to **C** (strong sealing), but **DZ** drainage ability is augmented considerably, with aperture increasing from 1 mm (reference scenario) to 1 cm, then 10 cm (darker-red-tone labeling in tab. 1 and figs.)

– entire **F** becomes intermediate between **C** (strong sealing) and **B** (no sealing), whereas **DZ** drainage ability is kept similar to the reference scenario (lighter red/orange-tone coding in tab. 1 and figs.)

– only over a certain depth interval (as indicated by layer-related letters \R, \B, \C), **F** looses its sealing ability (becoming similar to **B**), and **DZ** drainage ability is extremely augmented (violet-tone coding in tab. 1 and figs.)

– entire **F** becomes similar to **B** (no sealing any more), and **DZ** drainage ability is augmented considerably (green-tone coding in tab. 1 and figs.)

Obviously, all scenarios are 'ultra-conservative' (compared to Sauter et al. 2013, Lange et al. 2013), with an exaggerated 'worst-case' propensity in terms of:

– injection operations sizing: 500 m³ per day for 30 days uninterruptedly, representing a quasi-continuous series of 30 'frac jobs' in successive wellbore intervals, analogous to the 8-frac sequence mentioned in Ghergut et al. (2016[a], fig. 2), but with all 30 HFF slugs concentrated at one point at the reservoir's farthest reach, i. e., closest to the fault;

– injection pressures, as resulting when the aforementioned injection rates are applied to each scenario's permeability and compressibility distribution (cf. tab. 1), with tight BC at aquifer top and at basement bottom: up to 600 bar;

– pressure gradient vector directions: from reservoir towards aquifer, and towards the fault's opposite side for the entire scenario duration, in line with the assumed free-outflow BC at the remote domain edge opposite to the reservoir; this edge thereby acts like a 'drainage', pulling the HFF to 'spill across' the fault;

– "rupture" timing, duration, and permanent aperture: "rupture" occurs immediately after injection onset, and maintains its maximum aperture over the entire duration of each transport scenario, discarding any thermal effects like rock melting during the true rupture process soon followed by re-healing, etc.;

– "rupture" length and area: significantly larger than would be expected by generic effective-stress change estimations based on the simulated pore-pressure increase jointly with realistic assumptions on failure mechanisms; solely poroelastic simulations (Müller et al. 2018) tend to dramatically over-estimate the amplitude, duration and areal extent of significant stress changes;

– fault-core unsealing, damage-zone drainage augmenting, stimulated-reservoir permeability and size: assuming the reservoir were successfully stimulated over its entire volume, reaching – and maintaining over the entire scenario duration – a permeability of (sic) 50 Darcy (which is 10× higher than in the overburden aquifer).

All 12 besides the first (tightest and thus allegedly 'safest', reference scenario) may be deemed "rupture" scenarios just for brevity, but without implying any correlation, let alone equivalence between the sizing of hydrogeologic parameter changes (in terms of areal extent, duration, amplitude) and geomechanical 'rupture' sizes described by seismologists either empirically (Wells and Coppersmith 1994) or derived from stress-drop models (for simplified rupture geometries) and from considerations on event un-/boundedness (Stein and Wysession 2003, Zoback and Gorelick 2012; Gomberg 2016).

Single-phase incompressible-fluid flow and conservative endo-tracer transport were simulated using FEFLOW 5.4, a finite-element simulator of flow(, heat) and solute transport in 3D porous media (with the option of embedding finite sets of individually-defined fractures as lower-dimensional elements into the mono-porous continua), developed by Diersch (2014) and co-workers. Besides their efficient treatment of 'matrix diffusion' processes (Kolditz 1997; Carrera et al. 1998), i. e., transversal diffusive exchange of heat or solute at permeability-contrast interfaces, in particular between a lowly-permeable, porous continuum and some lower-dimensional, usually highly-conductive 'fracture elements', the latter further prove expedient when dealing with strong hydraulic contrasts, in particular for efficiently representing enhanced drainage along **DZ** (a process more important, in this work's context, than matrix diffusion). Furthermore, thanks to the lower-dimensional 'discrete feature elements' implementation in FEFLOW, we can more efficiently account for **DZ** anisotropy of permeability (vertical >> horizontal, unlike in the surrounding rock matrix where vertical << horizontal permeability), and the varying **DZ** thickness without the need for changes to surrounding rock blocks geometry and discretization from scenario to scenario. Hydrogeologic model setup in section 2.1 was conceptually a 2-D one, but we implement it numerically as a 3-D model, in order to exploit some FEFLOW-specific parametrization and computational advantages of 'planar fracture elements' representing **DZ**. The model domain was discretized by 10^5–10^6 hexahedral (rectangular prism) elements of variable size (higher mesh density around hydrogeological discontinuities and the injection well screen); adaptive time-stepping schemes were used (Δt from minutes to ~0.3 d).

3. RESULT AND DISCUSSION

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 endo-tracer concentration in this same (100 m) depth, after 300 days since injection start.

All solute concentrations shown were normalized by 1 % of M_{inj} / (1000 m³), with M_{inj} denoting the total mass of the particular solute considered ('the endo-tracer') that was introduced into the reservoir during stimulation operations (with a solute input rate of (M_{inj} / 30) / day, constantly over 30 days). This normalizing choice yields signals in the range of unity (≤≈10) by the end of the formal scenario duration. Breakthrough signals' first-order time derivative discontinuity (recognizable by bare eye only on the reservoir side, only for 'tighter' scenarios) reflects the cease of fluid injection after 30 days. Peak times range between one and two months on the reservoir side (thus horizontal profiles shown after 300 days on this side already represent 'tailings'), whereas on the opposite side a solute concentration peak is reached before 300 days only for the 'unsealing' (green-/violet-tone coding), but is far from being reached for the 'still sealing' scenario classes (red-tone coding).

It is easily recognized that the free-outflow BC at the reservoir-opposite domain edge, alongside with the impermeable BC at aquifer top, somewhat alleviates the 'spill' threat for the aquifer directly above the reservoir at the cost of aggravating it for the fault-zone's opposite side, whereas total solute freight remains similar to a case with switched BCs. Impermeable BC at all domain edges would have strongly 'repelled' the solute plume (forcing it to remain 'more confined' within the reservoir → scenario would no longer reflect the 'worst case', it would not be 'conservative' enough in the sense evoked in section 2), while on the other hand raising the injection-induced pressure build-up to several thousands of bars (→ scenario would become 'unreasonable', ibid.; and the same can be said of a scenario with free-outflow BC at all domain edges). Interestingly, the 'safest' (i. e., hydraulically tightest), reference scenario yields the highest solute fluxes to the aquifer (overburden); in all other, 'less safe' (hydraulically more permittive) scenarios, fluxes to the aquifer (overburden) stay below those predicted for the 'safest' scenario. Counter-intuitive at first glance, this is easily explained by the competing effects of PW augmenting:

– the larger the PW aperture, the higher its hydraulic transmissivity, thus the higher the amount of fluid flow (and, potentially, solute freight) that will be redirected to the PW from competing-transmissivity compartments;

– the larger the aperture, or cross section area, or volume, and/or effective porosity of that PW, the more retarded and diluted the solute transport through it; to a certain extent, this latter mechanism ('retardation') alleviates the effects of the former ('drainage').

3.1 Some Bearings on Fluid Monitoring System Design in the Overburden

In generic terms, endo-tracer plumes were seen (fig. 1) to be, not much surprisingly,

(i) redistributed by hydrogeologic discontinuities (these being of three different types: inter-layer discontinuities, as prescribed by stratigraphy; intra-fault discontinuities; discontinuities between fault-zone and adjacent rock matrix),

(ii) repelled / attracted by impermeable / drainage BC, respectively, and

(iii) roughly accelerated / retarded by permeability / porosity or aperture increase, respectively.

In quantitative terms, endo-tracer signals in the overburden may reach values as high as 10% M_{inj} / (1000 m³), 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 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' (cf. Kreft and Zuber 1978) concentrations.

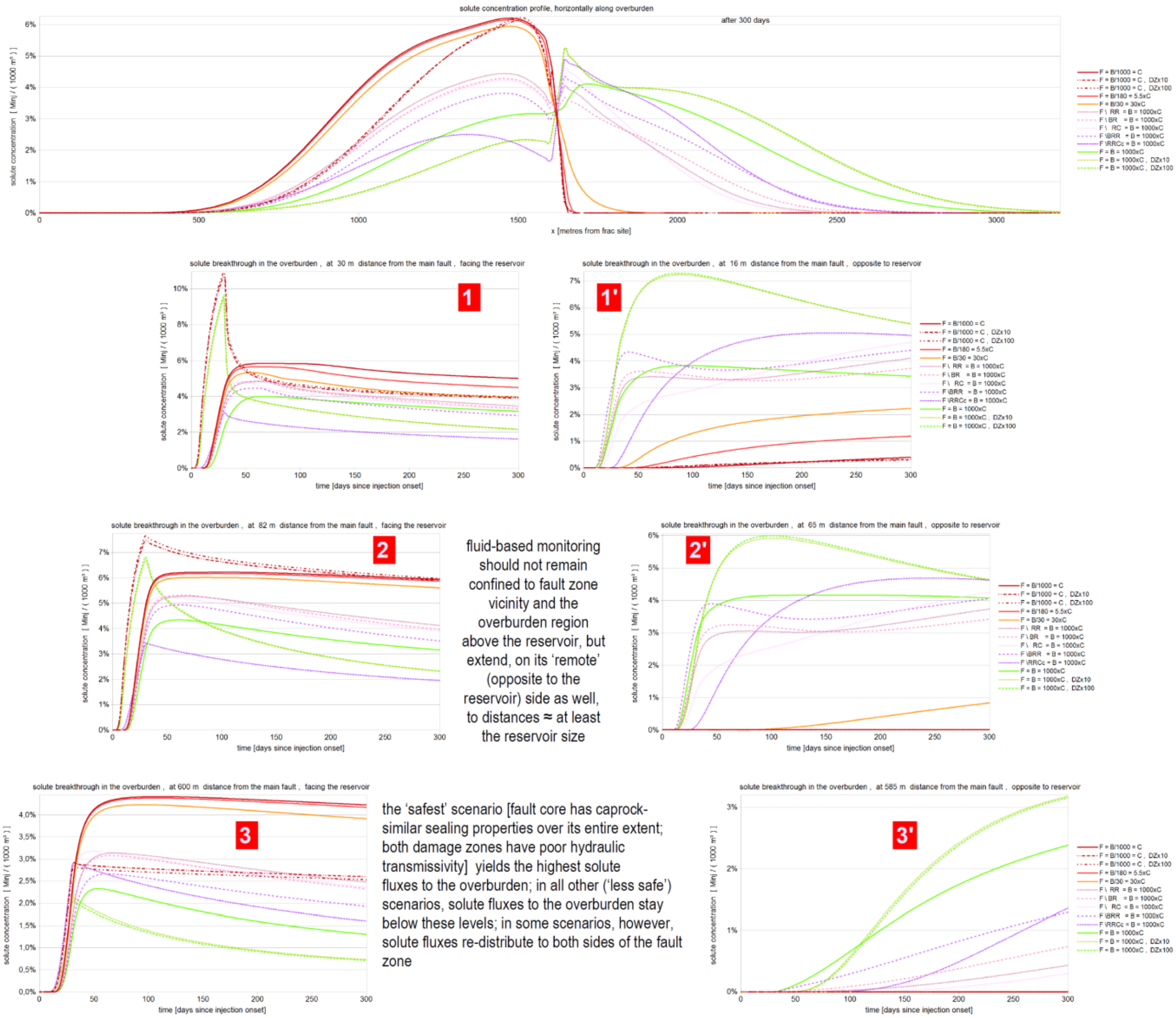

Figure 2: Endo-tracer concentration profiles, horizontally in 100 m aquifer depth, after 300 days since injection start (with injection stopping after 30 days), and endo-tracer breakthrough signals at six different locations in this same aquifer depth (cf. numbering shown in fig. 1), for the 12 "rupture"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

3.2 Bearings Within Some Projects in the Georeservoirs and 'Geo-Energy' Realm

The EU H2020 project **FracRisk** (grant no. 636811) set out to provide decision support tools for dealing with certain hazards associated with unconventional georeservoir development (www.fracrisk.eu). Unlike in the realm of nuclear waste management where F[eature] | E[vent] | P[rocess] databases have originally been initiated under the rationale of growing encyclopedically ("not to miss one detail") and getting ever more comprehensive, FracRisk's philosophy is to (i) rely on 'expert knowledge' for top-down approaches to FEP screening in order to reduce the risk assessment job to a small set of relevant scenarios, and (ii) use efficient, FEP-overriding, simplified S[ource] | P[athway] | R[eceptor] compartmenting to set up predictive models, quantify the relevant hazards, and (where applicable) design and specify mitigation measures. (Endo-)Tracers (artificial and/or natural, cf. section 2) can in turn serve as a decision support tool in early stages of reservoir development, and as a monitoring and/or early-warning tool during reservoir operation (Ghergut et al. 2016[ab], 2017[ab]). They may fulfill several purposes towards assessing environmental hazards, especially regarding un/-desired transport connectivity between S and R, or within S and P. Scoping simulations presented here are meant to perform somewhat differently: relating hypothetical endo-tracer signals and/or 'spill' patterns detectable in the overburden to putative changes in fault-zone hydrogeology (possibly induced by nearby reservoir stimulation), irrespective of whether the latter can pertinently or not be deemed as "fault reactivation". The underlying hydrogeological model compartmenting (sec. 2.1, tab. 1) adheres closely to FracRisk's S | P | R scheme (Edlmann et al. 2018). Further, assuming at least one HFF solute constituent behaves conservatively during transport through any S, P, R compartment, this constituent can serve as a 'tracer' in a twofold sense, i. e., pinpointing the 'spill' source (if a 'spill' event occurs), and early warning w. r. to further, possibly retarded HFF constituents.

The EU H2020 project **MEET** (grant no. 792037) provides new geostratigraphy and fault-zone hydrogeology information to feed into scenario definition for 'large-scale EGS' development (Trullenque et al. 2018; Leiss et al., Wagner et al. 2018: oral communications), with stimulated-reservoir sizes in the range of several km (as had previously been considered only for hydrothermal systems).

Tracer-methodical issues with 'large' systems (ensuing from 'very long' fluid residence times) were originally raised and analyzed within projects **LOGRO** and **TRENDS**, funded by German Fed. Min. for Econ. Affairs and Energy (BMWi, FKZ: 0325111, 0325515), in whose context also conservative-tracer transport was simulated for reservoirs of mixed hydrothermal and EGS kind, containing large-scale fault-zones that had been predicated to significantly influence (desirably: increase) the reservoir's thermal lifetime, as well as (possibly: impede) tracer breakthrough detectability at production wells – a posit sometimes confirmed (cf. Behrens and Ghergut 2014; Ghergut et al. 2015; Dewi et al. 2016), and sometimes not (Ghergut et al. 2017[b]; Mohandas Surekha et al. 2018) by predictive simulations. A particular reason for dealing with endo-tracers within **TRENDS** ("*Tracer-assisted evaluation of reservoir behavior under expansive deployment schemes for Malm geothermal resources in the Munich area*") was the event of 'some' tracer from a forced-gradient circulation system (f.-g. c. s.) 'showing up' (i. e., becoming instrumentally-detectable) in a different, more or less 'distant' f.-g. c. s. within few years time, though all these f.-g. c. s. (usually, injection/production well doublets or triplets) had originally been positioned and dimensioned such as to stay 'non-interferent', in terms of fluid transport, for at least three decades.

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 disodium fluorescein (uranine) 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). 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 upon fluid extraction at the KTB-HB, even after 13 years of shut-in. At such research sites (like the KTB spot, targeting the crystalline basement; or the Horstberg site in the N-German sedimentary basin – cf. Ghergut et al. 2013, 2016[b]; or certain spots beneath the Molasse basin) where large-scale faults and fractures are not the 'undesired, hazardous' feature, but the very target of a forced-gradient fluid-turnover based 'interrogation' (fluid extraction by long-term pumping, massive (re-)injection and partial withdrawal), (endo-)tracers are expected to convey those fluid transport properties that could not be told from geophysical and hydraulic signals.

Author contributions: Wiegand experimentally examined and validated that HF-related tracer species with the properties theoretically required in section 2 do exist, and can perform as desired in real-world applications. Wagner, Sauter and Wiegand provided representative geo-stratigraphy and fault-zone data. McDermott, Bensabat and Sauter performed an FEP appraisal underlying the scenario formulation in section 2.2. Ghergut and Sauter formulated the model, and the "rupture" scenarios. Ghergut and Bedoya González conducted numerical simulations, and processed simulation results. Ghergut wrote the manuscript.

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E. EPILOGUE: ENDO-TRACER AIDED EVALUATION OF STIMULATION OUTCOME FOR EGS PURPOSES

E.1 Is This a Dagger Which I See Before Me?

Emergent-EGS hunters (let's call them *Macbeth*) feel torn apart between their well-founded expectations (*The handle toward my hand / Come, let me clutch thee*) from microseismic imaging of HF and/or from reservoir-scale induced-seismicity monitoring (cf. Maxwell 2011, Jung 2013, Virues et al. 2016; Martínez-Garzón 2014, Shapiro 2015) and/or from the short- to mid-term monitoring of natural (micro-)seismicity (Malin et al. 2015; Leary et al. 2014, 2015, 2018, 2019), complemented by temperature data where available (Leary et al. 2017), and the deception of such expectations (*I have thee not, and yet I see thee still. / Art thou not, fatal vision, sensible / To feeling as to sight?*) well in line with Fu and Schoenball's remark (2019) that "*occurrences of microseismic events are neither sufficient nor necessary conditions for the presence of a hydraulic fracture at the mapped locations*".

Let us briefly recall what deep geothermal reservoirs are commonly (1°–4°), or less commonly (5°) typified by:

1° temperature and/or depth values: apart from active-magmatism areas, the deeper (and thus hotter) it gets, the more likely some kind of 'fracking' will be warranted; but from temperature and depth values alone, nothing can be inferred as to the most recommendable reservoir development technique for any particular site – cf. figures on p. 7 in Legarth (2003) meant to evaluate the geothermal reservoir 'odds' for the Groß Schönebeck site in the N-German sedimentary basin, or fig. 1 in Ghergut et al. (2013[a]), ibid. for the Horstberg site;

2° whether a geologically-based 'heat exchanger' of suitable geometry and sufficient size naturally preexists, or needs to be enhanced, or created 'from scratch' – yielding the most common definition of 'hydro-' vs. 'petrothermal', while obfuscating the more elusive features of spatial variability within the target formation, which, according to Leary et al. (2014, 2015, 2017, 2018, 2019), Malin et al. (2015), Pogacnik et al. (2015) is the actual crux of the whole matter;

3° the ratio between advective (hyperbolic) and non-advective (parabolic) terms in the heat transport equation, whereby categorizing becomes time-dependent, with 'petro-' / 'hydrothermal' contributions ratio unfortunately *decreasing* with increasing fluid turnover (i. e., with operation time) for a multi-frac HDR-like EGS (cf. examples in Ghergut et al. 2013[b]);

4° the ratio between transversal-conductive (matrix-diffusive, $\sim FAT^2$) and longitudinal-advective ($\sim FAT$) contributions to the reservoir's total thermal service life *TSL*), which yields an integral measure, no longer reflecting the time-dependent behavior – with *FAT* denoting the fluid *advection* time in the reservoir, between fluid inlet and fluid outlet, meterable by inter-well tracer tests, always shorter than the fluid's mean residence time *MRT*, and considerably shorter than *TSL* unless something went completely wrong with reservoir design (cf. discussion in Ghergut et al. 2016);

5° pragmatic 'collect & select' approaches (Sauter 2009 pers. comm., Moeck 2010 pers. comm., Philipp 2010 pers. comm., Hördt et al. 2011) as to what tectono-structures and litho-stratigraphies may be found 'out there', yielding

– at (over-)regional scale: the '*geothermal plays*' of Moeck and Beardsmore (2014)

– at generic (sub-)regional scale: the '*benchmark models*' of Philipp et al. (2010, unpublished manuscript), Hördt et al. (2011)

– at refined sub-regional scale: the so-called '*deep-geothermal reference models*' of Philipp et al. (2017)

To what extent can such distinctions be drawn (i) before drilling a first deep well, (ii) before conducting / attempting stimulation at this well, (iii) before drilling (and stimulating) a second well, … and so forth?

Owing to a wealth of hydrocarbon reservoir exploration and operation data, (5°) would have been feasible even without relying on dedicated-geothermal sites. Else, from all EGS experience gathered so far, it is easily recognized that (2°) – (4°) can only be told '*post festum*'. And, at quite a few EGS candidate sites – like Horstberg, Groß Buchholz, and Groß Schönebeck in the N-German sedimentary basin, KTB, Urach Spa, Soultz-sous-Forêts, Rosemanowes in Europe's crystalline basement, as well as some Malm formations beneath the Molasse basin –, hydraulic alongside with tracer data indicate a time-dependent, and spatially heterogeneous superposition of 'petrothermal' and 'aquifer'-like contributions – which, though lacking tracer data as yet, is likely true for St. Gallen in Switzerland and for Espoo in Finland, as well (cf., e. g., Blöcher et al. 2016 for the Groß Schönebeck site; Kolditz 1997 for the Rosemanowes site; McDermott et al. 2006 for the Urach Spa and KTB sites, with Ghergut et al. 2007 for a tracer-assisted assessment; Jung et al. 2005, Tischner et al. 2010, Wessling et al. 2009 for the Horstberg and Groß Buchholz sites, with Ghergut et al. 2013, 2016 for a tracer-based evaluation; Alber and Backers 2015 for the St. Gallen site; Vouillamoz 2015, Meier et al. 2015, Vouillamoz et al. 2016 for a seismo-tectonic analysis assisting georeservoir prospection and development at selected 'EGS candidate' spots in the Southern Molasse basin; Martínez-Garzón 2014 for a seismo-mechanical analysis and post-festum tableau of hydrocarbon and geothermal reservoir 'response paradigms'; Leary et al. 2017, 2018, 2019 for EGS development in Finland).

Also, quite a few drillings in Malm – presumed as 'aquifer' – formations beneath the S-German Molasse basin were typified as unsuccessful (German: *unfündig*) and therefore abandoned, though 'petrothermal' (Moeck et al., 2015, 2016, 2017, 2018, personal communications, invited talks and reports) might fit much better – which, however, would have required a different well-path orientation and wellbore completion, different legal steps and public-participatory decision-making, and so forth.

On the other hand, technical rationality imposes a rather inflexible design for HDR multi-frac EGS: first drill to the final bottom-of-well, then perform a 'backward' sequence of stimulation stages; else, disproportionately high costs would incur for packer-penetrator devices, alongside with significantly increased risk of technological failure.

To what extent can (endo-)tracers contribute to an expedient characterization of an EGS candidate, and to predicting its thermal service life (*TSL*) ? As to the three EGS 'mainstream' concepts that are more or less(!) established so far,

– the 'longitudinal', (elongated-)volume-based aquifer-like EGS, or 'Camborne' concept,

– the 'transversal', area-based multi-frac HDR-type EGS, or 'Los Alamos' concept, with surface area and geometrical complexity augmented by 'wing cracks' (Jung 2013, Jeffrey and Jung 2015), and with frac-induced local $\Delta\sigma$ to be compensated by adjusting well-path orientation angles (say, approximately 45° to σ_{min} as indicated by Zeeb and Konietzky 2015),

– the ideas of Leary, Malin, Pogacnik et al., which we very roughly summarize here as the 'augmented-radius effective well' concept,

table E and figures E1, E2 summarize their different challenges with regard to fluid transport quantification, and their associated (endo-)tracer test agenda.

Table E : Overview of thermal service life (*TSL*) controls associated with three major approaches to EGS development

<table>
<tr><td>EGS 'breed'

some details</td><td>create
a small (wing-)'cracken' sequence</td><td>find
natural mid-size 'kraken',
and enhance it artificially</td><td>release
a big 'kraken'</td></tr>
<tr><td>prominent advocates</td><td>Jung et al. 2005, Häring et al. 2008, Jung 2013, Jeffrey and Jung 2015, Meier et al. 2015</td><td>Leary, Malin et al. 2011ff.</td><td>Glenn Melosh 2019 (from whom 'kraken' is borrowed as a generic-purpose abbreviation)</td></tr>
<tr><td>attempted / endeavored EGS 'breed'</td><td>HDR-like EGS</td><td>'aquifer'-like EGS</td><td>crustal process-like rather than structure-borne EGS</td></tr>
<tr><td>major control on thermal service life (TSL)</td><td>transverse exchange surface area
(surface $\parallel$ flow)</td><td>flow cross section area
(surface ├ flow)</td><td>aperture
(while infinitely-acting area)</td></tr>
<tr><td>relationship between TSL, fluid advection time (FAT), mean residence time (MRT)</td><td>TSL roughly proportional to FAT squared;

$FAT \ll MRT \ll TSL$

(hours to days | few months | years)</td><td>TSL proportional to FAT

$FAT < MRT < TSL$

(months | years | decades)</td><td>TSL roughly proport. to FAT

$FAT < MRT < TSL$

(years | decades | centuries)

(for mixed-type systems: superposition of FAT and FAT^2 contributions with possibly time-dependent weighting, rendering the FAT^2 contribution less important at late times)</td></tr>
<tr><td>effective signal availability from (artificial) tracer tests</td><td>early, but not very useful because of disparity in aperture sensitivity (TSL is almost independent of aperture, whereas tracer signals vary strongly with aperture especially when frac area is small);
thermosensitive tracers more useful</td><td>rather late, but of greater relevance than in HDR-like systems;

conservative tracers more useful</td><td>seemingly 'too late' (Ghergut et al. 2015);

endo-tracers can 'accelerate' signal availability;

aperture sensitivity is of advantage</td></tr>
</table>

n. b.: further 'emergent' EGS concepts (Danko et al. 2019, Frash et al. 2018, …) were not considered here

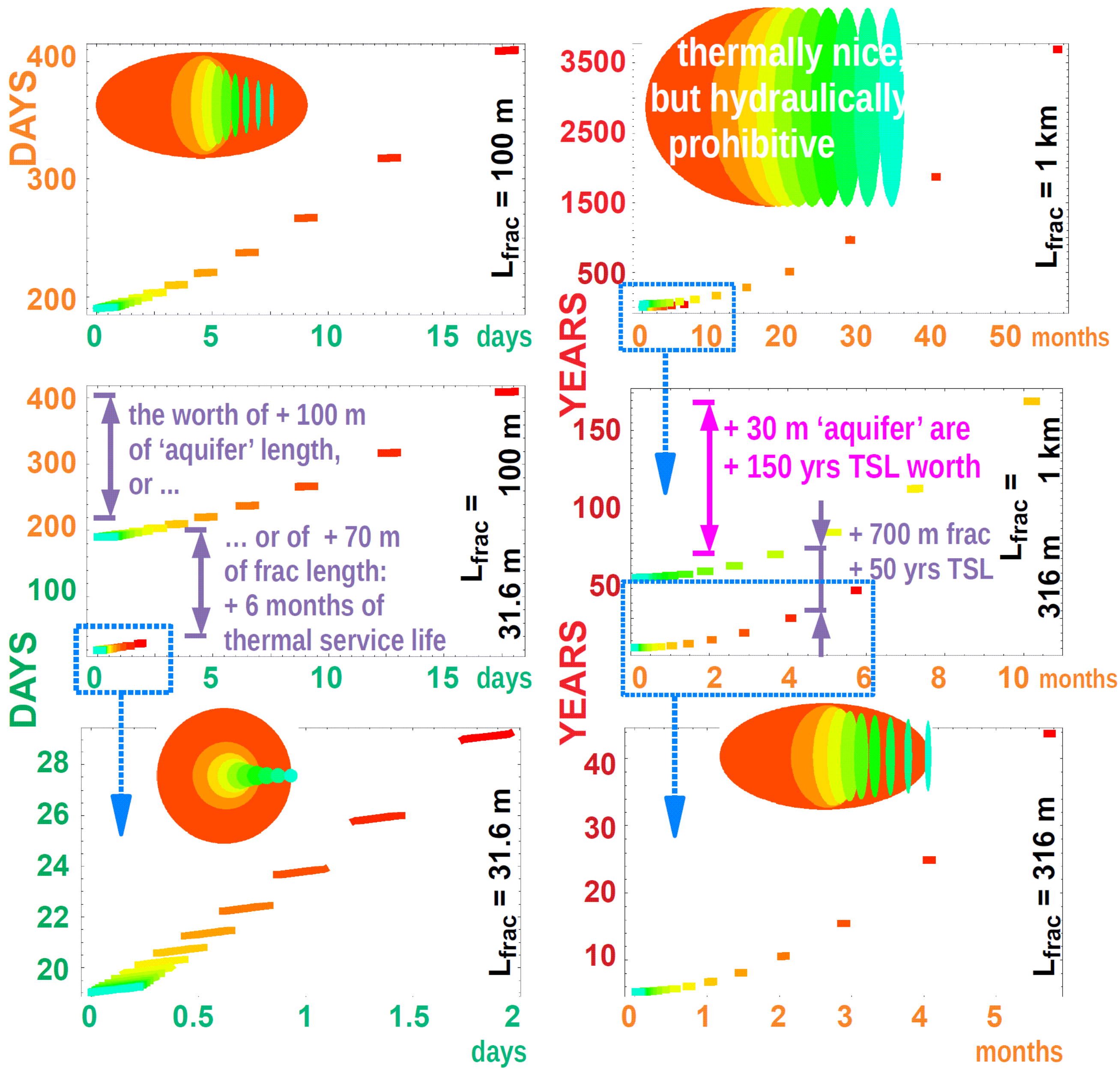

Figure E1: Parametric plots of thermal service life *TSL* (ordinates) against fluid advection time *FAT* (abscissae) for various EGS 'breed' formulations, with frac aperture varying, within each single-color segment, from 0.01 mm to 5 cm, and frac 'gap' (or, say, 'bridging aquifer') length ranging from 1/500 of frac half-length, L_f / 500 (parametric plot segment in light azure) to L_f (parametric plot segment in dark red).

The major issue persisting about what Jung (2013) deems his "*back-to-the-future*" concept concerns the ability to define a second well's trajectory that rules out any risk of thermal short-cut, while maximizing the inter-well effective multi-frac area – facing the complexity of multi-frac geometry incurred by so-called wing cracks (Jung 2013, Jeffrey and Jung 2015) and by sequentially frac-induced stress 'shadow' (Zeeb and Konietzky 2015). Even if this intricate geometry gets accurately mapped by microseismic monitoring, and its hydraulic parameters reliably inverted from pressure signals, its heat exchange area (controlling the reservoir's thermal service life *TSL*) remains unpredictable. As a workaround, one may consider the option of a single-well push-then-pull operation for HDR-based EGS anew (as had originally been endeavored by Jung et al. 2002, 2005, Tischner et al. 2004, 2010 for the so-called 'GeneSys' wells in the N-German sedimentary basin), now in guise of a multi-frac structure operated from opposite ends *in tandem*; this renders multi-frac EGS design more robust w. r. to wing crack geometry 'elusiveness' (cf. figs. 3, 4, 13, 14 in Leary et al. 2019). Else, one may decide to admit a frac 'gap' or 'bridging aquifer' up to a certain length, which may considerably add to *TSL*, as illustrated in fig. E1, while exorbitantly rising the hydraulic costs of the required forced-gradient circulation.

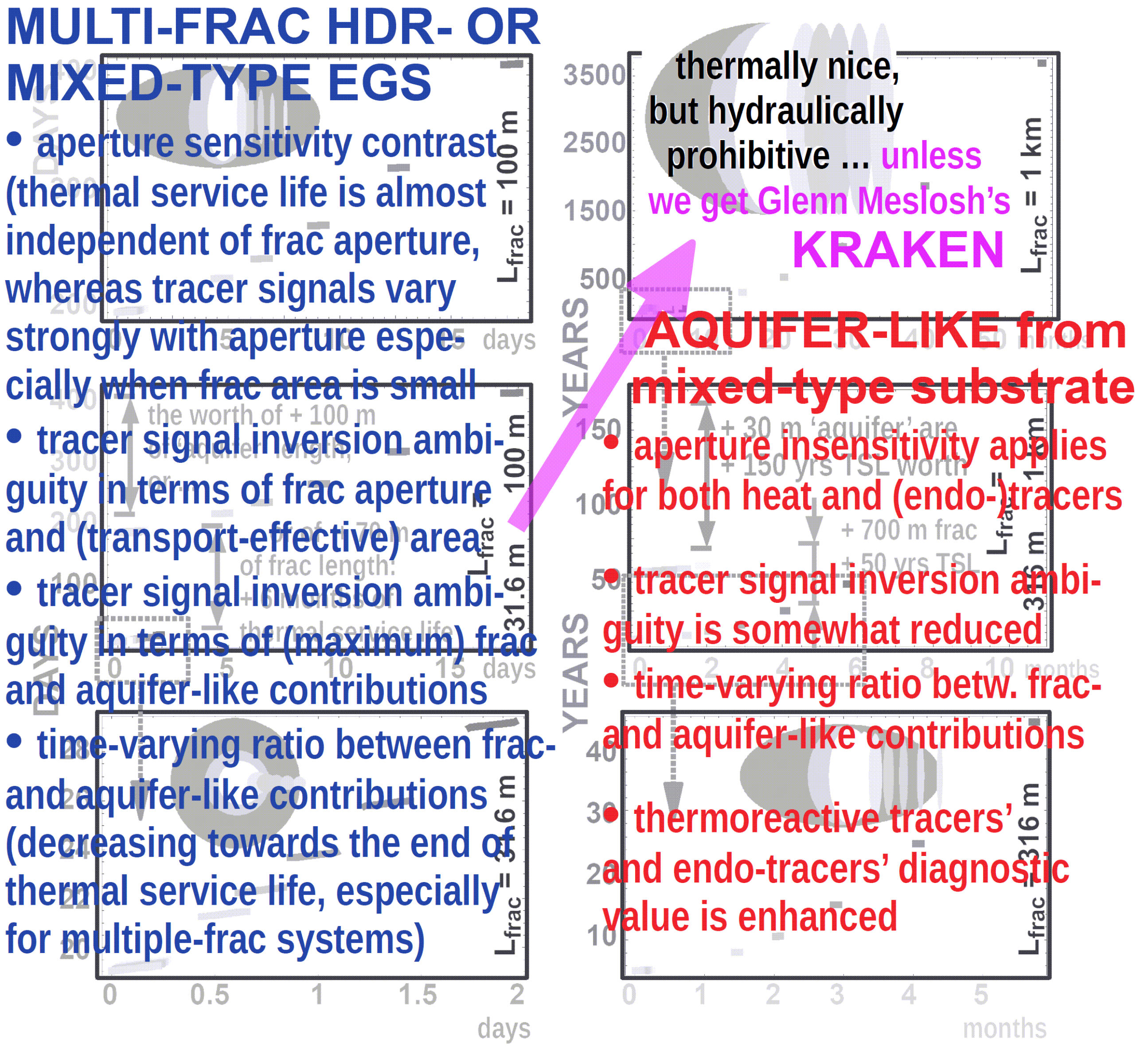

Figure E2: The violet arrow indicates the how the diagnostic value of endo-tracers increases in relation to EGS 'breed'. High-resolution versions of all figures can be found at sites.google.com/site/goetracerhydro/m-heg-320

E.2 It'S Not A Dagger

Deep-geothermal realm categorizing by 'petrothermal (HDR-like)', or 'aquifer-like' EGS, and so forth, is not a trivial exercise. Once having drilled down to the approximate target depth, reliable typifying would be needed before drilling further, to enable us decide about stimulation strategy and well-path deviation. But we get to know whether our guess was right only after stimulation with its subsequent hydraulic and fluid turnover testing was completed, evaluated, and analyzed. For quite some EGS candidates so far (as already mentioned in the previous section), the georeservoir 'breed' (or, to put it in more drastic German, whose *Satansbrut* or *Pudels Kern* the emerging EGS turns out to be) can only be told *post festum*, and artificial-tracer data, where available, seem to indicate a time-dependent, and spatially heterogeneous superposition of petro- and aquifer-like contributions. On the other hand, growing emphasis on avoiding human-felt seismicity imposes operational changes to stimulation protocols – altering stimulation outcome in ways that additionally blur the petro-/aquifer-like frontier. Fluid transport parameters controlling *TSL* can be metered only by (endo-)tracers, but the fluid transport agenda often gets superseded by a mono-focus on the induced-seismicity agenda.

The primary purpose of reservoir engineering is not to avoid human-felt seismicity, but to improve energy output, while reducing overall costs-per-output. The 'valid' EGS concept is not necessarily one that survives Popper's razor (falsification by evidence pieces like those invoked by Jung 2013); rather, the 'valid' EGS will be one that (most) people are willing to live with and pay for (Rorty's anarchism) – in possibly different shapes in Finland, France, Switzerland, Germany … Endo-tracers can aid in evaluating EGS engineering concepts – particularly in formations with low natural-fracture density, and the day may come for EGS development beneath selected 'spots' in the German Molasse basin (cf. Moeck and Beardsmore 2014) to grow 'petrothermally'.

Furthermore, the so-called 'softening' of the stimulation process, or 'fatigue hydraulic fracturing' (Zang et al. 2017, Kwiatek et al. 2017, 2018) also comes with some added benefits regarding tracer signal sensitivity to TSL-controlling parameters. It accelerates the onset of the so-called 'late-time' asymptotic regime of multi-rate diffusive tailings (cf. fig. 1 in Haggerty et al. 2000, fig. 3 in Ghergut et al. 2017, figs. 2 and 3 in Ghergut et al. 2018), and it further turns out to enhance (owing to cyclic injection and augmented outflow) the diagnostic value of endo-tracers, and their ability to tell 'petro-' and 'aquifer'-like contributions apart.

High-resolution versions of all **figures** can be found at sites.google.com/site/goetracerhydro/m-heg-320

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