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Five-year experience with deep-crustal fluid spikings: was it worth?

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During 2003 – 2007 the German Research Foundation (DFG) supported a campaign of tracer tests conducted by the University of Göttingen at the KTB site (*Kontinentale Tiefbohrung*, the German site of ICDP), embedded within a more comprehensive program of hydraulic and geophysical investigations mainly carried out by the Leibniz Institute of Geosciences (GGA) Hannover and the Geoscientific Research Centre (GFZ) Potsdam. Owing to additional funding from other German partners, like the Urach Spa Communal Supply Plants (*Stadtwerke Bad Urach*), the *BESTEC-for-nature* and *geoX* societies, and especially from the German Ministry of Environment (BMU), this deep-crustal fluid spiking program could be extended to further crystalline and sedimentary formations in Germany where boreholes in similar depths ($\sim$4 km) exist and for which geothermal energy extraction represented the main (research and/or economical) interest, including Urach and Landau/Palatinate in the South-West, Horstberg/Hannover and GroßSchönebeck in the Northern Sedimentary Basin.

The spiking applications included single-well intra-layer push-pull, single-well inter-layer and inter-well flow-path tracings, each of the experiments conducted remaining unique in its design, so far ('repetition' of each type of test at several sites would have been desirable for comparison purposes, but financial/operational constraints rendered this impractical).

The main endeavour of the tracer experiments was

- to assist in understanding solute and energy transport processes associated with natural or induced fluid flows in the deep crust, and quantify these especially

w. r. to fluid *residence times* and *fluid-rock contact surface areas* (as these parameters are not accessible to hydraulic and geophysical methods); and in particular

- to support the quantitative evaluation of the effect of *hydraulic stimulation* measures (including hydrofracing and gel-proppant fracing)
- to identify *economic designs* for specific sequences of fluid spiking and sampling phases such that these be embedded within hydraulic tests or the actual reservoir operation, without major additional effort
- to test the *physicochemical behaviour* of a number of known and new *tracer substances* under the extreme conditions of the deep formations under investigation

The main results of the tracer tests were

- for the pilot KTB hole: estimation of near-field and far-field *fracture densities* and of their increase/decrease during depletion/stimulation
- for the Horstberg site: estimation of inter-layer *flow capture angle* based on extrapolated tracer recovery; computing the *flow-storage distribution* of the induced hydrofrac based on a temporal moment analysis of the measured tracer breakthrough
- for the ongoing tests at the GroßSchönebeck site (provisionally): estimation of frac *volume* and of *fluid exchange* with adjacent regions
- for the Landau site: improved estimation of *least reservoir size* (and thus of earliest thermal breakthrough) from lowered detection limits in tracer analytics

The interpretation of the single-well (probably multi-layer) push-pull test conducted at the borehole Urach-3 remains unclear as yet.

Several kinds of difficulties and uncertainties associated with the conduction and interpretation of tracer tests in such formations are reviewed and discussed.

An economic design for continued sampling and new spiking phases at the KTB site is presented; new kinds of tracer tests are proposed for the Landau/Palatinate, Horstberg/Hannover and GroßSchönebeck sites.

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