Geothermal reservoir candidates in deep crystalline and sedimentary formations: tracer-assisted evaluation of hydraulic stimulation tests

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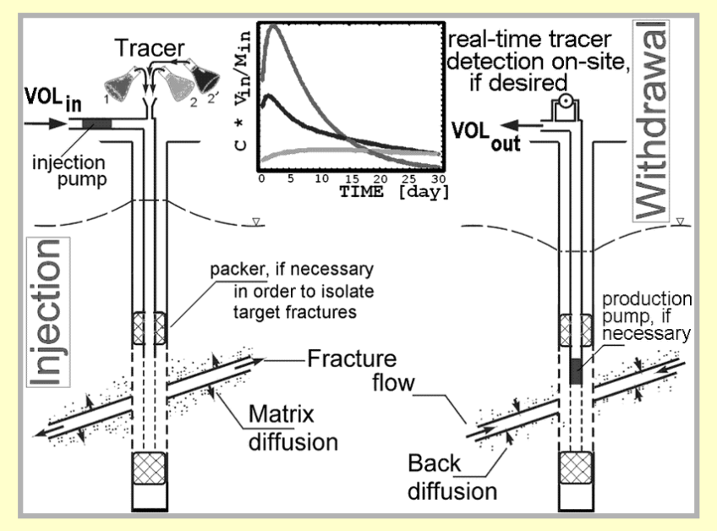
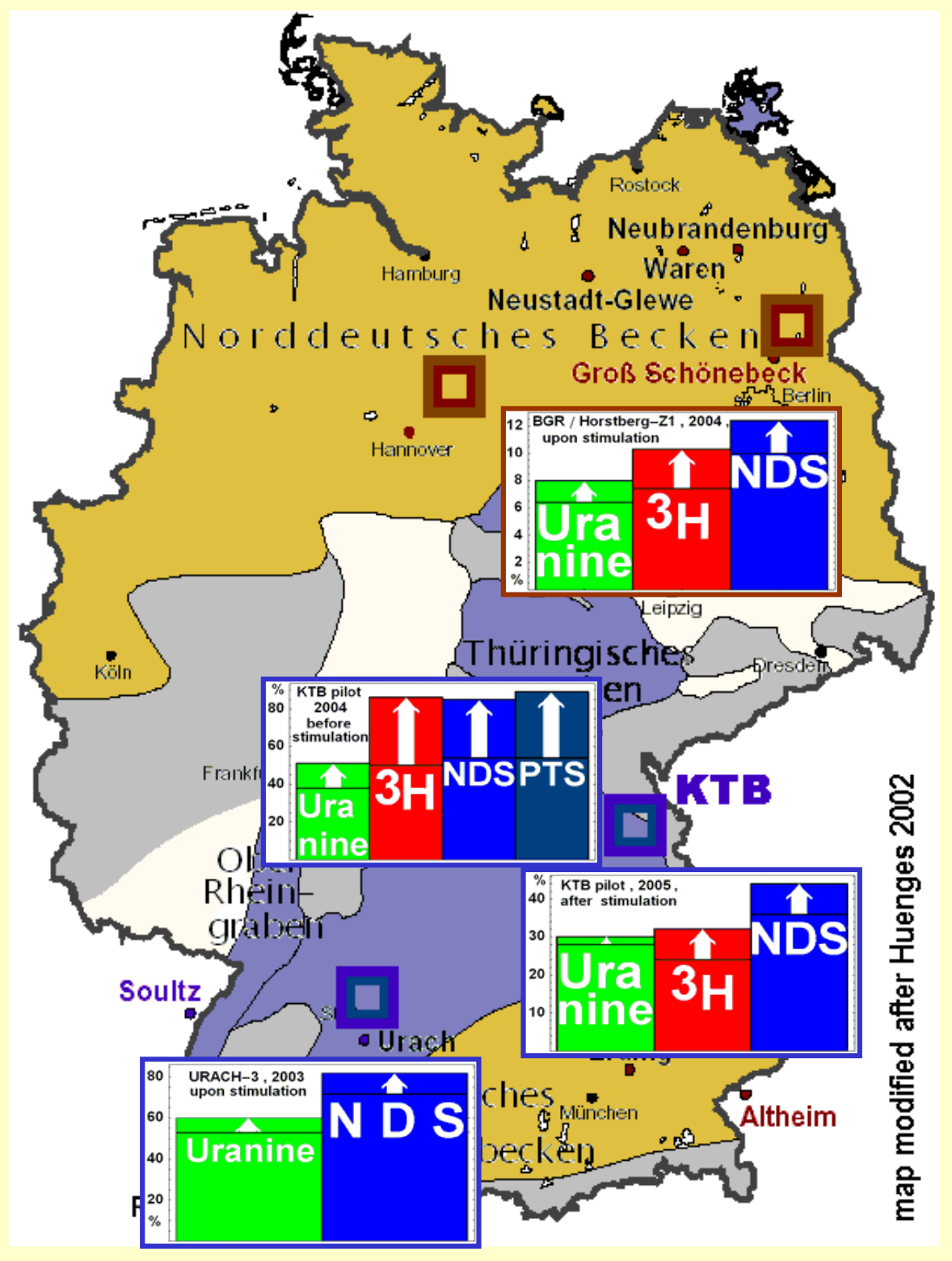
Tracer tests provide information on transport properties essential for heat exchange in geothermal reservoirs, like fluid residence times and fluid-rock contact surface areas – which are not properly determined by hydraulic or geophysical methods. Mostly, tracer tests can be conducted in parallel with hydraulic or hydromechanical experiments, without major additional effort. The use of push-pull and flow-path tracing tests to evaluate the effect of hydraulic stimulation measures is illustrated with some typical experiment settings at deep crystalline and sedimentary formations in Germany:

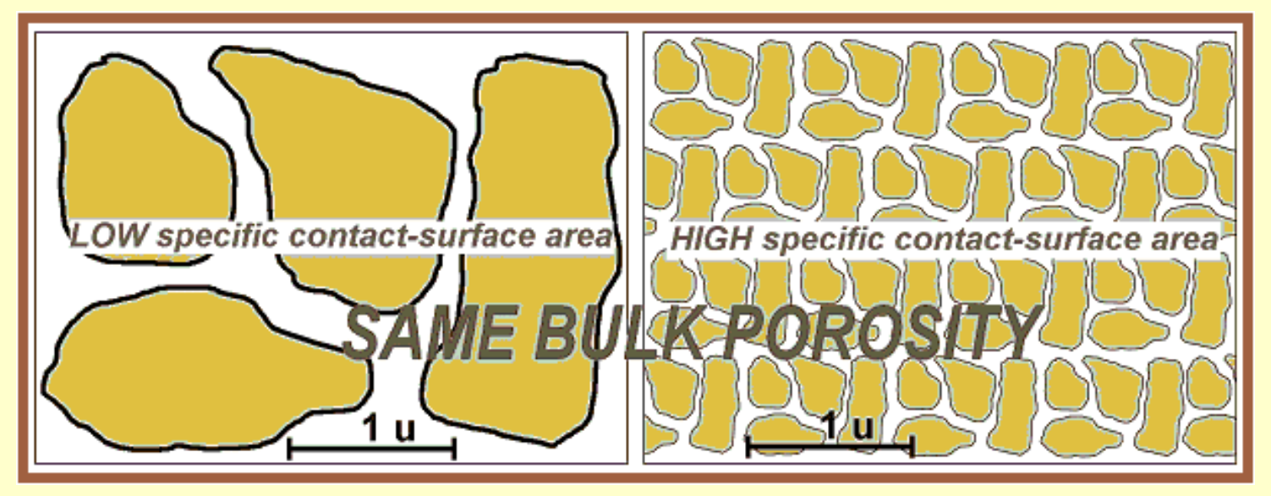


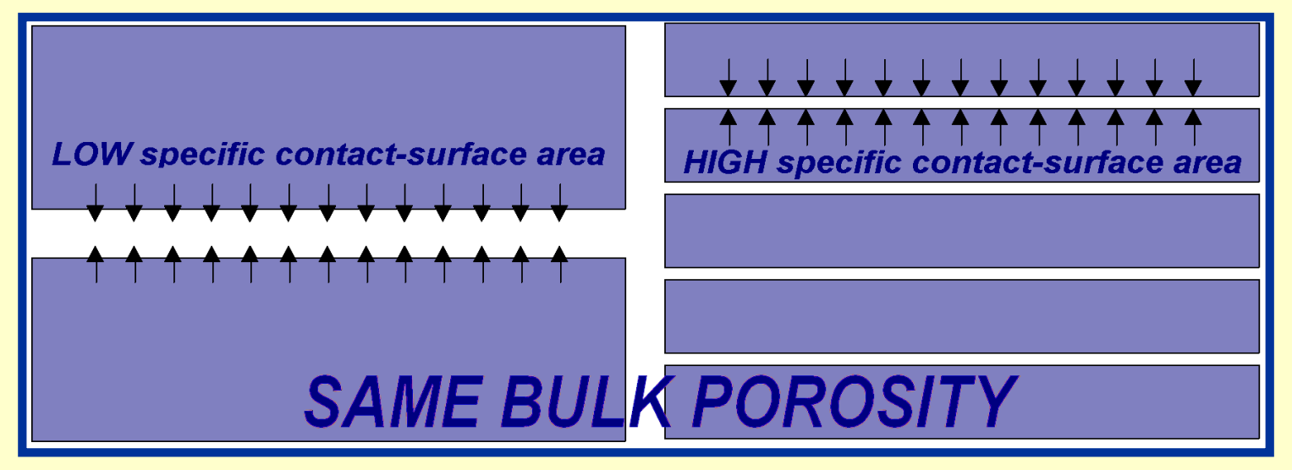
principle of a single-well, tracer push-pull test

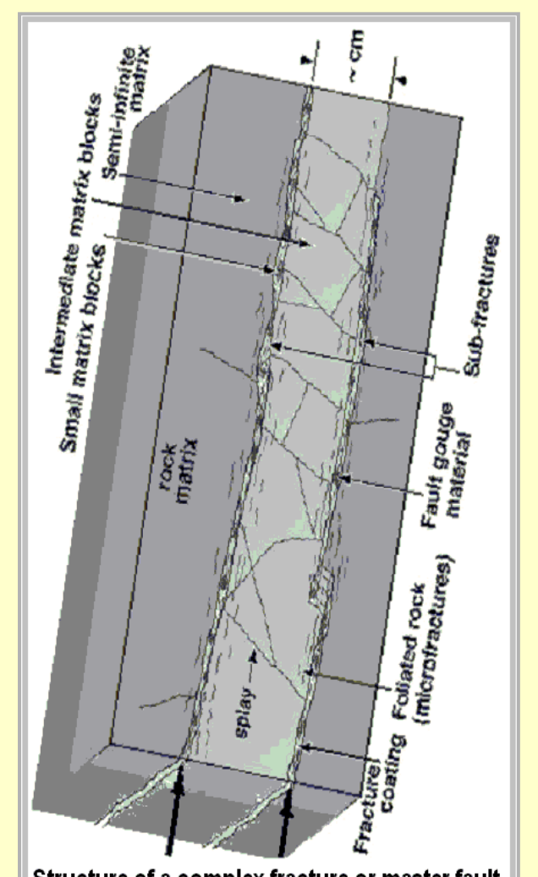
Heat versus solute tracer signals

Thermal diffusivities in low-porosity crystalline rock exceed solute diffusivities by at least three magnitude orders. Thus, temperature push-pull signals reflect intermediate- and large-scale features (even in short-term tests), but less of the small-scale features, whereas solute push-pull signals are more sensitive to small- and mid-scale features, but less sensitive to the large-scale features composing the fault structure.





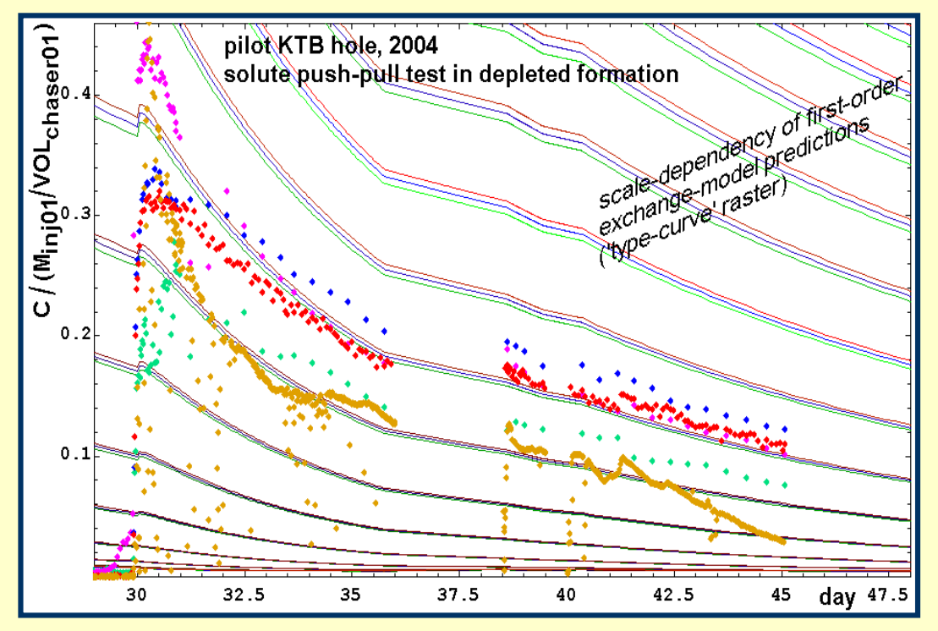


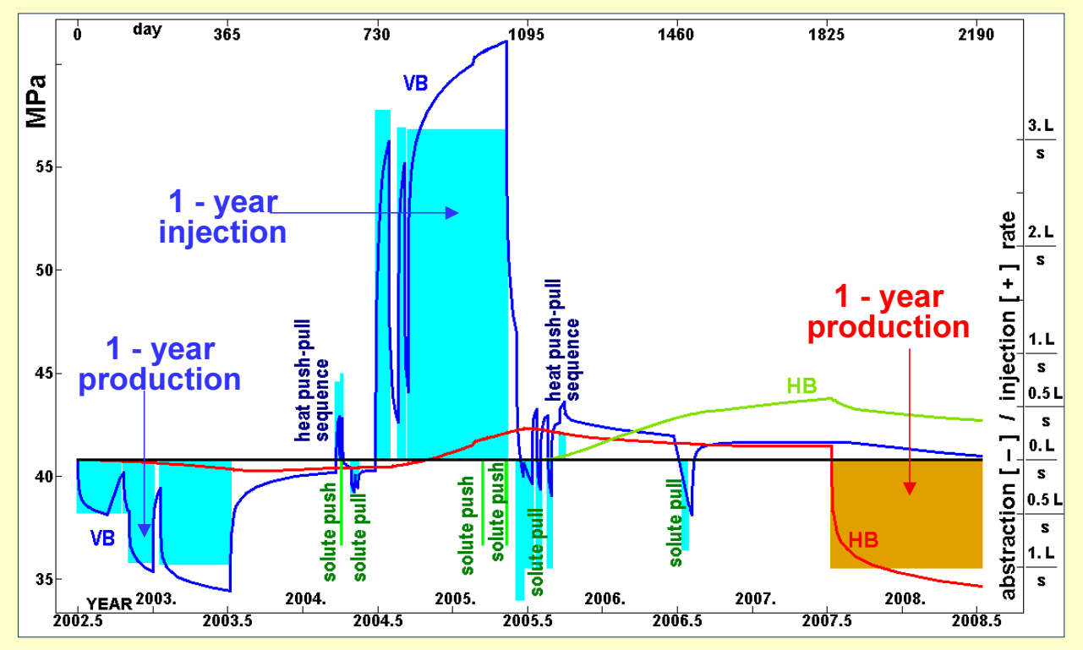


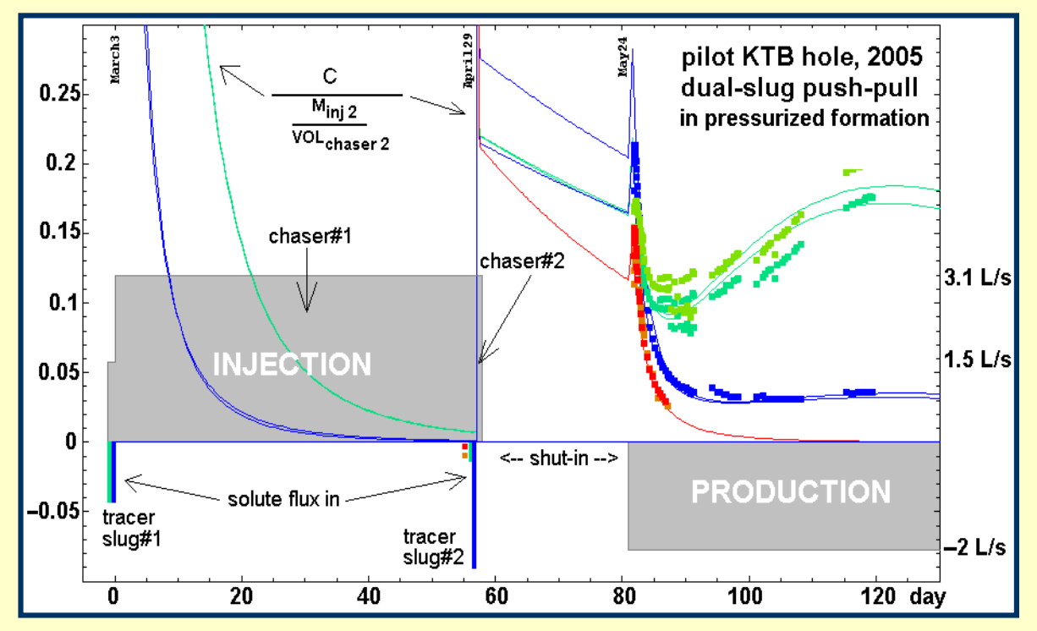
Structure of a complex fracture or master fault, adapted after Tsang and Doughty 2003 Water Resour. Res. 39(7), 1174

time scope geology	short-term	long-term
crystalline	**Urach** (SW Germany), 2003: three-week, high-rate fluid injec-tion 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); spiked fluid had to be disposed into same borehole	**KTB** (German site of Intl. Deep Continental Drilling Program), 2004 – 2006, at pilot hole (VB) intersecting fracture system in 4 km depth: push-pull test (2004) in depleted system, push-pull test (2005) in stimulated system, outflow phase (2006) in post-stimulation state; production at main hole (HB) intended as of 2007/2008
sedimentary	**Horstberg** (pilot site of BGR / GGA's geothermal demo project *GenESys*), 2004: short-term, high-rate injection aimed at connecting two sandstone horizons in ~3.8 km depth by large-area hydrofrac, followed by vertical flow test (~10 days) **GroßSchönebeck** (NE Germany, *In-situ Geothermal Laboratory* managed by the GFZ Potsdam), planned as of 2007: sequence of short-term, high-rate fracings in vulcanite (+ sandstone) formations in ~4 km depth, followed by flow-back tests	**Horstberg**, 2006: 1$^1/_2$ – year follow-up of short-term stimulation, with new test sequence: outflow from former production horizon, shut-in, outflow from former injection horizon (~1 week each) **GroßSchönebeck**, planned as of 2007: sequence of mid-term, moderate-rate flow-back (push-pull) tests in vulcanite + sandstone formations, followed by long-term production test

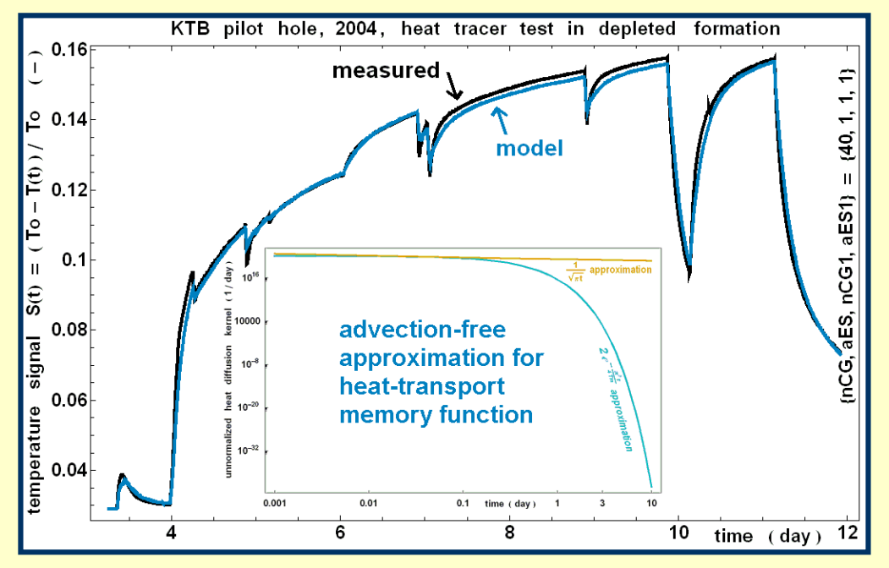
pilot KTB hole, 2004, following massive depletion

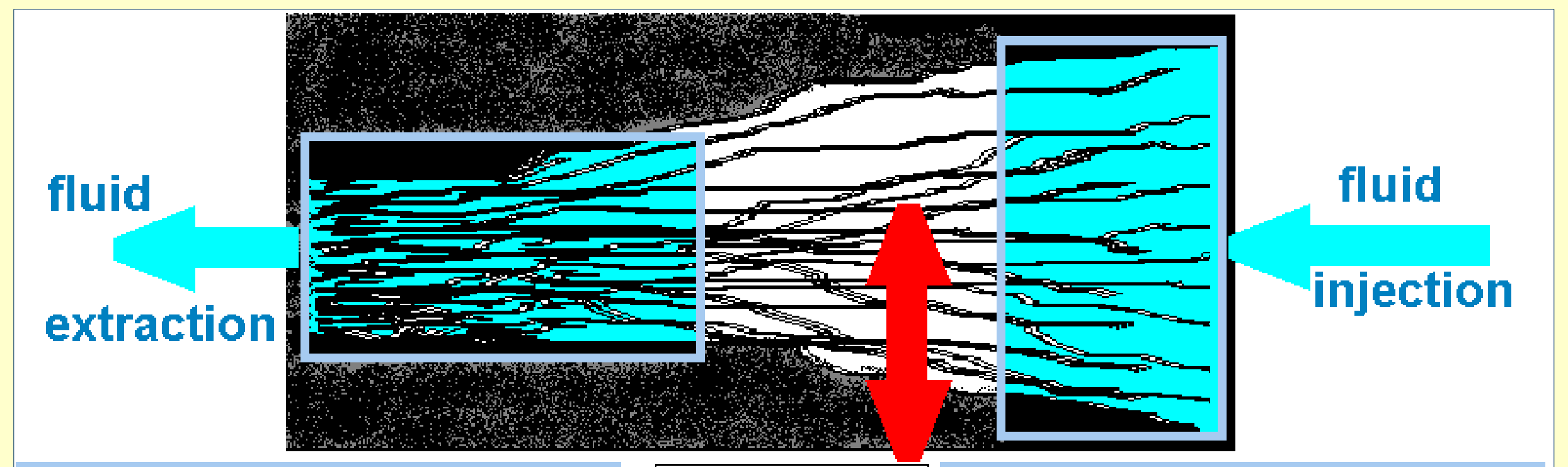






pilot KTB hole, 2005, following massive injection

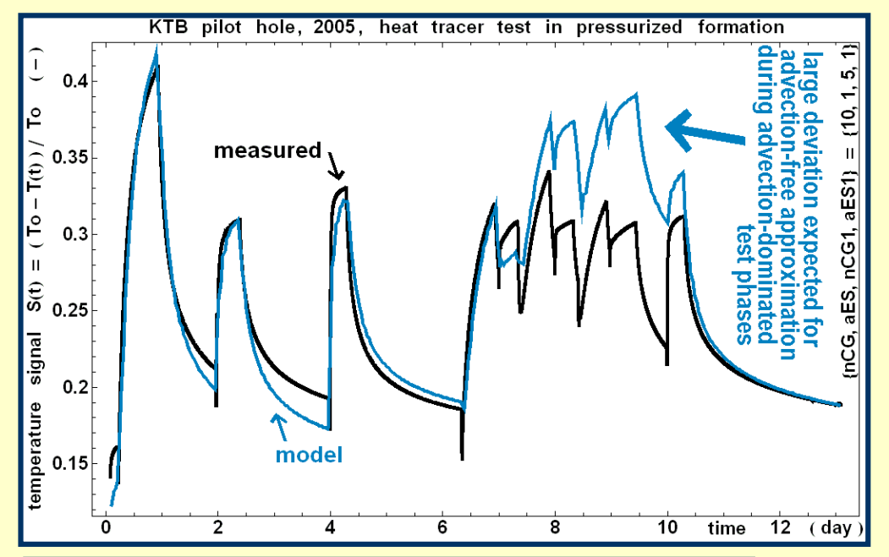


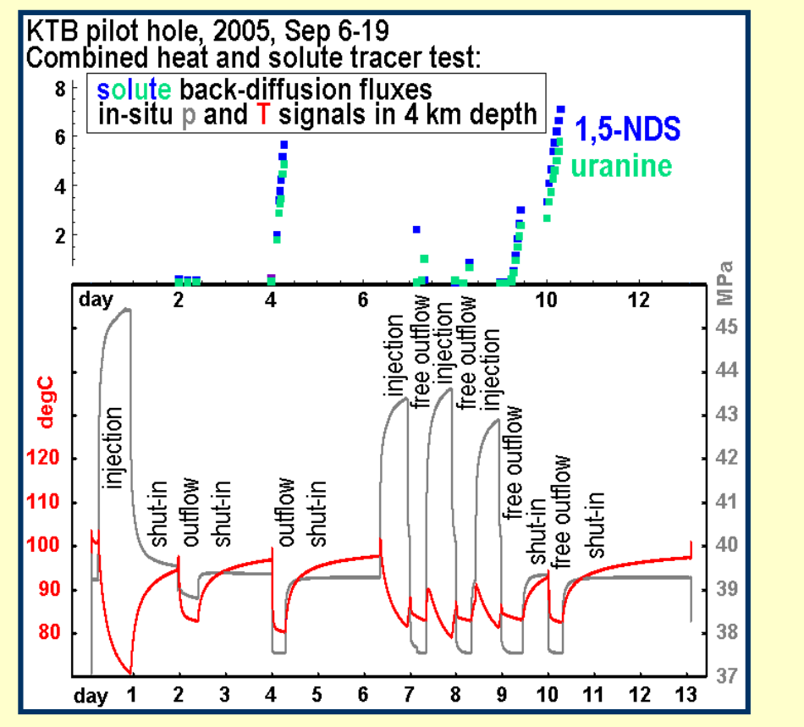


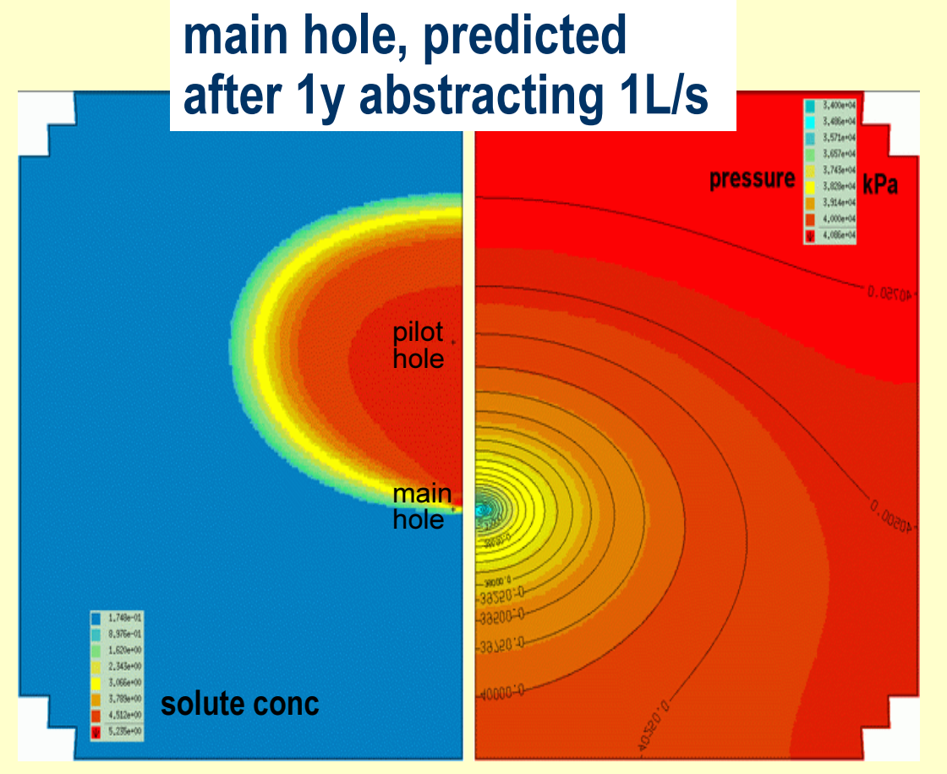
4 km deep fracture system
at pilot KTB hole, 2004
DEPLETED
larger radius / same volume
higher σ (by solute tracer test)
(far-field σ) < (near-field σ)
by heat tracer by solute tracer

2006, POST-STIMULATION
large scale (seen by earlier tracer slug which had been flushed with large chaser vol.)
$\sigma_{depl} > \sigma_{post\text{-}stim} > \sigma_{stim}$

4 km deep fracture system
at pilot KTB hole, 2005
STIMULATED
lower radius / same volume
lower σ (by solute tracer test)
(far-field σ) > (near-field σ)
by heat tracer by solute tracer







Field work contributed by Dr. M. Lodemann under extreme hardship conditions for a total of 10 weeks in Urach and at the KTB site, technical solutions by S. Fischer, field work by J.-U. Brinkmann, intellectual support from W. Kessels and S. Shapiro, and financial support from the German Research Foundation (DFG) are gratefully acknowledged.

Tracer-assisted evaluation of hydraulic stimulation tests – experiments in sedimentary formations –

At the Horstberg site in the Northern-German sedimentary basin, a former gas exploration borehole is now available for geothermal research and for testing various heat extraction schemes in supra-salinary horizons.

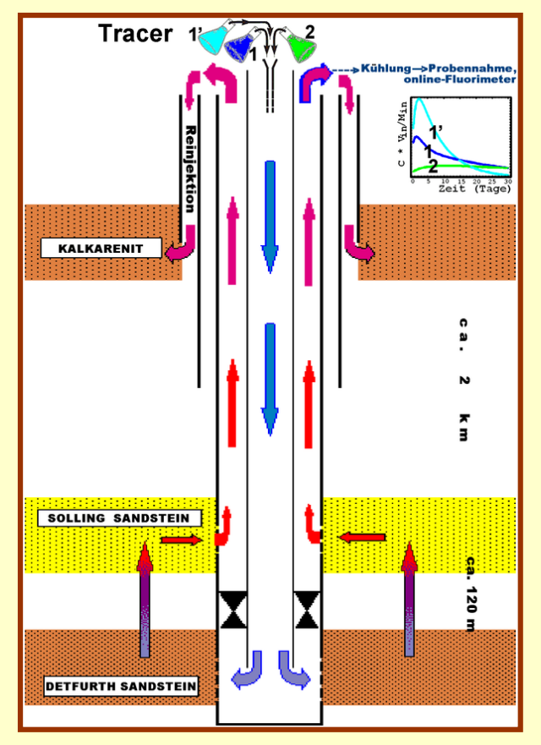
Using the hydro-frac technique, a large-area fault was created between two sandstone horizons in approx. 3.8 km depth. Assuming that the induced fault will maintain sufficient permeability over time (without the need for proppants), and that the same result can be achieved at many similar formations in the Northern-German sedimentary basin, a low-cost single-well, two-layer circulation scheme is endeavoured for heat extraction by the GGA and BGR Hannover.

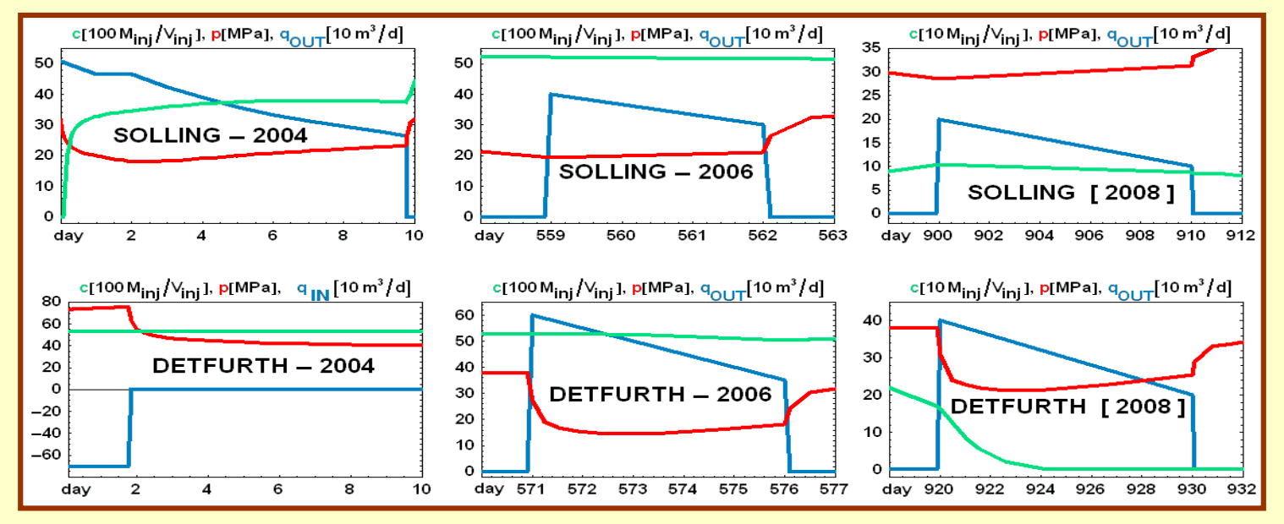
In order to better characterize flow in the induced fault, a tracer test was conducted at the Horstberg site. Extrapolated tracer recoveries showed that up to 12% of the (more or less radially divergent) flow field is focused to the production screen.

Horstberg

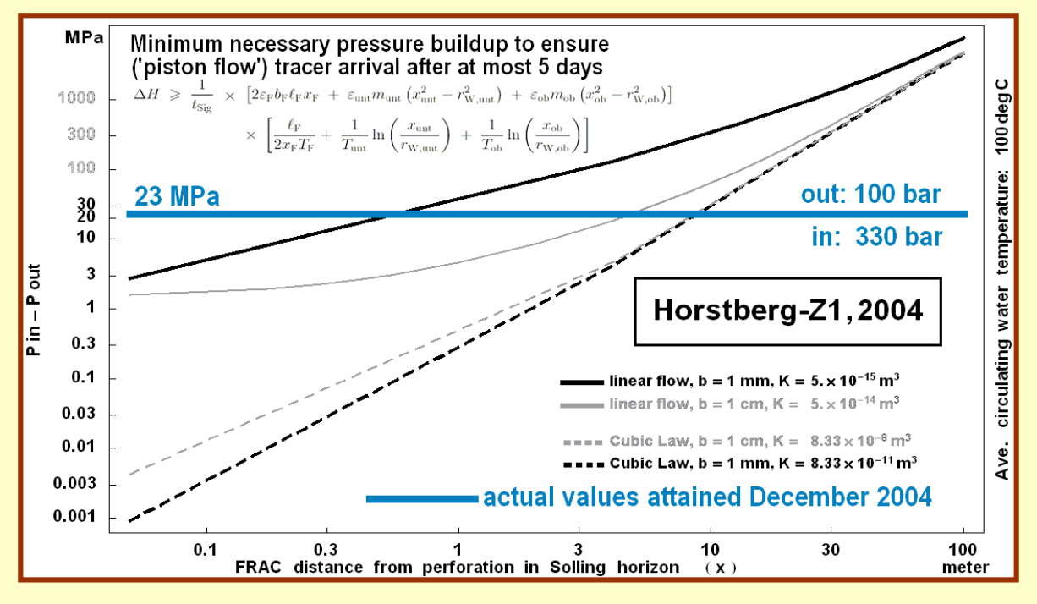
(supra-salinary horizons), pilot site of geothermics demonstration project *'GenESys'*, *GGA and BGR Hannover*

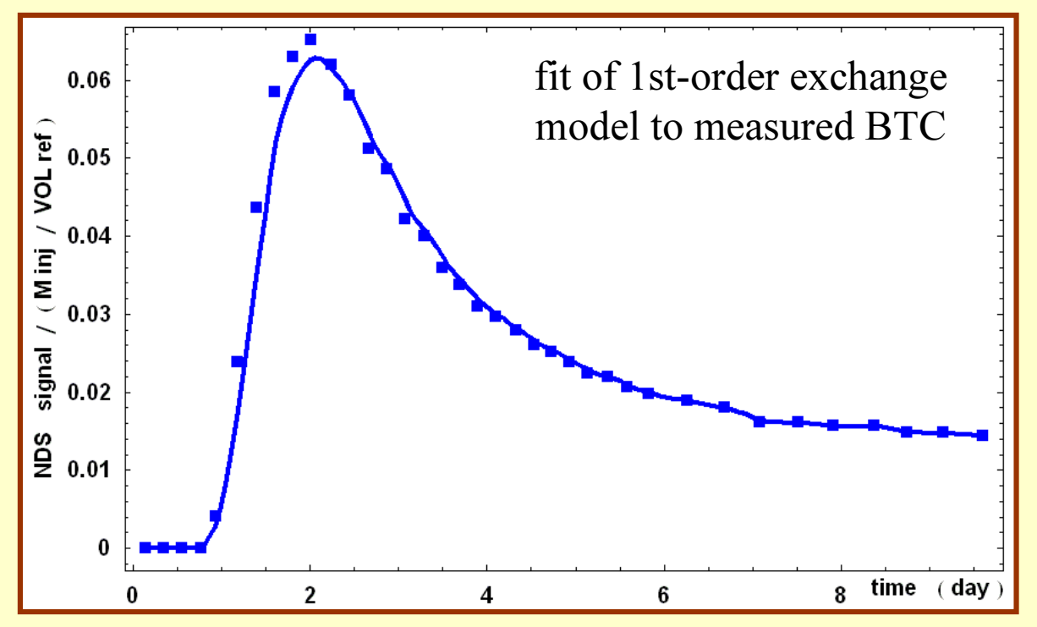
– first tracer test 2004, new sampling 2006

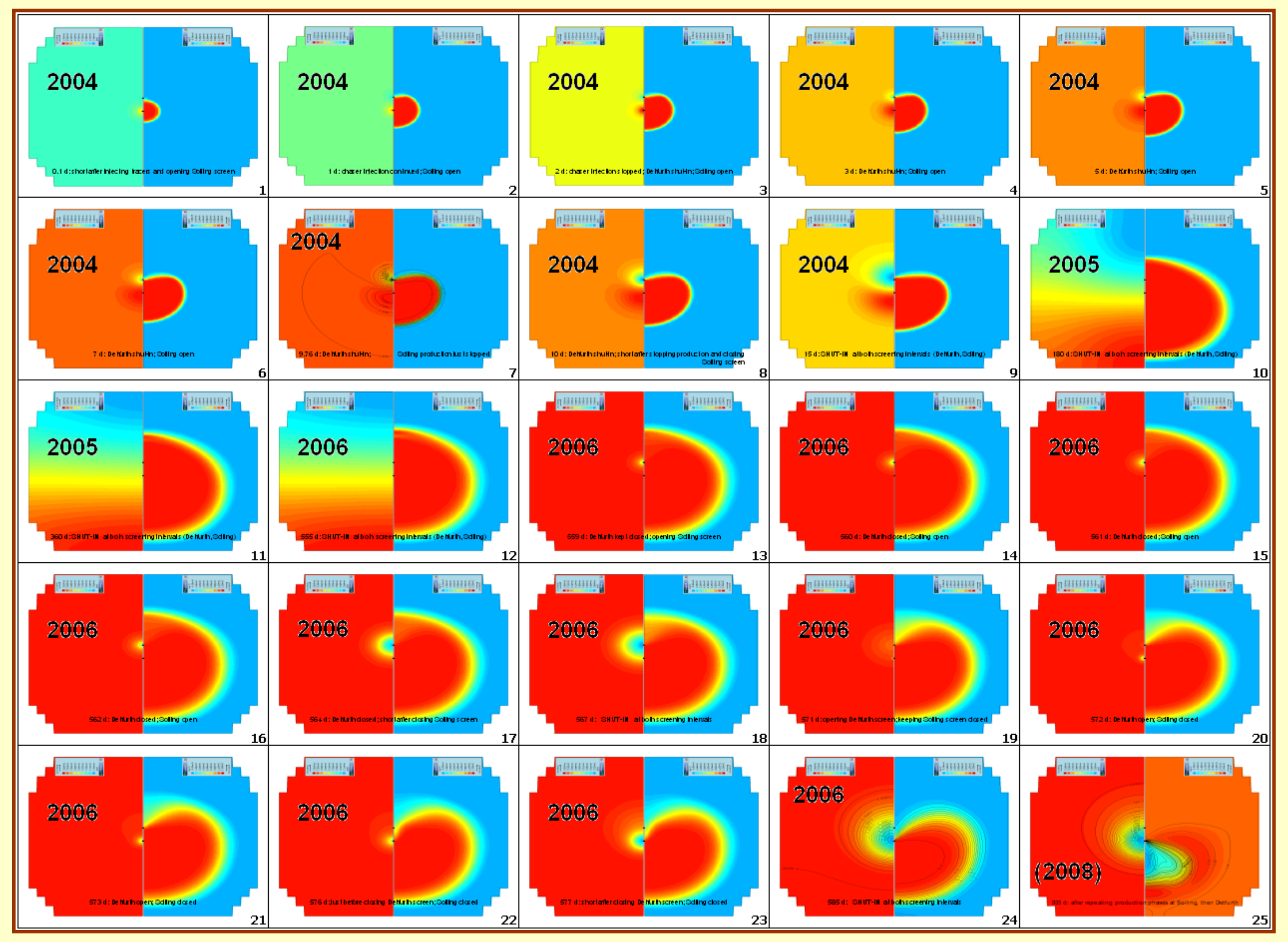


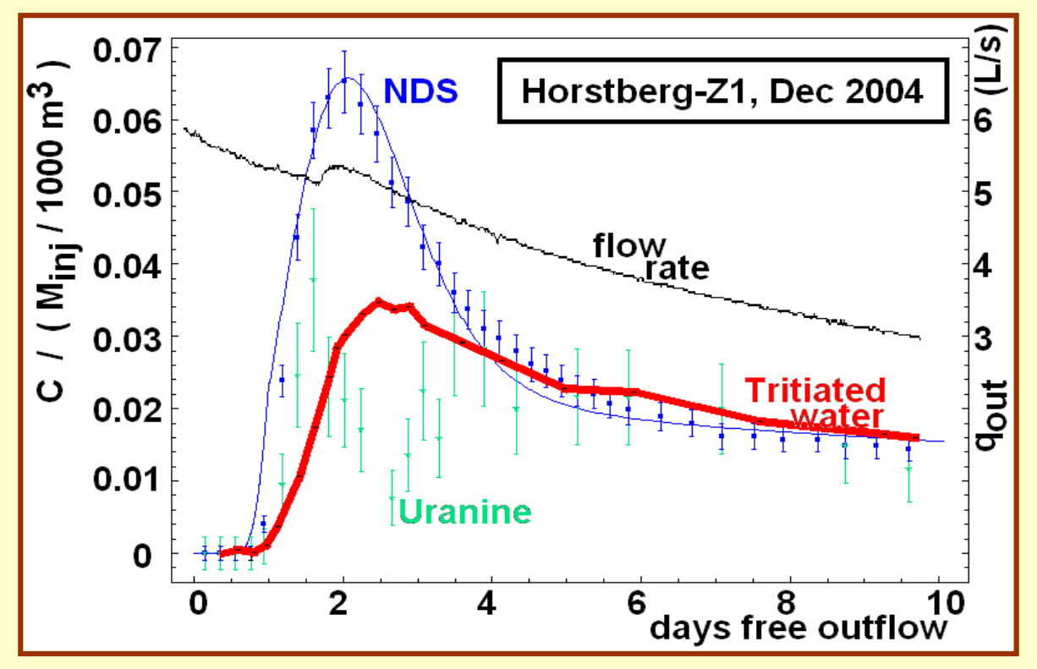


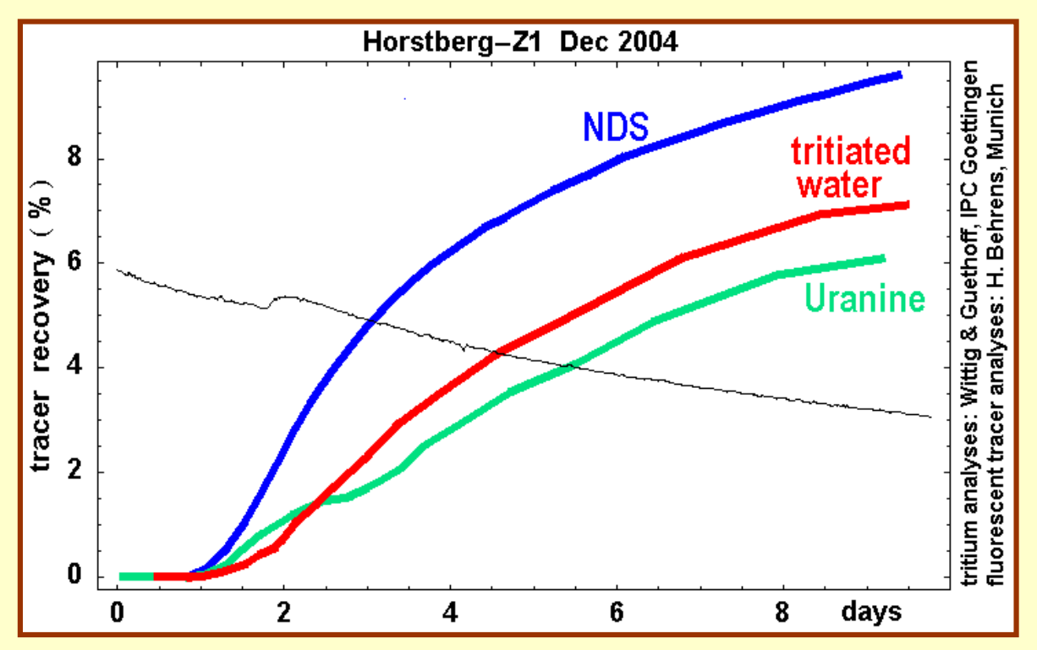
Schematic representation of the single-well, two-layer circulation scheme and of the flow-path tracing conducted in hydraulically-induced fault; 2004: injection into Detfurth horizon, production from Solling horizon; 2006: production from Solling, followed by production from Detfurth. Time sequence shows evolution of pressure (left half) and tracer concentration (right half) fields in a 2-D hydrofrac projection (idealized picture).

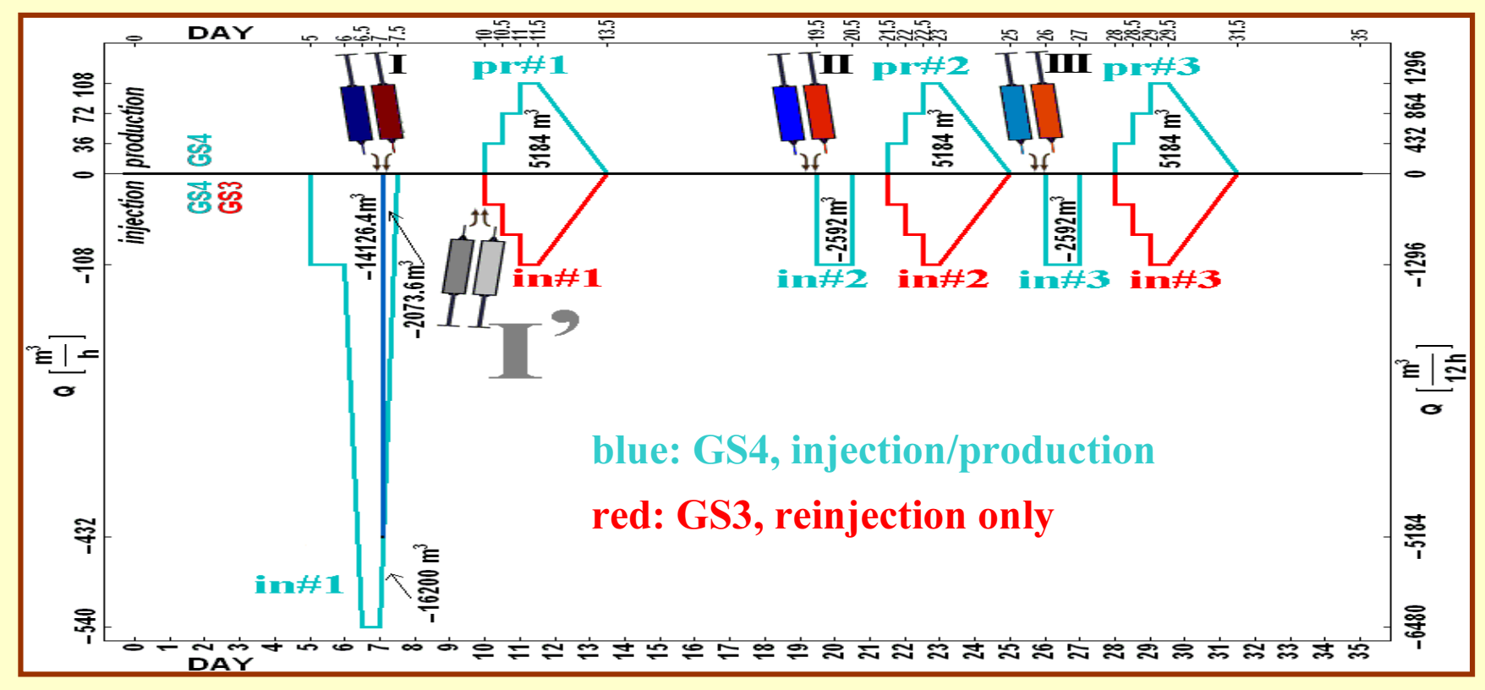










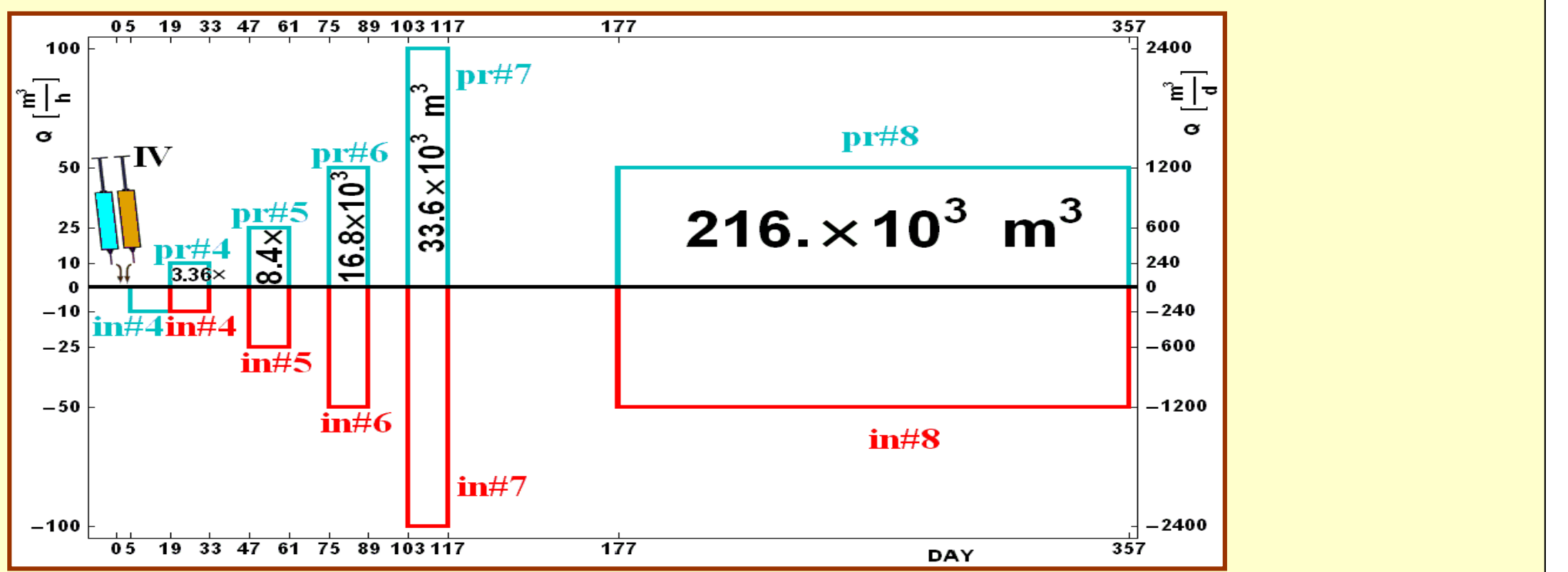


GroßSchönebeck

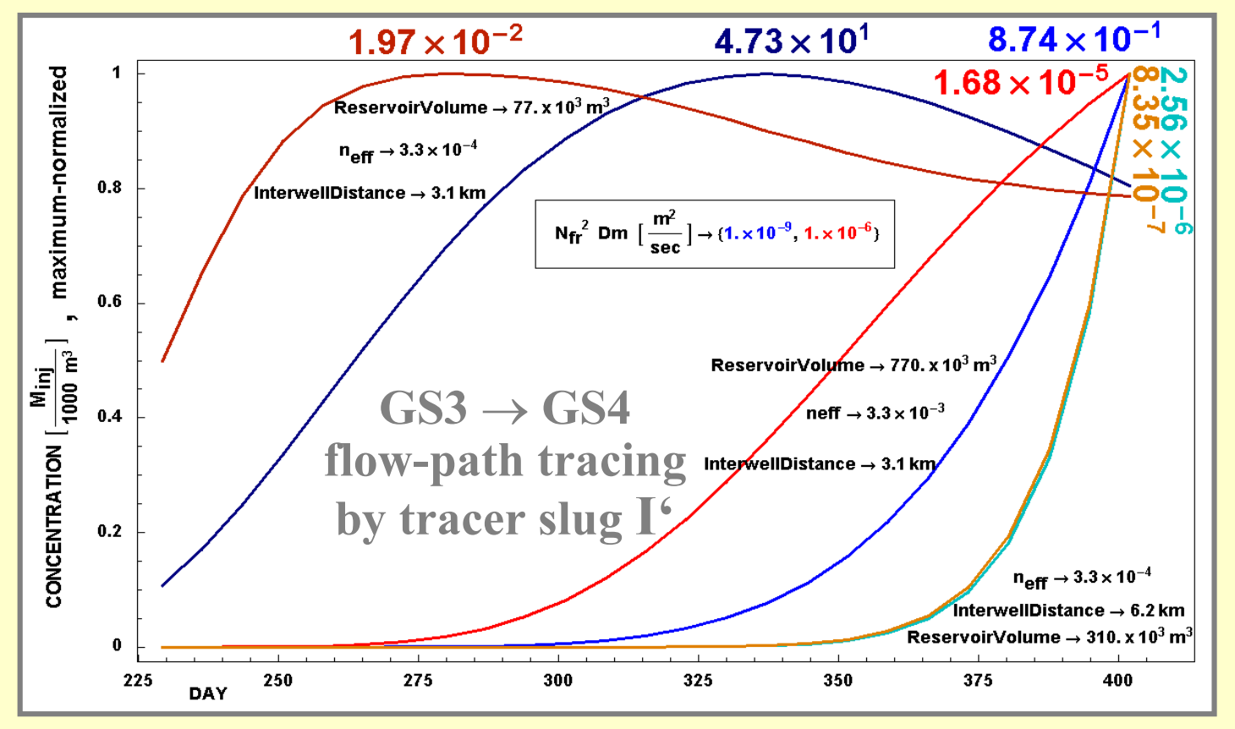
In-situ Geothermal Laboratory

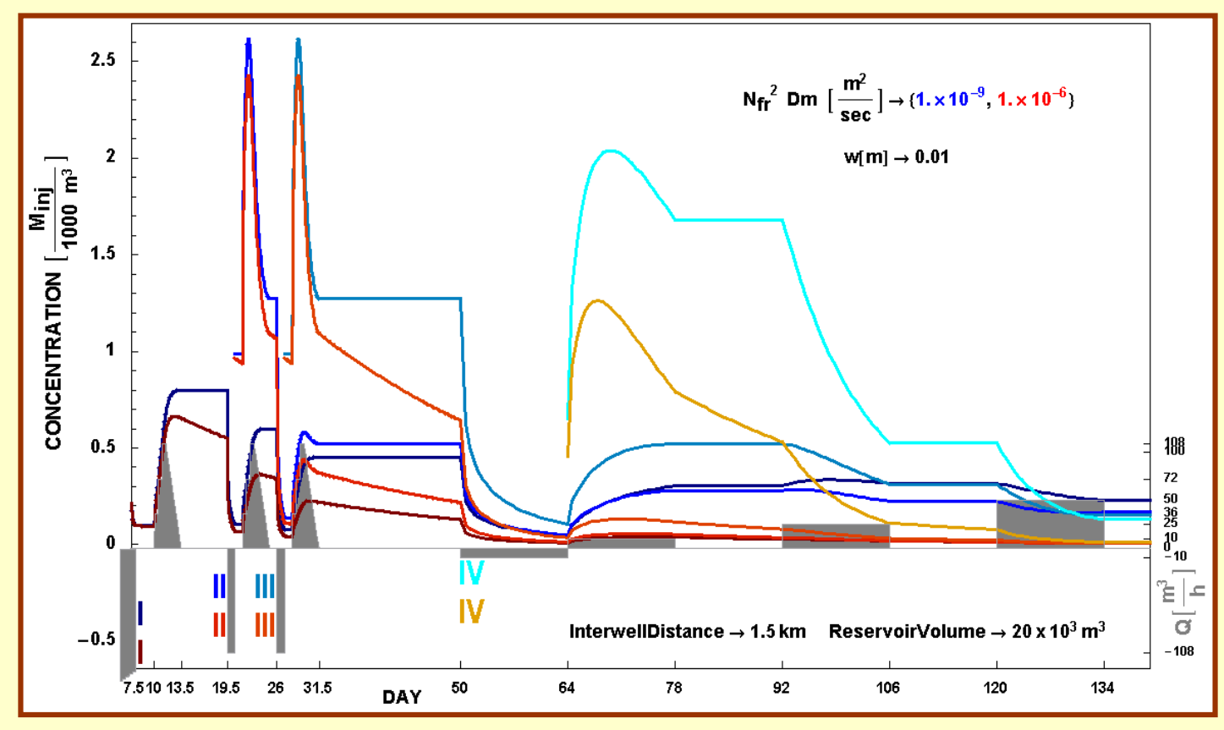
Sub-salinary geothermics demonstration project, GFZ Potsdam

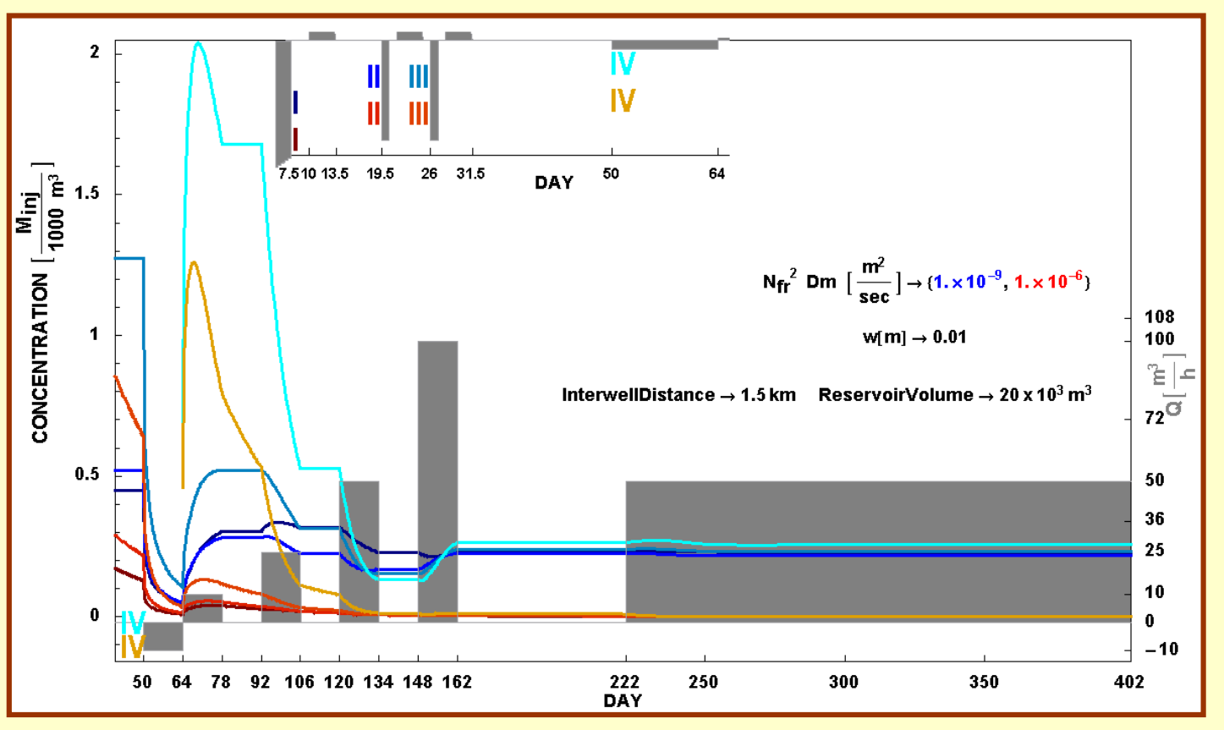
– new test program as of 2007



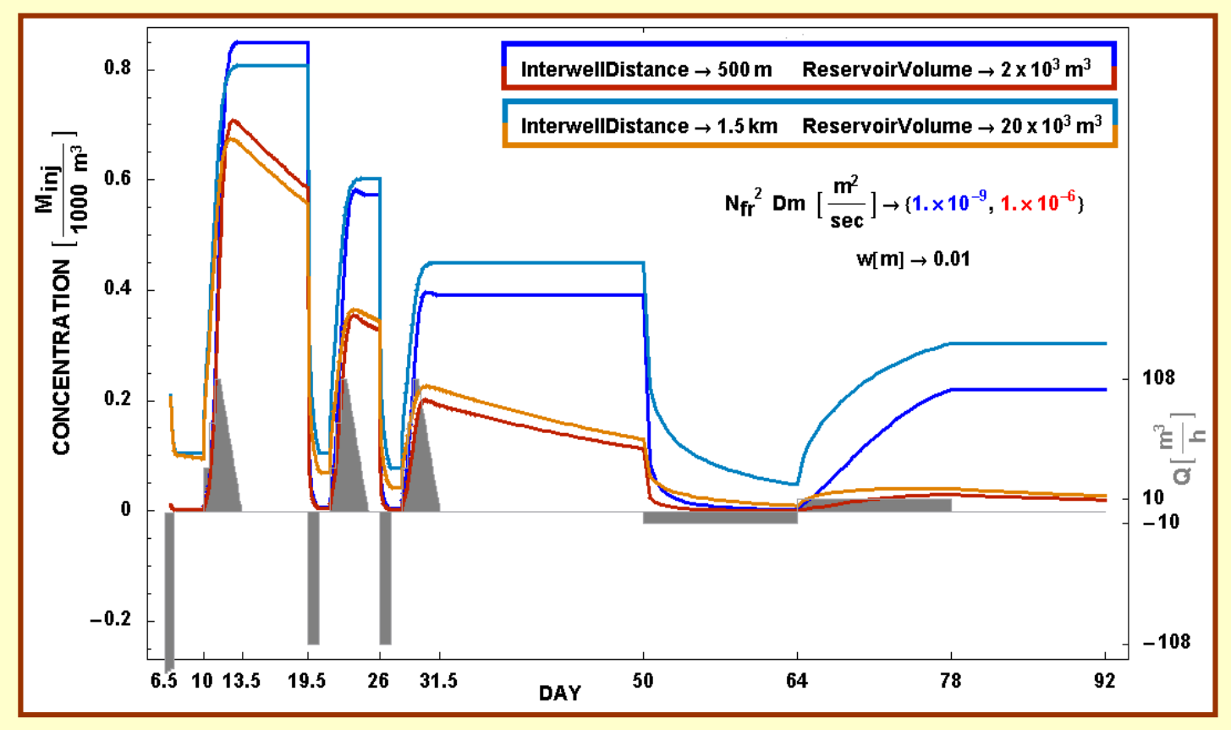
Our task: design and dimension 4 + 1 spikings at the boreholes GS4 + GS3 such that each individual spiking yields measurable signals during each of the subsequent outflow or abstraction phases (GS4 = new borehole, used for faulting, injectivity and sequential flow-back tests, 4 spikings; GS3 = old borehole, used for fluid disposal, i.e. reinjection, 1 spiking)

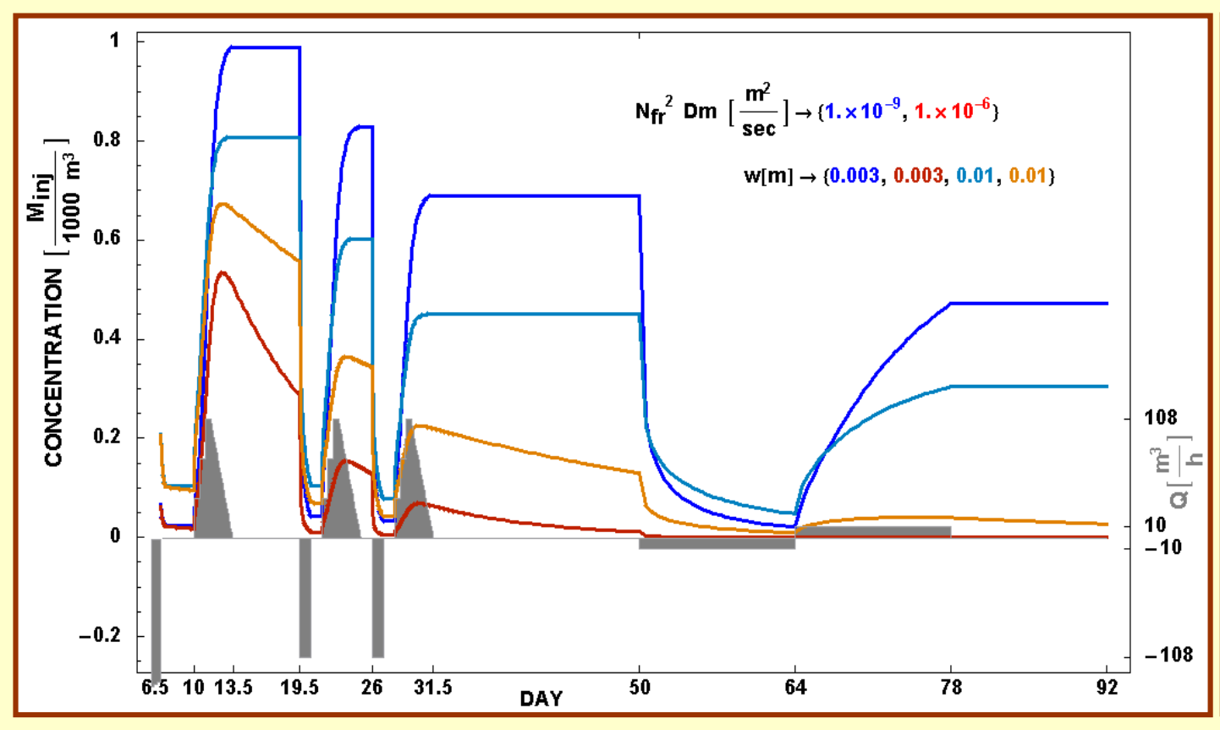


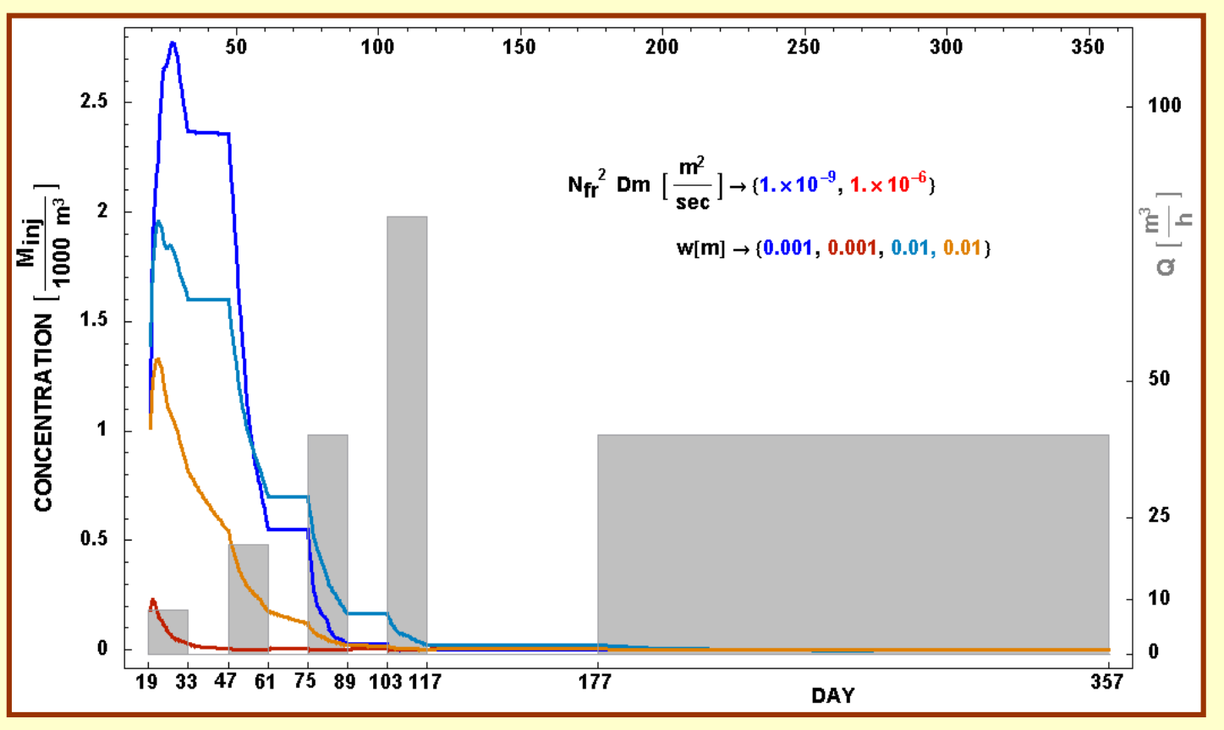




forward simulations and sensitivity analyses, based on simplified, radially-symmetric fault model – to assist in dimensioning the tracer tests







Tracer signals from flow-back (push-pull) tests at GS4 are more sensitive to effective aperture and specific contact-surface area (within the volume accessed by each test phase), than to total reservoir size. Tracer signals at GS4 originating from reinjection spiking at GS3 are very sensitive to reservoir size, and also to surface/exchange parameters.

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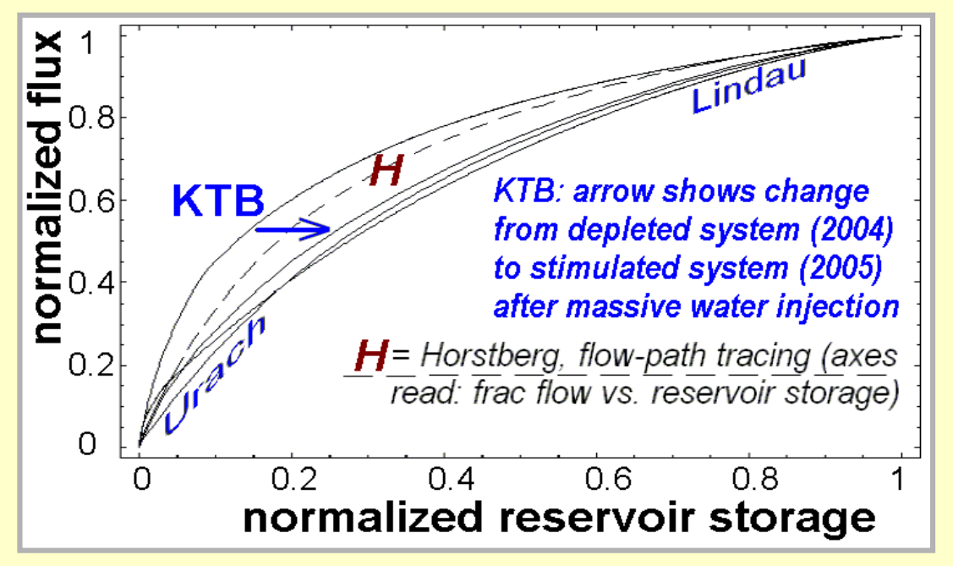

KTB: arrow shows change from depleted system (2004) to stimulated system (2005) after massive water injection
H= Horstberg, flow-path tracing (axes read: frac flow vs. reservoir storage)

Flux-capacity analyses indicate what percentage of reservoir flow (if derived from flow-path tracings), or what percentage of solute or heat exchange (if derived from push-pull tests) takes place in a given fraction of the total reservoir storage, in the form of a cumulative repartition function, sorted by fluid residence times. This type of analysis (being well-known from reservoir hydraulics) was first applied for interpreting tracer tests in geothermal systems in the USA by Mike Shook (2003).

more details on tracer tests conducted by the Göttingen Applied Geology Group can be found under:
www.cosis.net/abstracts/EGU06/02402/EGU06-J-02402-1.pdf
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