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SINGLE-WELL DUAL-TRACER SPIKINGS DURING EGS CREATION IN NORTHERN-GERMAN SEDIMENTARY LAYERS

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ABSTRACT

Dual-tracer spikings were conducted during or immediately after reservoir stimulation (chemical and/or hydraulic faulting, fracturing or fissuring) in single-well configurations in two different geological settings in the Northern-German sedimentary basin. The first one was a single-well flow-path spiking between two sandstone layers in and between which faulting and some limited-radius fracturing or fissuring had previously been induced: the massive water injection at the lower-layer well-screen created a divergent flow field; after opening the well-screen at the upper layer, the flow field became (more or less) focused to the latter. At the other site, the spiking configuration was that of a single-well injection-withdrawal (push-pull) into and back from one insulated layer out of several stimulated sandstone and volcanic layers: the flow field first diverging away from, then converging towards the same well-screen (natural background flow being negligible in all cases). In both configurations, the difference between the return signals of two tracers with differing 'diffusion coefficients' (or rates of exchange between im-/mobile fluid zones) was supposed to enable estimating the encountered fluid-rock contact-surface area, more or less equivalent to the heat exchange area that would become a crucial parameter for the envisaged EGS at each site. Besides an inherent limitation of their reservoir penetration scale, considerable ambiguity persists with the inversion of transport parameters from both tracer test types described. It also appears that this ambiguity can hardly be reduced by adding hydraulic information.

MOTIVATION

For any liquid-based geothermal reservoir, thermal lifetime prediction requires two parameters that can only be determined from tracer tests: the distribution of fluid residence times under given hydraulic regimes, and the density of heat exchange surface areas.

Preferably, residence times should be determined from flow-path spikings (Fig. 1-a), whereas the surface parameter (equivalent to, or at least estimative of, the density of heat exchange areas) should be determined from spikings whose design reduces the effect of advection-dispersion processes and enhances the effect of tracer fluxes at/through fluid-rock contact surfaces – as done, for instance, in single-well, single-layer push-pull tests (Fig. 1-b).

However, successful extinction of advective-dispersive influences onto a measured tracer signal does not automatically turn that tracer signal into an adequate carrier for the heat-exchange-area information, in particular not at the relevant reservoir scale.

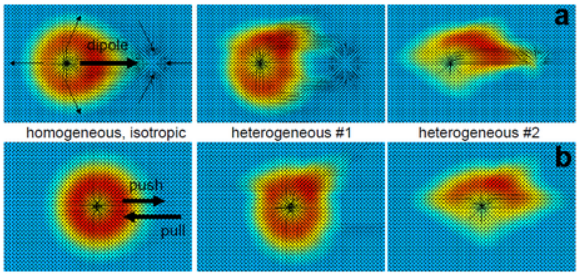

Figure 1: Schematic representation of (a) flow-path and (b) push-pull spiking configurations in more or less heterogeneous systems (2-D projections), using heat (cold-water slugs) and solutes as tracers.

SINGLE-WELL INTER-LAYER FLOW-PATH SPIKING AT HORSTBERG (2004)

Design Considerations

At the Horstberg site (located north-east of the city of Hannover, Germany, in an area formerly explored and used by gas industry) in the Northern-German sedimentary basin, a flow-path spiking was conducted between two sandstone layers (approx. 4 km deep and separated by some hundred meters of claystone), in and between which faulting and some limited-radius fracturing or fissuring had previously been induced (Fig. 2): the massive water injection at the lower-layer well-screen created a divergent flow field; after opening the well-screen at the upper layer, the flow field became (more or less) focused to the latter. - Spiking this single-well induced inter-layer flow was part of a more comprehensive testing program aimed at evaluating a innovative, single-well concept for heat extraction from tight sediments, as described by Jung et al. (2005).

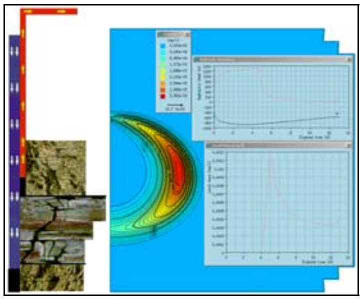

Figure 2: Schematic representation of endeavored single-well heat extraction method at Horstberg, and of spiking during 'water-frac' operation (roughly simplified 2-D projection).

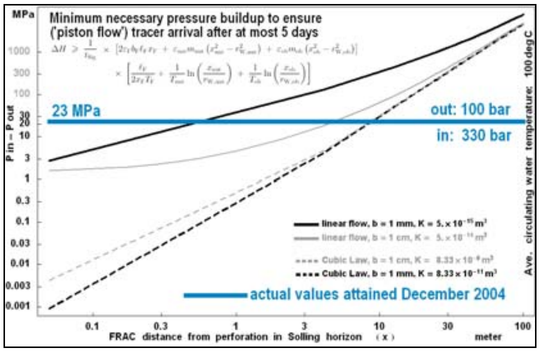

Figure 3: Estimating the minimum pressure buildup necessary to get 'piston-flow' tracer arrival within at most one week. It is hard to predict how far from the upper well-screen the claystone fault will intersect the upper sandstone horizon; this is the main controlling parameter for tracer arrival time(s).

The tracer transport simulation shown in Fig. 2 is not supposed to be quantitative, and not even realistic, it only shows the ideal case of a vertical fault plane connecting both well-screens (2-D structure). To get a rough estimate of the minimum inter-layer pressure buildup necessary to ensure tracer arrival (in the sense of 'piston flow') within at most one week (Fig. 3), the residence time in parallel flow (PFRT) within a claystone fault plane obliquely intersecting the lower well-screen was added to the PFRT within the upper sandstone layer, intersected by the claystone fault plane at a distance “x” from the upper well-screen. The maximum distance “x” still compatible with the actually attained pressure buildup (about 15 meters for 23 MPa) from Fig. 3 cannot be interpreted as a physical maximum, as there will be considerable dispersion, nor as a 'normative' target, since only a small percentage of the injected tracer quantity is supposed to be recovered at the upper well-screen. - From the EGS point of view, a high-permeability fault should be created and this should be 'confirmed' in terms of tracer arrival at the upper well-screen, but it is desirable that *most* of the injected tracer will *not* be recovered during the short test duration.

A key idea with spiking design had been to use chemically conservative solute tracers with different 'effective diffusion coefficients': the difference between their return signals would then be due to solely processes of exchange between im-/mobile fluid zones, thus enabling to estimate the encountered fluid-rock contact-surface density (area-per-volume or 'specific area'), more or less equivalent to the heat exchange specific area that would become a vital parameter for the envisaged EGS at this or similar sites. For this reason (and also because they were supposed to be reliably quantifiable in brine samples using standard laboratory techniques), naphthalene-1,5-disulfonate (NDS) and tritiated water (HTO) were chosen as tracers. - Fluorescein di-sodium (a. k. a uranine) was simultaneously added as a third tracer, expecting that it would exhibit non-conservative behavior.

After having pressed, in several stages with varying rates, something in the order of E+6 m^3 of cold freshwater into the lower sandstone horizon and having achieved a non-ambiguous pressure response at the upper sandstone horizon (Fig. 4), the tracer mixture was flushed with approximately 1500 m^3 of freshwater into the lower sandstone horizon. From the upper horizon, approximately 3600 m^3 of fluid (brine with varying proportion of the added freshwater) were produced over 10 days (injection at the lower horizon being discontinued after 2 days). Much more outflow would have been possible (in the order of E+5 m^3) by the existing pressure buildup, but the test had to be discontinued for various other reasons.

Horstberg: Tracer Test Data

The measured tracer breakthrough curves (BTCs) and their computed recoveries by the end of the test are shown in Fig. 5.

Uranine exhibited a strongly non-conservative behavior, which was explained by Behrens et al. (2006) as being mainly a reduction reaction, upon encountering reservoir brines of very low redox potential, to its leuco-dye form. After re-oxidizing the leuco form to the original uranine in fluid samples (treated under laboratory conditions), a uranine signal could be reconstructed which roughly resembles the measured signals of NDS and HTO. As such, it was not used for deriving information about the spiked flow field; nor about fluid-rock contact-surface areas, since its 'reactivity' was mainly in the aqueous phase.

The freshwater-brine mixing ratio, as inferred from electrical conductivity data, provided a consistent picture with the NDS tracer. Figure 6 shows the computed proportion, in the produced fluid, of only that freshwater that came into the system *after* the tracers were added.

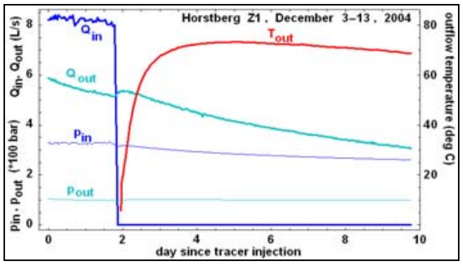

Figure 4: Flow data for the Horstberg spiking.

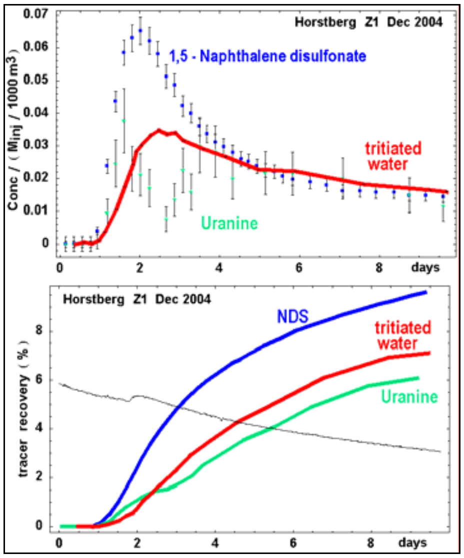

Figure 5: Tracer BTCs and 10-day recoveries from the Horstberg test.

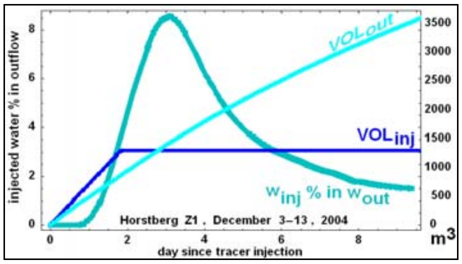

Figure 6: Proportion of 'post-tracer' freshwater in produced fluid during the Horstberg spiking.

Horstberg: BTC Curve Fitting Exercise

Almost nothing was known in advance regarding flow path geometries (lengths and transport-effective apertures of induced or stimulated fault, fractures, fissures), nor about the nature of solute exchange processes within them or at their boundaries, except the non-specific expectation that *zones of different fluid mobility* must have developed within the enhanced features themselves, and that *hydrodynamic-diffusive exchange* within those zones (apart from matrix diffusion) could have played an important role. Thus, even assuming that NDS and HTO must have experienced *identical* advection-dispersion, complemented by *similar* hydrodynamic-diffusive exchange only differing by the value of one exchange coefficient (whose ratio between the two tracers should be a physical constant), there are yet too many degrees of freedom left for BTC matching.

Therefore, the goal here shall not be to minimize the sum of squared deviations, from measured BTCs, of tracer fluxes simulated by some many-parameter model. Using the well-known three-parameter first-order model of Cameron and Klute (1977) in which the 'equilibrium' and 'kinetic' components are re-interpreted to describe hydrodynamic-diffusive exchange processes, it is possible to achieve almost 'perfect' matches of the measured NDS and HTO signals, by varying only the presumed 'tracer-specific' exchange rates while keeping all 'hydrogeological' parameters equal for NDS and HTO. Even with one less degree of freedom, setting the retardation factor $R_3 = 1$ (as NDS is supposed to be non-sorptive), using just a two-parameter first-order kinetic model (with different rates K_{in} and K_{out}) it is possible to get a 'nice' match for the NDS signal (Fig. 7-a). Else, assuming only pure matrix-diffusion besides advection-dispersion, simulations with Feflow (Fig. 7-b) on the idealized model of Fig. 2 reveal various possibilities of interpreting the NDS and HTO signals as the superposition between two parallel flow paths with different characteristics; but there is much ambiguity with such decompositions.

Instead, we attempt to match the NDS and HTO signals simultaneously by assuming just *1 flow path is controlling the observed RTD*, and using only 1 tracer-specific parameter per tracer (whose ratio between different tracers should somehow relate to physico-chemical constants determining their effective hydrated-ion or hydrated-molecule size). Irrespective of what precisely is taken to be their 'hydrodynamic-diffusive exchange' – be it mainly between 'primary' and 'secondary' porosity domains (a. k. a. 'matrix diffusion'), or be it mainly between zones of different fluid mobility all within the 'secondary porosity' domain (fault, fracture,fissure) – the 'effective area' of exchange surfaces should somehow correlate with the fluid-rock contact-surface area, and thus to the heat exchange area. Unfortunately, no detailed knowledge could be made available about the effective sizes of HTO and NDS molecules with possibly salinity-limited hydrating layers (under in-situ conditions of the spiked reservoir). Therefore, the specific area (area density) of exchange surfaces (whatever their nature) cannot be determined from matching the diffusive-exchange rate parameter as yet, but this knowledge gap can be overcome, in principle. Figure 8 presents a possible (yet non-unique) matching of NDS and HTO signals in terms of such a model, the assumed HTO exchange coefficient being about twice as large as the NDS one. The advection-dispersion parameters and the effective apertures found for this match indicate that the RTD-controlling feature should have been be a fractured-fissured region of < 30 m length within the upper sandstone layer (convolved by a rapid, low-exchange and low-dispersion signal from the claystone fault). An additional constraint with this single-component model was that the relative contribution attributed to the simulated component (factor multiplying the tracer mass put into it) must match the value of its simulated, asymptotic large-time tracer recovery (only approximately since flow rates decrease with time). For the component identified in Fig. 8, its relative contribution is found to be about 23%. This means that about 77% of the flow has considerable larger residence times (good for the thermal lifetime of the reservoir created) and tracer signals from those components could appear at later times. If the system is open, some of the injected tracer mass might never appear at the upper well-screen.

Horstberg: From BTC Fitting Towards a Model-Based Understanding?

A major difficulty with the 'inversion' of measured tracer signals from the Horstberg test is that, given its very short duration and thus the very low tracer recoveries, the tracer BTCs as available cannot reliably be extrapolated for times beyond the end of the test. Figure 9 illustrates two different models that would yield similar signal components for t < 10d, but quite different evolutions on longer term. And it is precisely these missing times that matter for thermal prediction.

All major parameters to be inverted from measured tracer BTCs depend on this extrapolation:

- mean residence time (MRT) and residence time distribution (RTD) – they control the thermal breakthrough time in the created reservoir;
- flow-storage repartition (FSR) – it would provide, according to Shook (2003), a “geometric characterization” of the created reservoir;
- the value of asymptotic tracer recovery – it would allow to tell if the reservoir is isolated or open-boundary, or how much of the flow would remain focused to upper well-screen on the long-term.

To estimate the overall fluid-rock contact surface area else than from solute exchange coefficients discussed in the previous subsection, one could take the ratio between the fluid turnover volume (roughly: flow rate times MRT), and the estimated mean aperture (the “transport-effective” one, cf. Tsang, 1992) from the achieved BTC inversion; this means relying on advection-dispersion rather than on BTC tailing information for determining a single-surface area rather than the density of solute exchange areas. But, besides the ambiguity in aperture determination (which is more of a 'technical' problem with transport-parameter inversion), there is, again, the essential uncertainty of MRT resulting from tailing extrapolation uncertainty (as illustrated in Fig. 9).

Further, in order to derive a FSR, or reconstruct the “reservoir geometry” according to Shook (2003), from a tracer-based RTD, one would first need to subtract the influence of diffusive exchange processes from the measured tracer BTCs. This in turn presupposes that process identification (separation between advection-dispersion and diffusive process), i. e., the underlying parameter inversion is non-ambiguous. - Which, again, does not seem achievable with the available Horstberg tracer data.

Most probably, the measured tracer BTCs represent the 'parallel' superposition (weighted sum) of two or three dominant flow paths with contrasting MRTs (and maybe also contrasting RTD and exchange rate characteristics); each of the 'parallel' paths is in turn the convolution of two or three signals from 'serially-connected' sandstone fault, claystone fault and sandstone matrix 'segments', of which the upper-sandstone matrix 'segment' plays the controlling role (longest MRT and highest exchange rates), whereas the fault segments (in the claystone and maybe also in the lower sandstone) might roughly be approximated by a finite sum of 'piston-flow' or lowly dispersive components. *But only few*, out of all advection-dispersion and hydrodynamic-diffusive solute exchange parameters of all these components, *will be relevant for long-term heat transport*. Whichever these few parameters are, they do not seem to be uniquely-invertible from the tracer data available at Horstberg. More effort on forward modeling is necessary in order to identify them, and to plan future fluid sampling campaigns (and new spikings) for the Horstberg site accordingly.

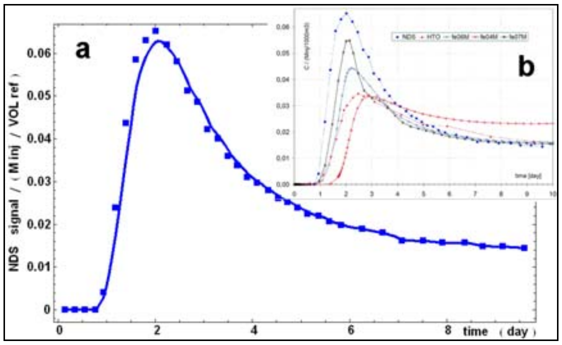

Figure 7: (a) Two-parameter kinetic model matching of NDS signal from the Horstberg spiking. (b) Some parallel flow-path contributions with matrix diffusion from which the NDS and HTO signals could be matched.

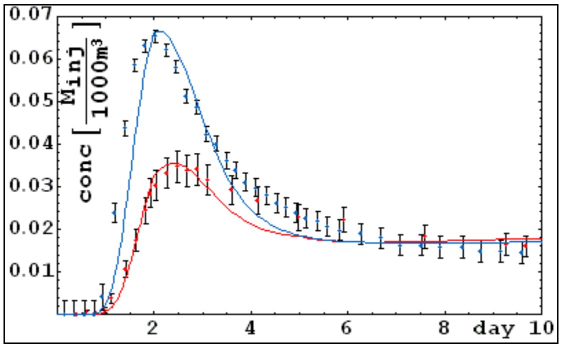

Figure 8: Hydrodynamic-diffusive exchange (single-parameter kinetic) model matching of NDS and HTO signals from the Horstberg spiking.

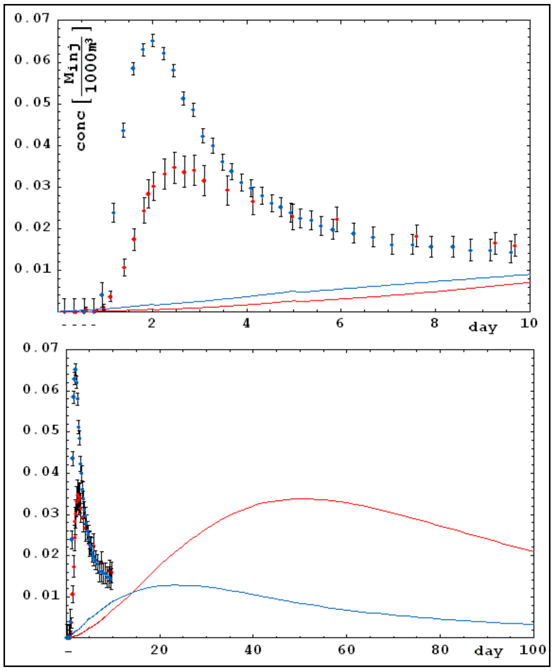

Figure 9: Tailing extrapolation ambiguity for the Horstberg spiking.

SINGLE-WELL ONE-LAYER PUSH-PULL SPIKING AT NEW SITE (2007)

At the other site (located north of Berlin, again in an area formerly explored and used by gas industry) in the Northern-German sedimentary basin, the spiking configuration was that of a single-well injection-withdrawal into and back from one insulated layer out of several stimulated sandstone and volcanic layers: the flow field first diverging away from, then converging towards the same well-screen. - This is the 'push-pull' configuration, as had been proposed for different in-situ physico-chemical investigation purposes by Tomich et al. (1973), Istok et al. (1997), Schroth et al. (2001), for quantifying advection-dispersion (in the presence of natural flow) by Bachmat et al. (1984), Leap and Kaplan (1988), for quantifying diffusive or kinetic-exchange processes by Haggerty et al. (2001), or fluid-rock contact surface areas by Sauter and Herfort (2002), and as it has further been analyzed by Neretnieks (2007).

At this site, different fracturing techniques had to be applied for each layer, given their different hydro-geomechanical characteristics. Natural background flow was assumed to be negligible in each case, but there could have been some degree of influencing between the flow fields established during outflow phases from each layer – thus also between the spreading of individual tracers that hat been added into each layer separately.

Since tests at this site are still running, and laboratory analyses of tracer samples are not complete, we present just one example (Fig. 10) of measured dual-tracer signals (both suffering from rather high measurement uncertainty) with some parameter inversions indicating that basically two contrasting transport scenarios are possible.

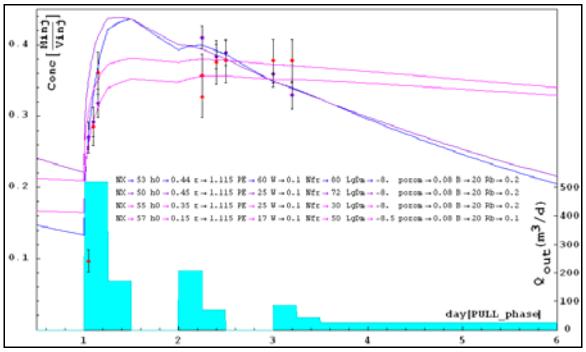

Figure 10: Tracer BTCs and provisional parameter inversions (non-unique) at the new site (tests still running).

The push-pull spiking at this (stimulated) sandstone layer was conducted with two tracers with undoubtedly different diffusion coefficients, and since push-pull spikings should generally suffer less from ambiguity between advective-dispersive and diffusive-exchange processes, the example of Fig. 10 suggests it would be worthwhile spending more work to reduce the measurement uncertainty (improve the quality of laboratory-instrumental tracer analytics, including pre-analytical steps of fluid sample conditioning and extraction), in order to render the difference between the two tracer signals more clearcut.

OUTLOOK

Dual-tracer spikings were conducted during or immediately after reservoir stimulation (chemical and/or hydraulic faulting, fracturing or fissuring) in single-well configurations in two different geological settings in the Northern-German sedimentary basin, both in about 4 km depth, adjacent to former gas exploration layers.

In both configurations, the difference between the return signals of two tracers with differing effective molecule sizes (thus differing 'diffusion coefficients' or rates of exchange between im-/mobile fluid zones) was supposed to enable estimating the encountered fluid-rock contact-surface area, more or less equivalent to the heat exchange area that would become a vital parameter for the envisaged EGS at each site. - This task is yet to be accomplished. Besides an inherent limitation of their reservoir penetration scale, there is considerable ambiguity persisting with the inversion of transport parameters from the two tracer test types described.

It also appears that transport parameter ambiguity can hardly be reduced by including hydraulic information, since hydraulic and transport parameter inversions (from measured rate-pressure, and from solute flux data, respectively), only weakly correlate with each other, and transport-effective apertures need not be identical with hydraulically effective apertures, as has been explained by Tsang (1992). However, out of all the parameters describing solute transport, *only few* do matter for thermal prediction. On the other hand, the ambiguity in transport parameter reconstruction from solute tracer signals could be reduced by considering in-situ temperature evolutions (especially after massive cold water injections), whenever available (during the Horstberg spiking only outflow temperatures could be measured, blurred by strong influence from adjacent cold-water injection, as well as from spent-brine re-injection into the same borehole with poor insulation between inner and outer tracks – a problem yet to be solved before implementing this single-well heat extraction concept in practice). Kocabas and Horne (1987) have shown that it is reasonable to use inter-well *flow-path spikings by solute* tracers for determining advection-dispersion parameters (RTD of reservoir fluids), and to use *single-well thermal* injection-backflow tests for determining a certain parameter which is equivalent to the density of heat exchange areas. If the solute BTCs from flow-path tracings, however, do contain diffusive-exchange effects, then the RTD of reservoir fluids cannot be taken as equal to the measured solute RTD, but diffusive-exchange effects need to be subtracted from the latter, i. e. they need to understood and quantified, as well.

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