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Comparative evaluation of tracer tests in deep crystalline and sedimentary, candidate geothermal reservoirs in Germany

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Fluid residence times and transport-effective fracture densities (or specific heat-exchange areas) are important parameters of subsurface flow systems in fractured-porous formations (or geothermal reservoirs). To determine them, tracer tests are indispensable. 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 do not correlate unambiguously with fluid motion and with solute or heat fluxes across fracture surfaces. Fluid temperature variations accompanying hydraulic operations do in principle reflect these parameters, but high thermal diffusivities usually make temperature signals rapidly reach quasi-equilibrium values, obliterating parameter dependencies.

For deep (candidate) geothermal reservoirs in Germany, fluid spiking experiences are not very numerous. A systematic campaign of deep-crustal fluid spiking applications was made possible since 2003 with a basic research project funded by the German Research Foundation (DFG) within its Priority Program engagement to the International Continental Scientific Drilling Program (ICDP). This 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. The tests' main endeavour was to help understanding processes associated with fluid transport in the deep crust, while also assisting in the quantitative evaluation of hydraulic stimulation measures – which were either short-term, high-rate (Urach, Horstberg) or long-term, moderate-rate (KTB). Further it was hoped that, via the integral parameters they usually provide, tracer tests would reduce the dependency of characterization and prognosis tools upon the availability of detailed discretizing site models and powerful numerical solvers. A subsidiary aim of these tracer tests 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).

At the German ICDP site, 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, a combination of short- and long-term tracings could be applied in parallel with a long-term hydraulic, geophysical and seismic testing program. The pilot KTB hole is known to intersect a moderately-permeable fracture system in 3.8–4 km depth, and is fully cased except for this interval. Here, solute and heat push-pull tests were performed in the depleted state (2004), the stimulated state (2005a), the early post-stimulation state (2005b), with a late outflow phase (2006) in the still weakly pressurized, late post-stimulation state. Tracer breakthrough curves (BTCs) from solute push-pull tests, and temperature responses from heat push-pull tests, respectively, enable to estimate a transport-effective contact-surface area per volume between fractures and rock matrix (or a transport-effective fracture density) S, and an effective radial extension R of the accessed reservoir (or the space scale 'seen' by the tracers). In general, these estimation will slightly depend upon the type of conceptualization used for the fracture network, and upon the kind of exchange processes or fluxes assumed across or close to fracture surfaces.

The effects of long-term depletion (by fluid abstraction, 2003-2004) and of long-term stimulation (by fluid injection, 2004-2005) on the fracture network around the pilot KTB hole were sensitively reflected by solute and heat push-pull BTCs in terms of S and R, with good sensitivity especially w.r. to parameter S. The solute tracer test in the depleted system indicates higher values of S and R (for an equal chaser volume), than in the stimulated system; the post-stimulation, still weakly pressurized state of the system is characterized by intermediate values of S and R; whereas the heat push-pull tests which paralleled the solute push-pull tests yield complimentary far-field values:

$$S_{stim.,far-field} > S_{stim.,near-field} \text{ , } S_{depl.,far-field} < S_{depl.,near-field} \text{ .}$$

This implies 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 that cooling-induced cracking would prevail.

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. After various hydraulic and stimulation tests (2003-2004) not accompanied by fluid spikings, a combined hydro-mechanical and tracer testing campaign was started in late 2004. Using the hydro-frac technique, a large-area fault was created in the heterogeneous formation at $\sim$3.8 km depth, comprising two sandstone layers separated by less permeable, clayey sandstone layers (with a total thickness of $\sim$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 endeavoured 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 was conducted in early post-stimulation state by spiking the fluid injected at the lower horizon and sampling the fluid produced from the upper horizon, with expectably high tracer dilution 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 early test phase showed that up to 12% of the (more or less radially divergent) flow field is focused to the production screen. A useful representation of the induced flow-path properties is provided by a cumulative, truncated-temporal moments diagram: a parametric plot of the zeroth-order, time-t-truncated moment, against the first-order, time-t-truncated moment of tracer concentrations, with time t as a parameter, shows what fraction of reservoir flow takes place in any fraction of reservoir storage (cumulatively). Similar approaches have been used by Behrens (1989) and Shook (2003).

Good knowledge of the tracers' physicochemical behaviour under given reservoir conditions, sensitive and reliable tracer analytics are prerequisite for the correct interpretation of test results. Major differences between BTCs of several simultaneously-injected organic tracers, as seen in the KTB and Horstberg tests, far beyond what one would expect by their different molecular diffusion, graphically demonstrate the need for more research on these issues. During the forthcoming stimulation (short-term) and hydraulic (short-, mid- and long-term) tests at a new borehole (GroßSchönebeck-4) in the Northern-German sedimentary basin, single-well fluid spikings at 4 different stages and 1 inter-well flow-path tracing are planned, all tests more or less overlapping each other. For a correct interpretation of these tests, at least 3 conservative solute tracers should be available; moreover, their analytics should be able to meet reasonable detection limits in saturated brine, for the necessary tracer quantities to inject not to become prohibitive.