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TRACER TESTS EVALUATING HYDRAULIC STIMULATION AT DEEP GEOTHERMAL RESERVOIRS IN GERMANY

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ABSTRACT

Fluid residence times and fluid-rock contact surface areas are important parameters in geothermal reservoir design and prediction. To determine them, tracer tests are the method of choice. In contrast with geophysical and seismic methods, the use of tracer tests for characterizing candidate geothermal formations at several km depth is relatively new in Germany. A more systematic campaign of fluid spiking applications, originally emerging from theoretical research interests but finally tailored to the specific needs of German pilot geothermal projects was made possible, since 2003, by a basic research project funded by the German Research Foundation (DFG) within its Priority Program engagement to the ICDP (International Continental Scientific Drilling Program). So far, the tracer testing campaign comprised single-well push-pull tracings, as well as a single-well and a inter-well flow-path tracing, in crystalline (KTB, Urach) and sedimentary (Horstberg) formations in ~4km depth; these tests' main endeavor was to help understanding processes associated with fluid transport in the deep crust, and subsidiarily also to assist in evaluating the effect of hydraulic stimulation measures, which were either short-term, high-rate (Urach, Horstberg) or long-term, moderate-rate (KTB). For the GroßSchönebeck site in the Northern-German sedimentary basin, a sequence of short-, mid- and long-term hydraulic experiments is planned, with single-well fluid spiking at four different stages and one inter-well flow-path tracing.

Good knowledge of the tracers' physicochemical behaviour under the given reservoir conditions, and reliable tracer analytics is a prerequisite for the correct interpretation of test results. Clearly, more research will be needed in this area.

AIMS

With growing awareness of a geothermal energy resource in deep crystalline or sedimentary formations in Germany, there is also an increased interest for assessing fluid flow, and heat and solute transport in candidate geothermal reservoirs by targeted quantitative methods, beyond the information provided by geophysical and seismic investigations. Fluid spiking provides the sole way to identify and characterize flow connections and determine fluid residence times in subsurface systems; in complex fractured-porous formations, it also enables to quantify fluid-rock contact surfaces; Hydraulic and geophysical investigation methods provide no, or only limited access to these parameters, because the signals on which hydraulic or geophysical test methods rely do not depend on, or they don't unambiguously correlate with fluid motion and with material fluxes through fracture surfaces. Moreover, it is hoped that tracer tests repeated in different stages of reservoir life as part of long-term monitoring can help in understanding and quantifying the coupled THM processes associated with the creation and exploitation of a deep geothermal reservoir, and their effects in the short, mid and long run. It is also imaginable that, via the integral parameters tracer tests usually provide, they may reduce the dependency of characterization and prognosis tools upon the availability of discretizing site models and powerful numerical solvers. For the tracer applications described here, a subsidiary aim was to probe the behavior of a number of organic tracers, a priori believed as 'good', under the physicochemical conditions of target formations (>100° C, saturated brine, very low redox potential, broad pH range), and, last but not least, to improve tracer test execution skills under specific geothermal 'site constraints'.

METHODS

Tracer-test types

The tracer tests conducted at the sites shown in fig. 1 are of one (or a combination of) following types (fig. 2): flow-path tracings (single-well or inter-well, monopole or dipole, mostly forced-gradient in stimulated systems), or single-well push-pull tests (method described by HERFORT ET AL. 2003). Even when only one borehole is available, a flow-path tracing can be conducted in a single-well setting, by isolating the target open-hole sections from each other, following a concept proposed by JUNG ET AL. (2005). The tracers used in the field tests are indicated on fig. 1 with their respective recoveries (measured, versus extrapolated – using a suitable model – until outflow rates approach zero).

Such tracer methods are directly suited, or can be adapted for the investigation of either fracture–dominated (HDR type) or of pore-space – dominated systems (fig. 1); a single-well, tracer push-pull test (fig. 2) can be especially useful for discerning between different fracture densities or specific (per-volume) contact-surface areas, whereas hydraulic test methods (pressure signals) are rather insensitive to this parameter, only reflecting the total void-space volume (cf. fig. 1). Injected fluids can be spiked at different times, in order to characterize flow and transport in different regimes (cf. fig. 3: solute push-pull tests *before* and *after* stimulation at the KTB site); or a dual-tracer spiking can be undertaken with different flushing volumes, in order to characterize different spatial scales of a reservoir (cf. fig. 3: *dual-slug* push-pull after stimulation at the KTB site). Under certain conditions, fluid temperature information can complement the solute tracer information.

Quantitative tools for test design and analysis

Often more than just the proof of the existence of a flow connection is desired. Quantitative approaches to test interpretation include: time-moment or flux–capacity analyses (cf. SHOOK 2003), integro-differential formulation for matrix diffusion(–type) problems (cf. CARRERA ET AL. 1998), response-function approaches, asymptotic approximations (KOLDITZ AND DIERSCH 1993), sometimes in combination with discretizing methods (KOLDITZ 1995).

Sensitivity analyses

assist in both the design and dimensioning of tracer experiments, and the interpretation of measured signals. E.g., tracer separation by diffusion/sorption coefficients in a single-well push-pull test is found to revert monotonicity upon transition from peak to tailing phases; it is advisable to use the latter in matching the contact-surface area parameter. While the dimensioning of tracer slugs can often rely on a bulk estimate of the total void-space volume, a forward modeling may be advisable for estimating the least necessary duration and frequency of sampling.

Memory function approach

Tracer output signals or (a linear combination of them and) their time derivatives can, under certain circumstances, be regarded as the temporal convolution product between their input signals and a characteristic system function $g(\tau)$. For transport affected by matrix diffusion, the function g can be related to the geometry of rock matrix blocks and an advection-free approximation leads to the following equation for the first derivative $f(t)$ of tracer concentrations:

$$f(t) = \frac{\sigma^2 \phi_m D_m}{R_f \phi_f (1-\phi_f)^2} \int_0^t g(\tau)\, f(t-\tau)\, d\tau$$

$$g(\tau) \approx -\frac{2}{\pi^2}\Gamma\left(1;\frac{1}{2}+N_{\mathrm{trunc}}\right)\delta\left(\frac{\sigma^2 D_m}{R_m(1-\phi_f)^2}\tau\right) - \sum_{n=1}^{N_{\mathrm{trunc}}} a_n \exp\left(-\frac{\alpha_n^2 \sigma^2 D_m}{R_m(1-\phi_f)^2}\tau\right)$$

with numeric coefficients a_n, α_n in the approximation of $g(\tau)$ depending on the geometry and size of matrix blocks.

Asymptotic approximations

Independently of rock matrix block shapes and sizes, it is expected that the memory function $g(\tau)$ always exhibits the same characteristic behaviour for short times, for mid-late times, and for late times, respectively. However these behavior patterns can depend upon the type of ‘multi-rate’ or pore-size repartition assumed to describe solute fluxes in the immobile phase (HAGGERTY ET AL. 2000, 2001).

Flux-capacity analyses

indicate what fraction of reservoir flow (if derived from flow-path tracings), or what percentage of solute or heat exchange (if derived from single-well push-pull tests), takes place in any fraction of the total reservoir storage, in the form of a cumulative repartition function, sorted by fluid residence times (cf. fig. 5). This type of analysis (being familiar from reservoir hydraulics) was first applied for interpreting tracer tests in geothermal systems in the USA by M. Shook (1998; 2003).

Heat versus solute tracer signals

In any test involving fluid injection/production, down-hole temperature data can be used to complement the information provided by solute tracer signals. Since thermal diffusivities in low-porosity crystalline rock exceed solute diffusivities by at least three magnitude orders, temperature signals here will reflect intermediate- and large-scale features (even in relatively short-term tests) but less of the small-scale features, whereas solute tracer signals will appear to be more sensitive to small- and mid-scale features, but less sensitive to the large-scale features composing the fracture network or fault structure (cf. fig. 3: heat versus solute push-pull results at the KTB site).

Tracer candidates

Solute tracers include: spiked water molecules (best choice for most situations: tritiated water), inorganic ions with ascertainedly low background concentrations in the investigated system (iodide can be a good choice in many situations, cf. BEHRENS 1986), organic compounds (mostly fluorescent ones, thanks to their sensitive detection), dissolved inert gases. At least one assuredly conservative tracer should be available in every application. The information derived from conservative tracers can be greatly enriched if specially-tailored reactive tracers (LICHA 2003, pers. comm.) are applied simultaneously. The properties of the latter should (ideally) be assessed independently from their field application, by laboratory experiments reproducing the physicochemical milieu of the target formation.

The information derived from artificial tracer applications can, under certain circumstances, be complemented by environmental tracers (– usually environmental isotopes; compounds introduced into the system as drilling additives may also behave like 'quasi-environmental' tracers, if their spreading is no longer localized). Fluid temperature, if measured in situ, provides an extremely valuable 'tracer' (for heat exchange rather than for fluid flow), whose diffusivity in lowly-permeable crystalline rock exceeds that of solute tracers by several orders of magnitude.

Tracer analytics is often a non-trivial task, especially for organic tracers (cf. BEHRENS 1970, 1971, 1973, 1982, 1986) in geothermal brine fluid (ROSE ET AL. 2000, 2001, 2003; BEHRENS ET AL. 2006). For radioisotopes (like tritium) that are preferably measured by scintillation counting, distillation of samples from concentrated brine may be necessary to avoid scintillator de-mixing (BEHRENS AND WITTIG 2005, pers. comm.). Budget limitations are often prohibitive of advanced analytical techniques: analytics must be kept 'simple and inexpensive' without sacrificing too much in quality. The environmental tolerance of most of the tracers used in geothermal applications has been assessed by several ecotoxicological and structure-activity relationship studies, e.g. GREIM ET AL. (1994), BEHRENS ET AL. (2001), ROSE ET AL. (2001), but the public urge to keep the injected tracer quantities to their 'least possible minimum' – despite the fact that fluids produced from geothermal reservoirs are usually disposed of in such a way that they won't enter the hydrological cycle within historical time – creates additional (unnecessary) pressure on tracer analytics.

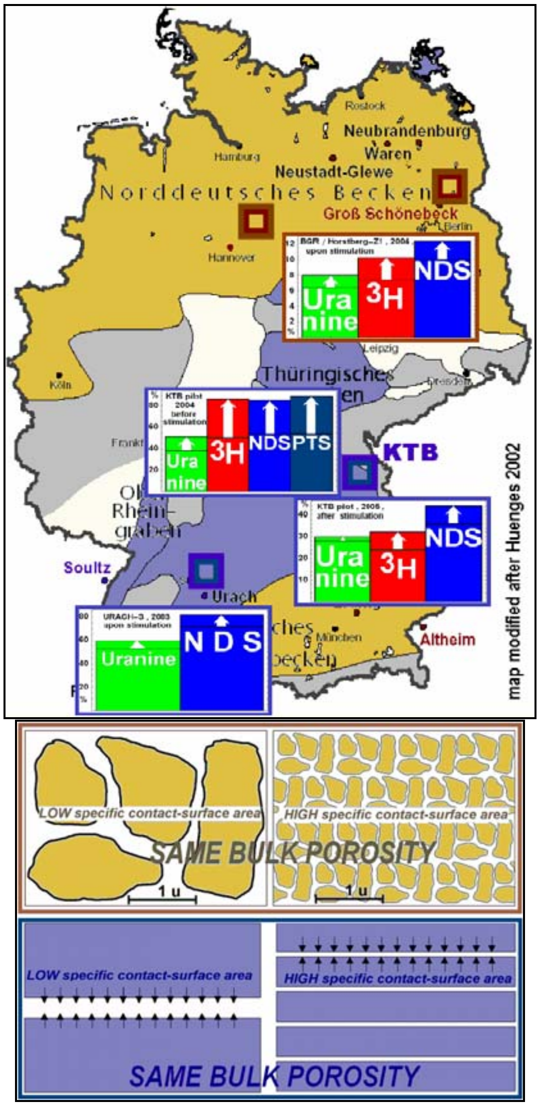

Fig. 1: Test sites, tracers used, tracer recoveries; specific fluid-rock contact-surface area in pore- or fracture -dominated systems

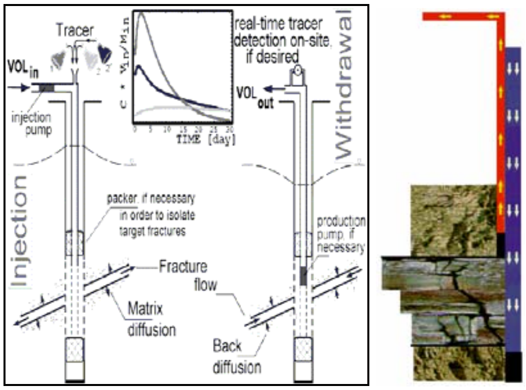

Fig. 2: Idea of (single-well) tracer push-pull test, and of a single-well flow-path tracing

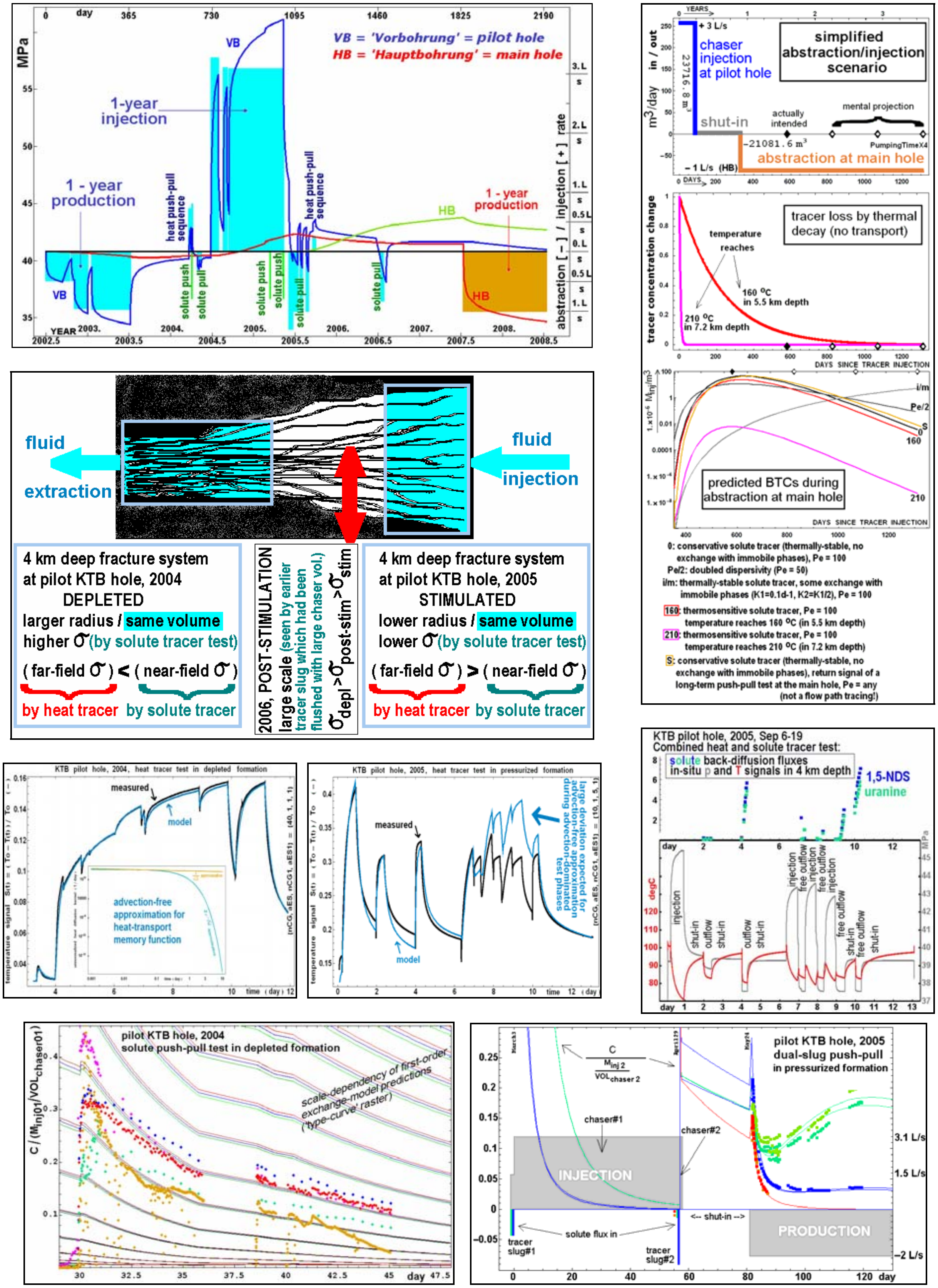

Fig. 3: Long-term testing at the KTB site

TRACINGS IN CRYSTALLINE FORMATIONS

Single-well push-pull tracings in deep crystalline formation at the KTB site

At the German ICDP (Intl. Deep Continental Drilling Program) site, known as the KTB (*Kontinentale Tiefbohrung*), comprising two boreholes (4-km deep pilot hole, and 9-km deep main hole) in the crystalline basement and enjoying extra-ordinary research opportunities (ERZINGER AND STOBER 2005, ZIMMERMANN ET AL. 2005a), a combination of short-term and long-term tracings could be applied in parallel with a long-term hydraulic and seismic testing program (KESSELS ET AL. 2004, STOBER AND BUCHER 2005, GRÄSLE ET AL. 2006, KÜMPEL ET AL. 2006, MCDERMOTT ET AL. 2006). The pilot KTB hole is known to intersect a relatively permeable fracture system in 3.8–4 km depth, and is fully cased except for this interval. Here, both solute and heat push-pull tests were performed in the depleted state (2004), the stimulated state (2005-a), the early post-stimulation state (2005-b), with a late outflow phase (2006) in the still weakly pressurized, late post-stimulation state. The change in specific fracture-surface areas (or fracture densities), derived from fitting a parallel-fracture, radial flow and transport model to the measured heat and solute push-pull signals (fig. 3), indicates that the prevailing effect of long-term, moderate-rate, cold-fluid injection was to enlarge pre-existing fractures, rather than creating new ones, despite some expectations as to a prevaillance of cooling-induced cracking. A long-term production test is intended at the main hole as of 2008; tracer levels in produced fluids could reveal the (least) size of the reservoir accessed between the two holes. Existence, location and geometry of a fracture system connecting them are yet unclear.

Single-well push-pull tracing in deep crystalline formation at the Urach site

At the 4-km deep borehole ‘Urach-3’ in the SW German crystalline (pilot geothermal plant), only one short-term tracer test was conducted (2003), comprising: three-week, high-rate fluid injection for permeability enhancement of possibly several fracture systems in 2.8 – 4 km depth; followed by tracer push-pull test (~2 weeks), shut-in (~3 weeks), new outflow phase (~1 week); the produced spiked fluid had to be disposed into the same borehole, which somewhat impairs on future tests using analytically similar tracers in the same reservoir. The tracer push-pull signals did reflect the presence of several fractures in different depths, but their unambiguous quantification seems difficult to achieve in terms of this sole tracer test. A major drawback with the test at the Urach site was that the tracer mass actually entering the target system cannot be estimated reliably (due to a problem during tracer injection); without proper normalization, tracer breakthrough curves cannot be interpreted correctly.

TRACINGS IN SEDIMENTARY FORMATIONS

Single-well flow-path tracing in deep supra-salinary, sedimentary formation (Horstberg-Z1)

At the Horstberg site in the Northern-German sedimentary basin, a former gas exploration borehole is available for geothermal research and for testing various heat extraction schemes (JUNG ET AL., 2005) in supra-salinary horizons. Besides various other hydraulic test series not accompanied by tracer tests, a combined hydro-mechanical and tracer testing campaign was started in late 2004. Using the hydrofrac technique, a large-area fault was created in the heterogeneous formation at ~3.8 km depth, comprising two sandstone layers separated by less permeable, clayey sandstone layers (with a total thickness of ~120 m). Assuming that the induced fault will maintain sufficient permeability over time (without the need for proppants), and that the same result can be achieved at many other similar formations in the Northern-German sedimentary basin, a low-cost single-well, two-layer circulation scheme (described by JUNG ET AL., 2005) is endeavored for heat extraction by the GGA and BGR Institutes (Hannover). In order to better characterize flow in the induced fault, a single-well flow-path tracing (cf. fig. 2, right half) was conducted at the Horstberg hole by spiking the fluid injected at the lower horizon and sampling the fluid produced from the upper horizon, with expectably high tracer dilution (fig. 4) due to the divergent flow field. After a 1.5-year shut-in phase, short outflow phases from both the production and the former injection horizon yielded further information, of both flow-path and push-pull type; tracer analytics for these late breakthrough signals is under completion. Extrapolated tracer recoveries from the first test phase showed that up to 12% of the (more or less radially divergent) flow field is focused to the production screen.

Design of single- and inter-well push-pull and flow-path tracings of deep sub-salinary, sedimentary formations at the GroßSchönebeck site

At the GroßSchönebeck site in the NE German sedimentary basin (MOECK ET AL. 2005), two newer boreholes, deemed as GS3 and GS4 (of which the latter is currently under completion), reaching down to sub-salinary horizons, are envisaged for further tests. Comprehensive geophysical investigations and hydraulic/mechanical tests have already been conducted at GS3 and neighboring holes in the same or similar formations (REINICKE ET AL. 2005, ZIMMERMANN ET AL. 2005b, HUENGES ET AL. 2006). At the new hole GS4, the GFZ Potsdam plans to conduct, as of 2007, a sequence of short-term, high-rate fracings in ~4 km deep volcanics and sandstones, followed by short- and mid-term flow-back tests, and by a long-term, moderate-rate production test, with fluids produced at GS4 to be reinjected at GS3. The first task was to design and dimension several spikings at both boreholes, such that each individual spiking potentially yields measurable signals during each of the subsequent outflow or abstraction phases. There are to be four spikings accompanying the faulting, injectivity and sequential flow-back tests at GS4, whereas the reinjected fluids, at GS3, shall be spiked just once, at the beginning of reinjection (fig. 6). Forward simulations and sensitivity analyses were undertaken as an aid in dimensioning the tracer slugs and sampling phases, based on a simplified, radial flow and transport model of the induced or stimulated fractures. From these analyses, tracer signals from flow-back (push-pull) tests at GS4 appear to be more sensitive to effective aperture and specific contact-surface area (within the volume accessed by each test phase), than to the total reservoir size, whilst tracer signals at GS4 but originating from reinjection at GS3 appear to be very sensitive to the total reservoir size, and also to dispersion and surface/exchange parameters (fluid-rock contact-surface area, im/mobile exchange rates or alike).

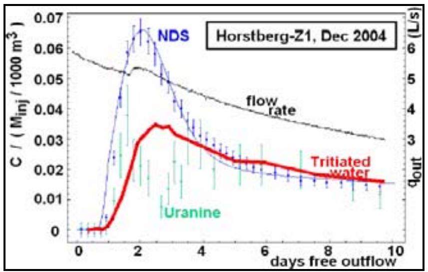

Fig. 4: *Tracer BTCs, 1^{st} outflow phase of hydrofrac tracing at the Horstberg site; in blue: fit of radial transport model with 1^{st}-order im/mobile exchange to the measured signal of the highest-recovery tracer*

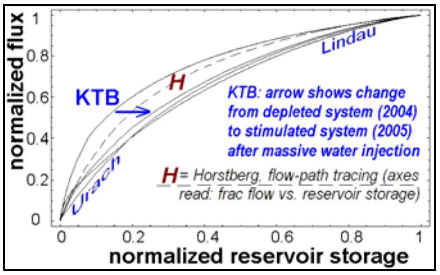

Fig. 5: *Comparison of flux-capacity repartitions derived from various tracer tests*

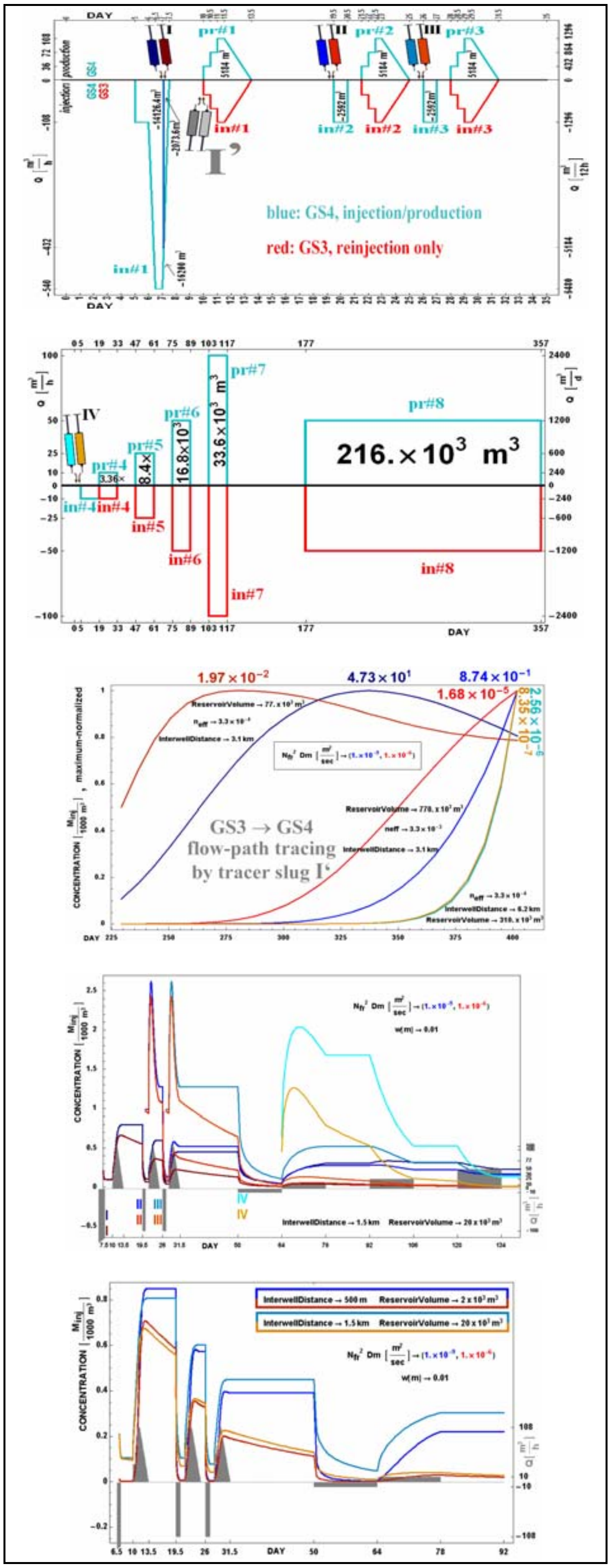

Fig. 6: *Tracer test design for GroßSchönebeck with some BTC sensitivity analyses w.r. to reservoir size and contact-surface parameters*

CONCLUSION

From tracer breakthrough curves in single-well push-pull tests (at the KTB site), the specific area of the fluid-rock contact surface could be estimated; its change with different hydraulic regimes could be used to appreciate the effect of hydraulic stimulation. From tracer BTCs in the hydrofrac push test (at the Horstberg site), a fluid residence time distribution could be derived and analyzed (cf. fig. 5), and the flow 'capture angle' to the target horizon could be estimated from the tracer recovery fraction. In all cases described, tracer tests are conducted in parallel with hydraulic tests or stimulation measures, without significant additional expenses.

Regarding organic tracer behavior, it is worth mentioning that uranine (di-natrium fluorescein), used as a tracer in all tests, showed systematically lower recoveries than the other, simultaneously injected organic tracers (cf. fig. 1); a massive conversion to its leuco-dye form (reduction reaction in-situ), during the hydro-frac tracing in the Horstberg sedimentary formation, was identified, explained and quantified by BEHRENS ET AL. (2006).

Theoretically, tracer tests can provide information on transport properties essential for heat exchange in geothermal reservoirs (fluid residence times, heat exchange areas), which are not properly determined by hydraulic or geophysical methods. Generally, the idea of any tracer test is to derive information on the target formation from artificially-induced solute and/or heat transport processes whose basic mechanisms are assumed as known. The process interpretations and parameter estimates derived from solute tracer tests are only as reliable as the knowledge of the tracers' physicochemical behavior under the given reservoir conditions, and the tracer analytics itself. More effort will need to be spent on these issues.

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