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

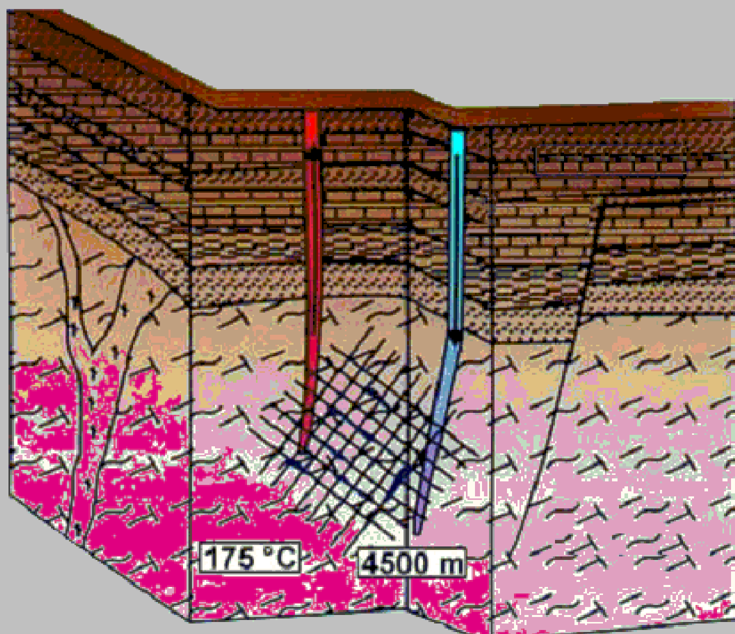
University of Göttingen, Applied Geology Group

in co-operation with

GGA and BGR Hannover , GFZ Potsdam

tracer tests provide:

- fluid residence time (reservoir size)
- heat exchange surface area

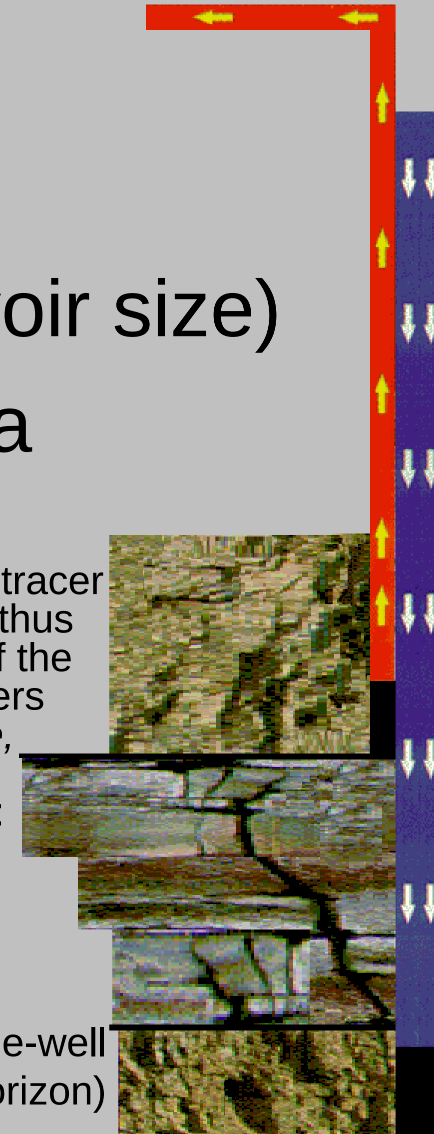


the principles of tracer transport, and thus the meaning of the two parameters is the *same, whichever* the setting:

inter-well,

or

single-well (inter-horizon)

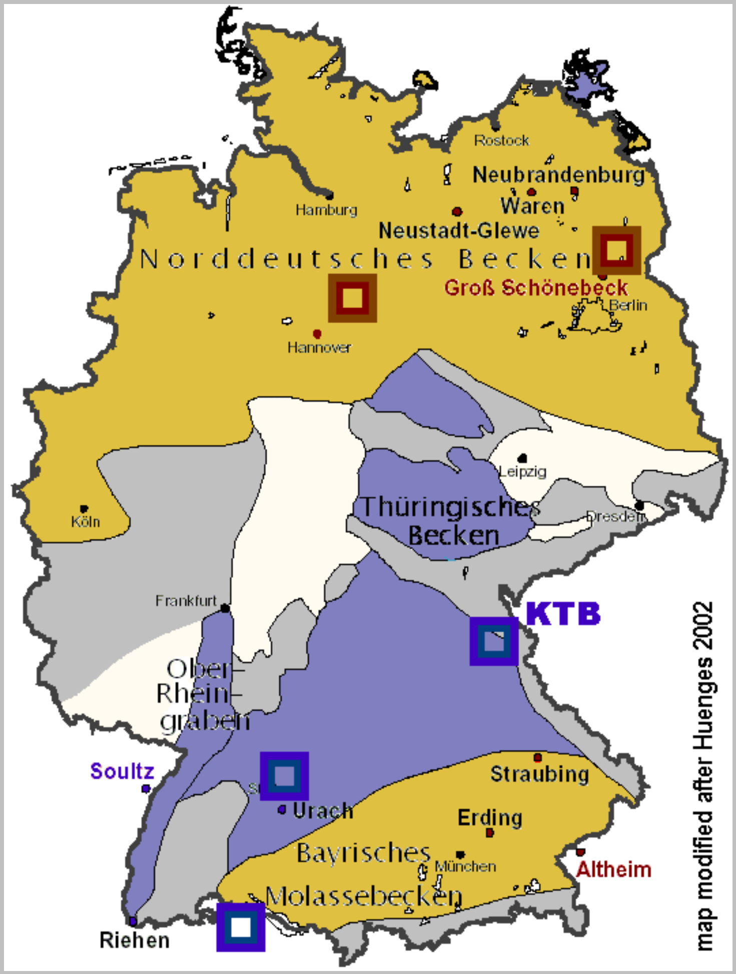


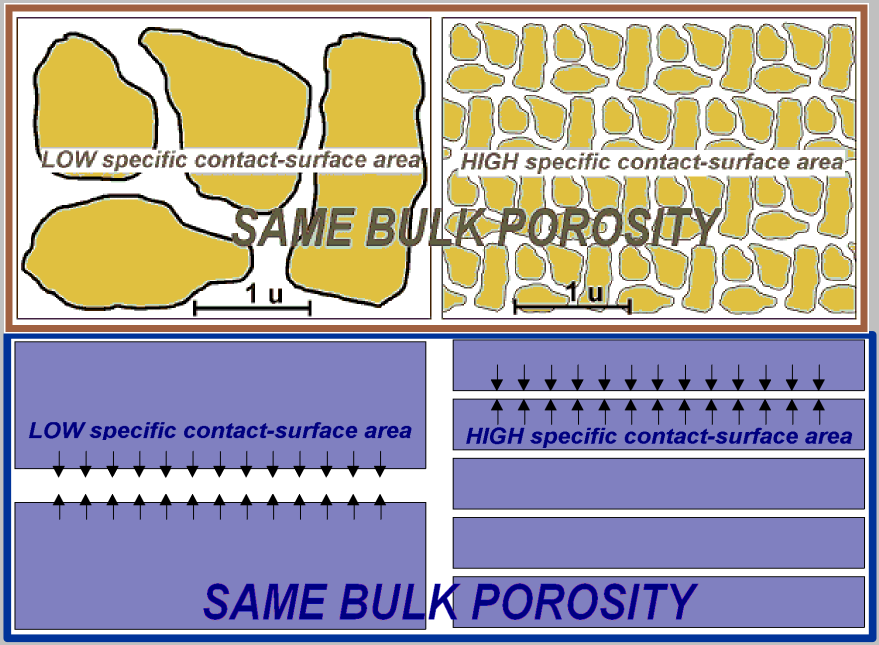
first an overview
of tracer applications of different kinds,
conducted in several types of deep reservoirs

- Lindau 2003 ('playground' site, not a geothermal reservoir)
- Urach 2003
- KTB 2004, 2005, 2006
- Horstberg 2004, 2006
- in preparation: GroßSchönebeck, as of 2007

overview: deep-reservoir types

crystalline / sedimentary, supra- / sub-saline



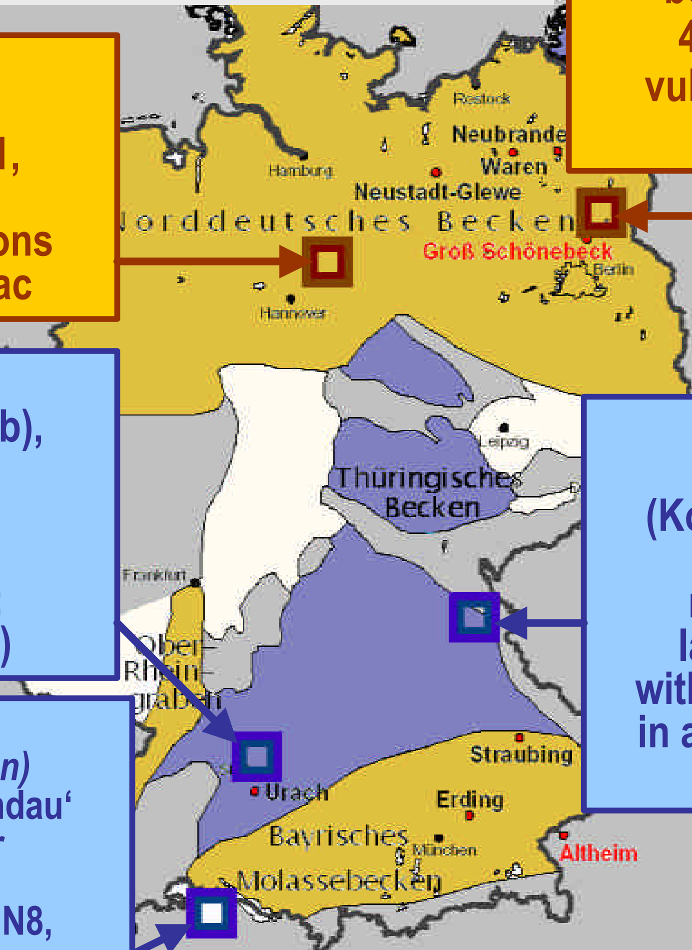


- long-term scope testing (> 1 y)
- key to evaluation: contact-surface area changes

overview: tracer test sites

Sedimentary
BGR/GGA Hannover
borehole Horstberg-Z1,
4 km deep,
clayey sandstone horizons
connected by hydro-frac

Sedimentary
GFZ, Groß Schönebeck,
boreholes GS-3 and GS-4,
4 km deep, hydro-frac in
vulcanites (propagating into
sandstone horizons)

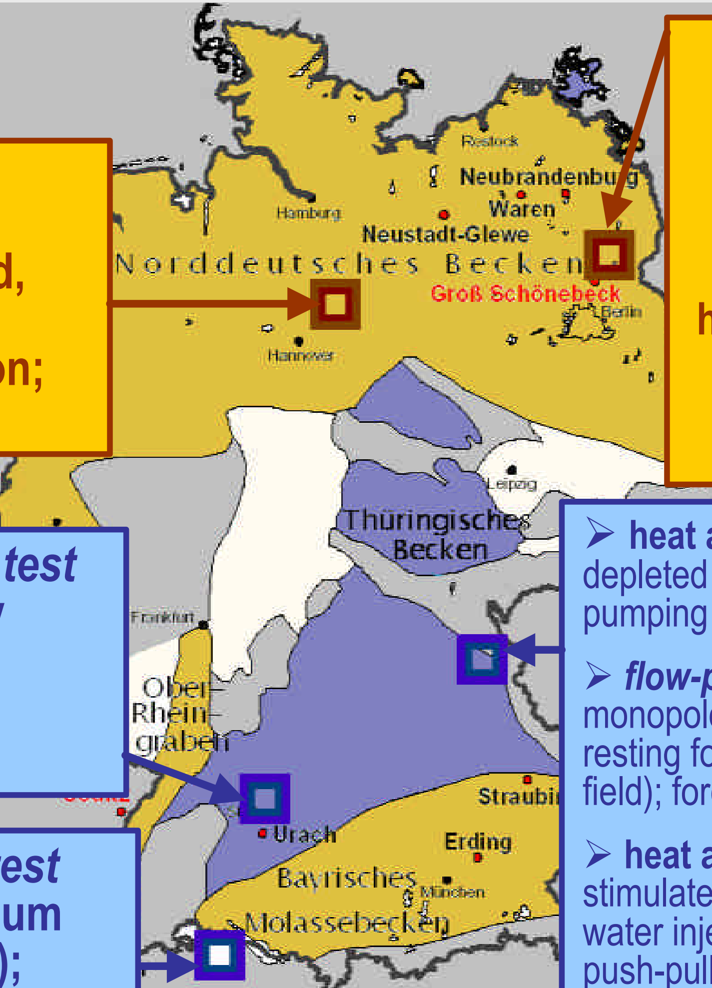


Deep Crystalline
Bad Urach (Swabian Alb),
borehole Urach-3,
4.4 km deep,
several fracture
systems below 3 km;
HDR type (stimulated)

Deep Crystalline
KTB
(Kontinentale Tiefbohrung),
pilot hole (4 km deep),
main hole (9 km deep),
large-scale fault system
with highly-permeable zones
in about 5, 7, 9 (?) km depth;
HDR type (stimulated)

Crystalline
(shallow granite formation)
University of Karlsruhe: ‘Lindau‘
underground facility for
fractured-rock testing
(S Black Forest), borehole N8,
highly-permeable fault zone,
hydrothermally altered

overview: tracer test types



flow-path tracing
monopole,
divergent flow field,
directly upon
hydrofrac generation;
free outflow

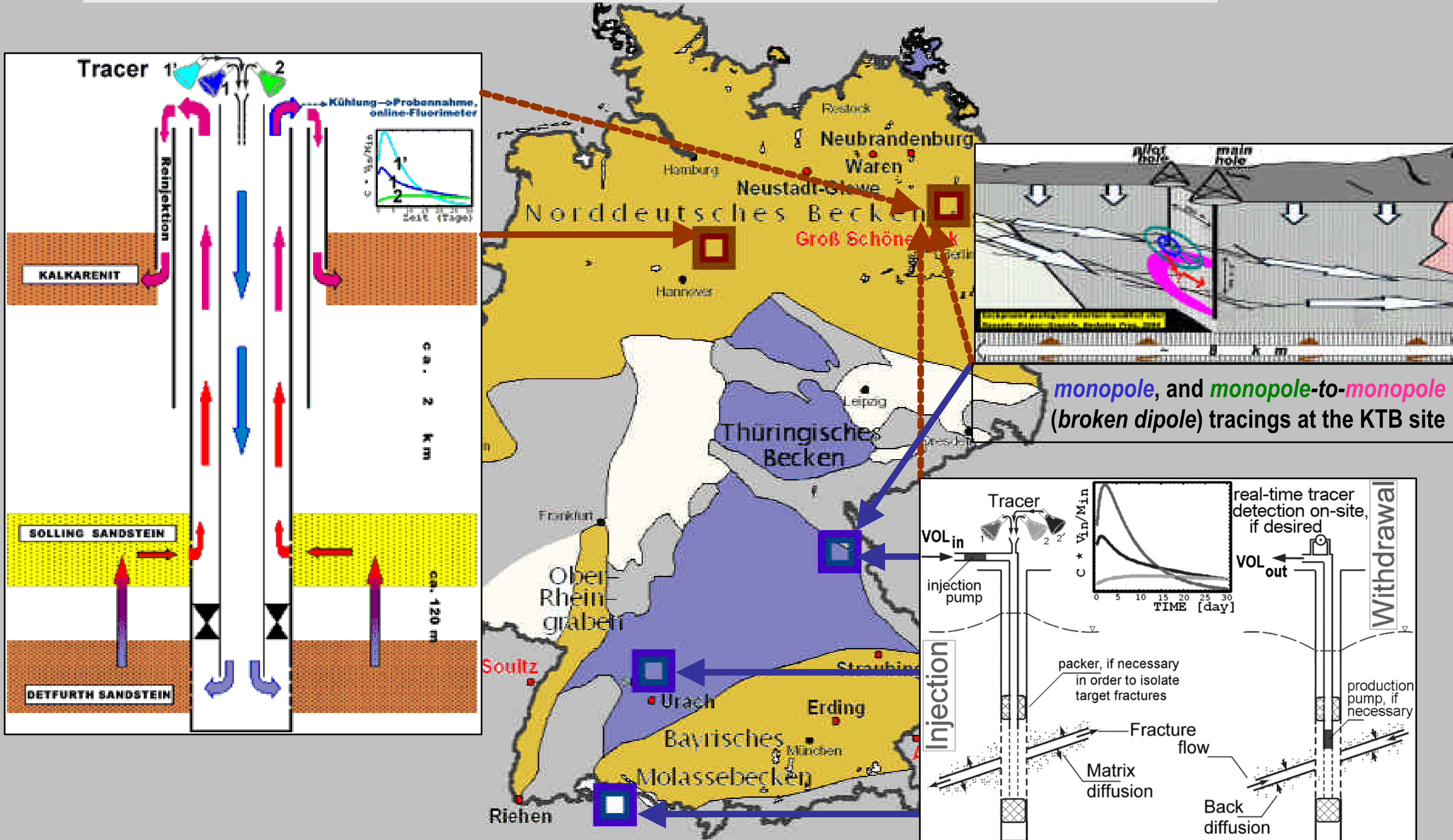
complex test sequence:
7 push-pull tests and flow-path tracings (vertical or horizontal connection) within hydraulic test sequence (frac tests, flow-back tests and long-term pumping test)

tracer push-pull test
(preceded by moderate stimulation);
free outflow

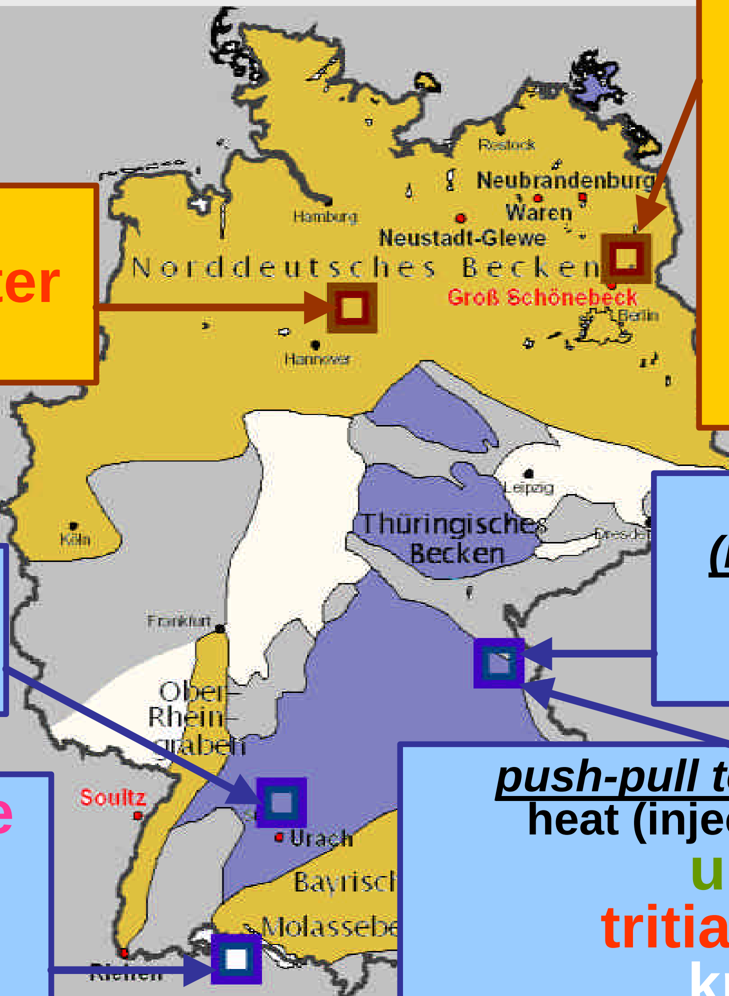
tracer push-pull test
(in quasi-equilibrium formation state);
free outflow

- **heat and solute tracer *push-pull*** in depleted system (following long-term pumping test); forced outflow (2004)
- ***flow-path* tracing** (monopole / monopole, first divergent flow field, then resting for >1 year, then convergent flow field); forced outflow (slug injected 2005)
- **heat and solute tracer *push-pull*** in stimulated system (after massive cold-water injection) — with superpo-sition of push-pull signals from both tracer slugs; free outflow (2005)

overview: tracer test design



overview: tracers used



(final selection pending)
tritiated water,
inert gases,
naphthalene-sulfonic,
further tracer candidates under evaluation

uranine
tritiated water
NDS

***flow-path tracing (injected as of 2005)*:**
uranine
NDS

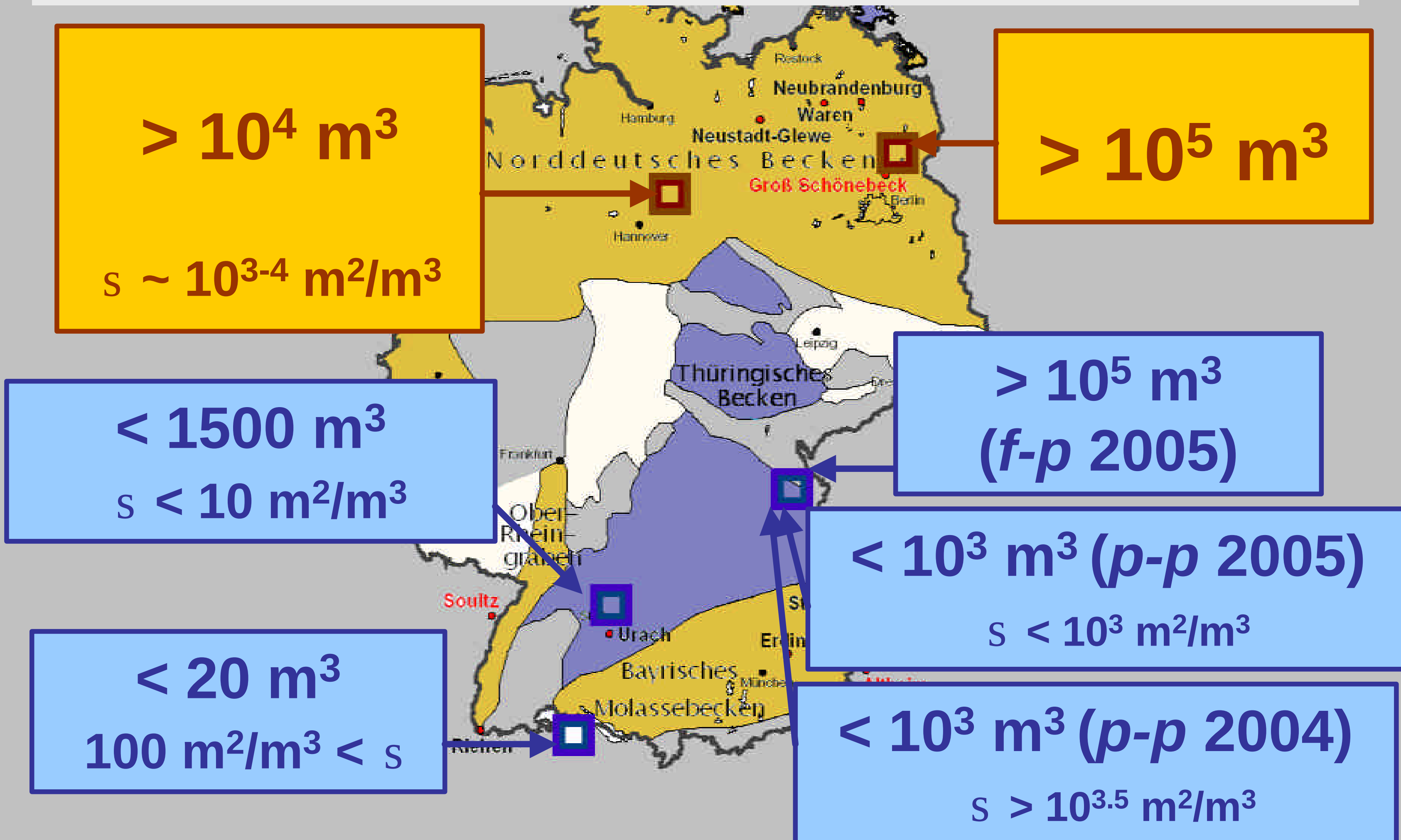
uranine
NDS

***push-pull tests (2004, 2005)*:**
heat (injected cold water)
uranine
tritiated water
krypton
NDS, PTS

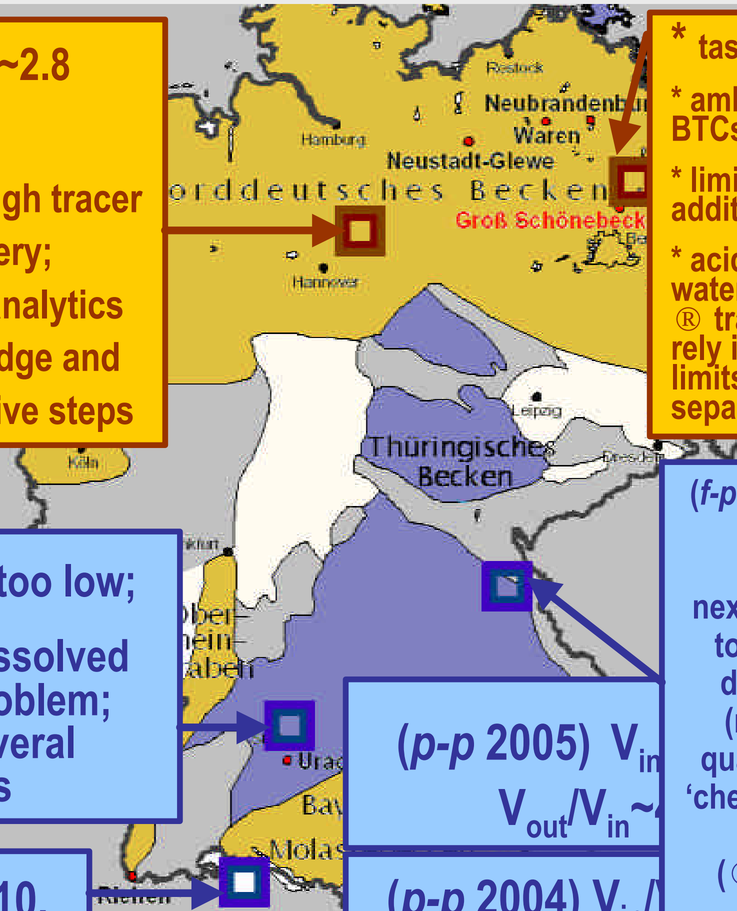
naphthionate
Lithium
uranine
Bromide
NDS

overview: formation scale, S (m²/m³)

(as captured by these tests)



overview: drawbacks with test design / failures in test execution



V_{in}/V_b~14 , V_{out}/V_{in}~2.8
almost ok;

divergent flow field ® high tracer dilution, low recovery;
high salinity ® tracer analytics requires expert knowledge and work-intensive preparative steps

* task complexity is a problem in itself
* ambiguous resolution of overlapping BTCs‘
* limited no. of tracers available ® additional constraints on test design
* acid-conditioning of injected fresh-water, high salinity of formation fluids ® tracer analytics may become seve-rely impaired (increased detection limits, reduced accuracy, difficult separation)

V_{in}/V_b~1.5 , V_{out}/V_{in}~3.2 too low;

tracer incompletely dissolved ® BTC calibration problem;
bulk signal from several fracture systems

V_{in}/V_b~5 , V_{out}/V_{in}~10,
packer failure

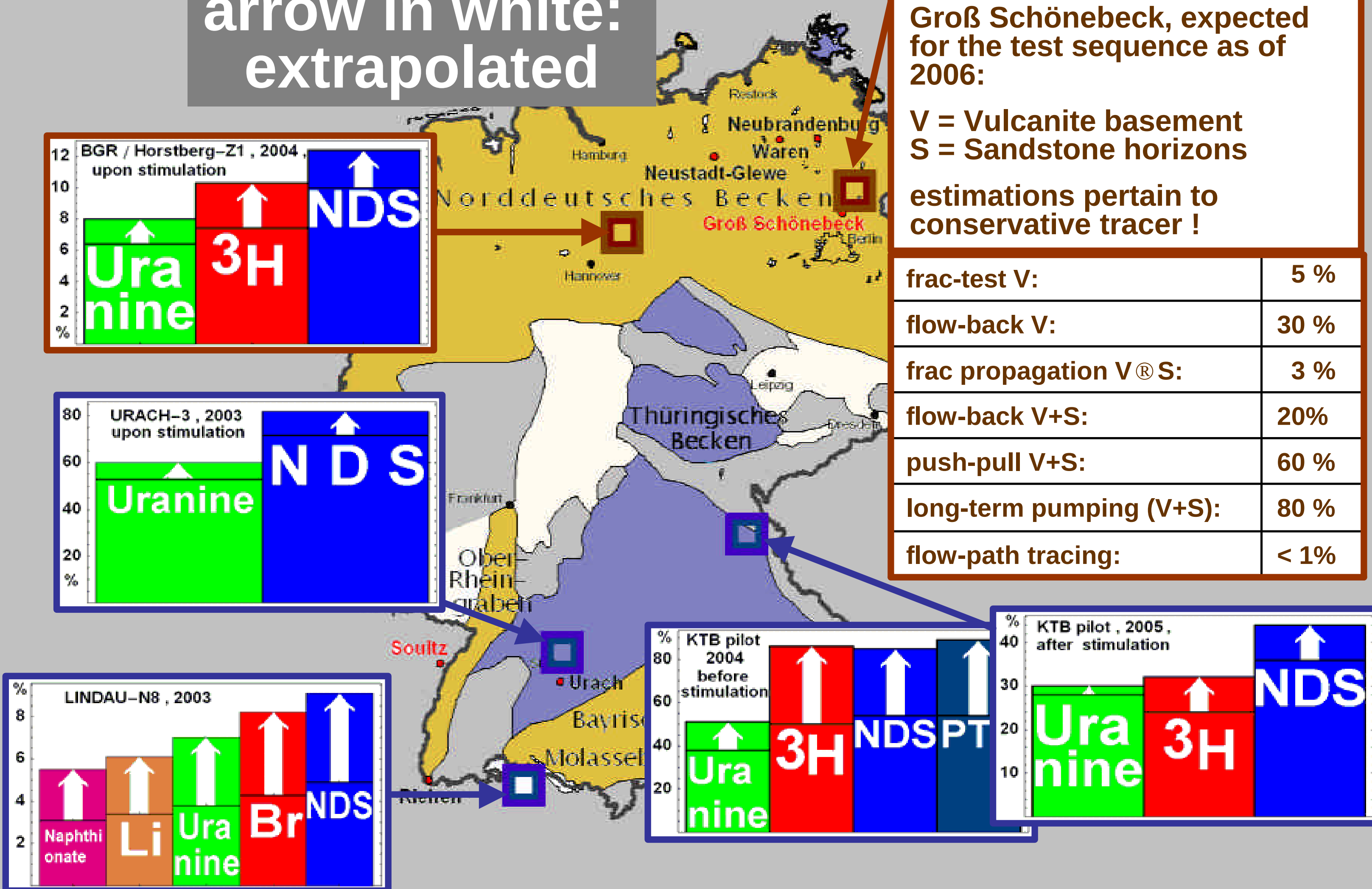
(*p-p* 2005) V_{in}
V_{out}/V_{in}~

(*p-p* 2004) V_{in}/
both

(*f-p* 2005-2007) test design imposed by project financing schedule: first divergent flow from pilot hole, next >1y resting, then convergent flow to main hole ® unnecessarily high dilution of tracers in the formation (requiring injection of huge tracer quantities, which prohibits the use of ‘chemically inert’ tracers like HTO), and long in-situ residence times (® increased risk of tracer loss by thermal decay);
V_{in} / V_B was large enough, but
V_{out} / V_{in} is likely to be insufficient

overview: tracer recoveries

arrow in white: extrapolated



Groß Schönebeck, expected for the test sequence as of 2006:

V = Vulcanite basement
S = Sandstone horizons

estimations pertain to conservative tracer !

frac-test V:	5 %
flow-back V:	30 %
frac propagation V ® S:	3 %
flow-back V+S:	20%
push-pull V+S:	60 %
long-term pumping (V+S):	80 %
flow-path tracing:	< 1%

approaches to test interpretation:

– flux–capacity analyses (normalized, cumulative RT distributions)
– integro-differential formulation for matrix diffusion(–type) problems,
– (attempting to convert hybrid features into distributed parameters, whenever possible)
– response function approaches,
– asymptotic approximations,
– in combination* with discretizing methods

* with a certain preference for approaches not heavily relying on site-specific information (*Stichwort: “Übertragbarkeit“*)

now, a selection of these tests presented in more detail

– Lindau 2003

– Urach 2003

– KTB 2004, 2005, 2006

– Horstberg 2004, 2006

– in preparation: GroßSchönebeck, ab 2007

KTB (the German site of ICDP)

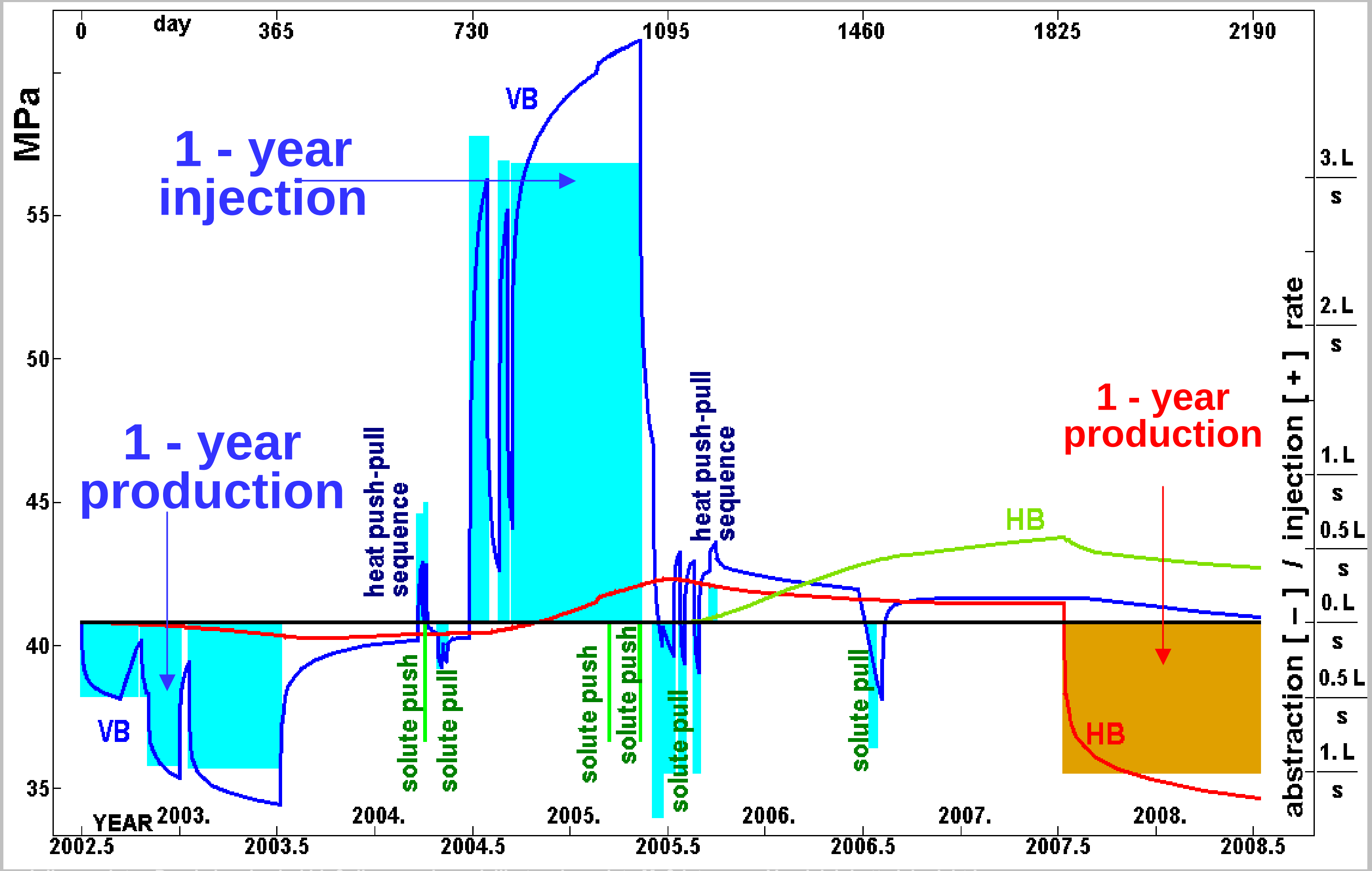
At the KTB site, two boreholes are available:

- **PILOT** borehole ‘VB‘ (with tests conducted so far shown in **CYAN/BLUE**), and
- **MAIN** borehole ‘HB‘ (with planned tests shown in **ORANGE/RED**).

Solute & heat push-pull tests were conducted in

- ***the depleted***
- ***the stimulated***
- ***the post-stimulation (still weakly pressurized) state***

tests conducted at the KTB pilot hole (VB) and planned at the main hole (HB)

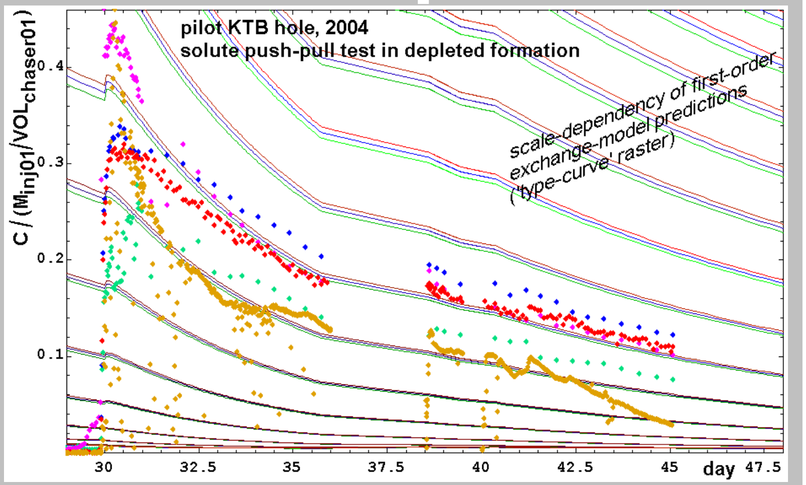


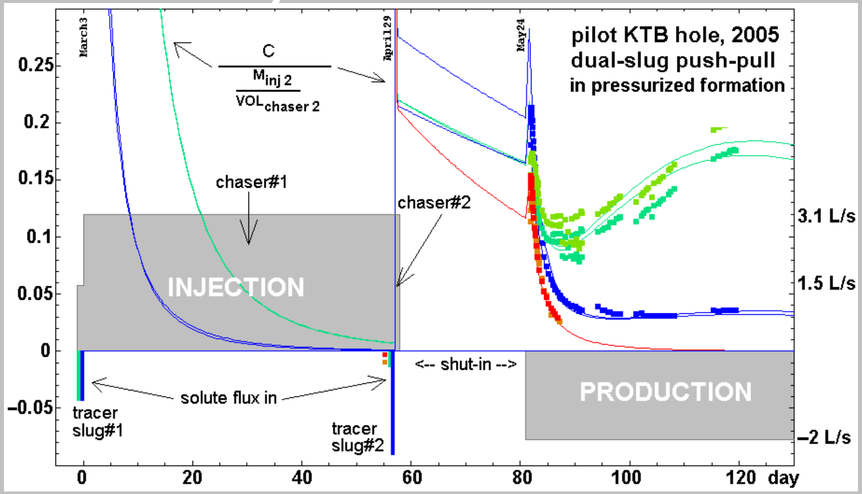
! die gezeigten Drucksignale sind bloß die von mir modellierten, komplette Meßdaten zum Vergleich hatte ich nicht !

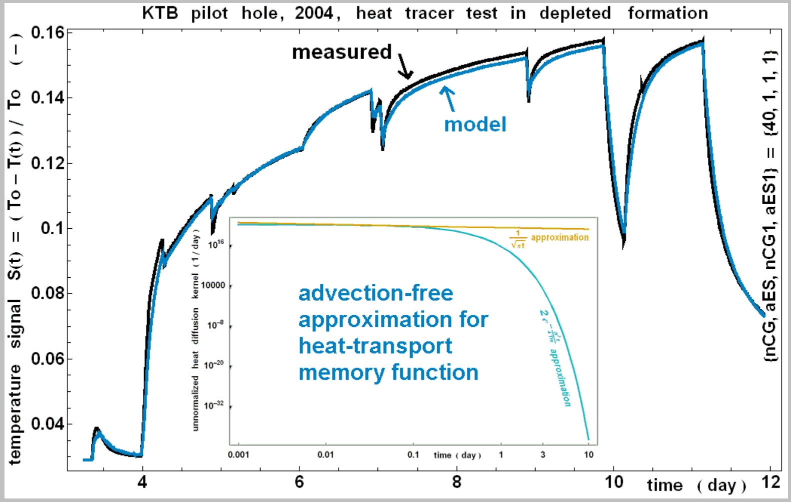
KTB pilot hole: heat and solute push-pull signals
(parallel-fracture, radial model fit, versus measured)

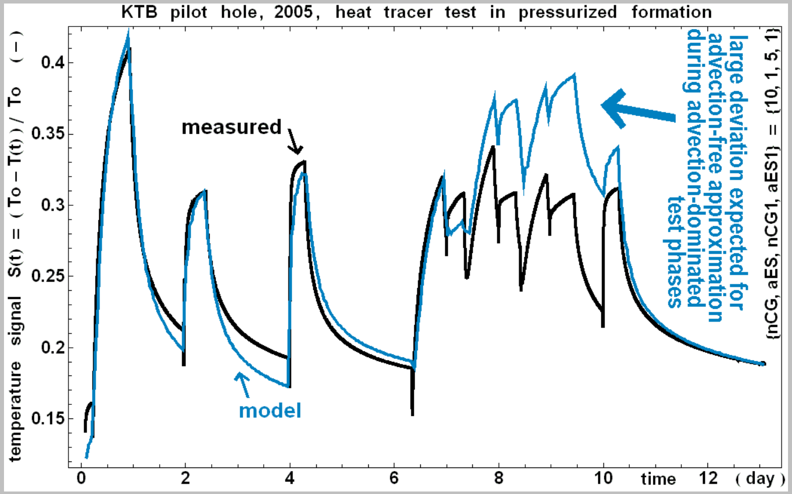
2004, depleted

2005, stimulated

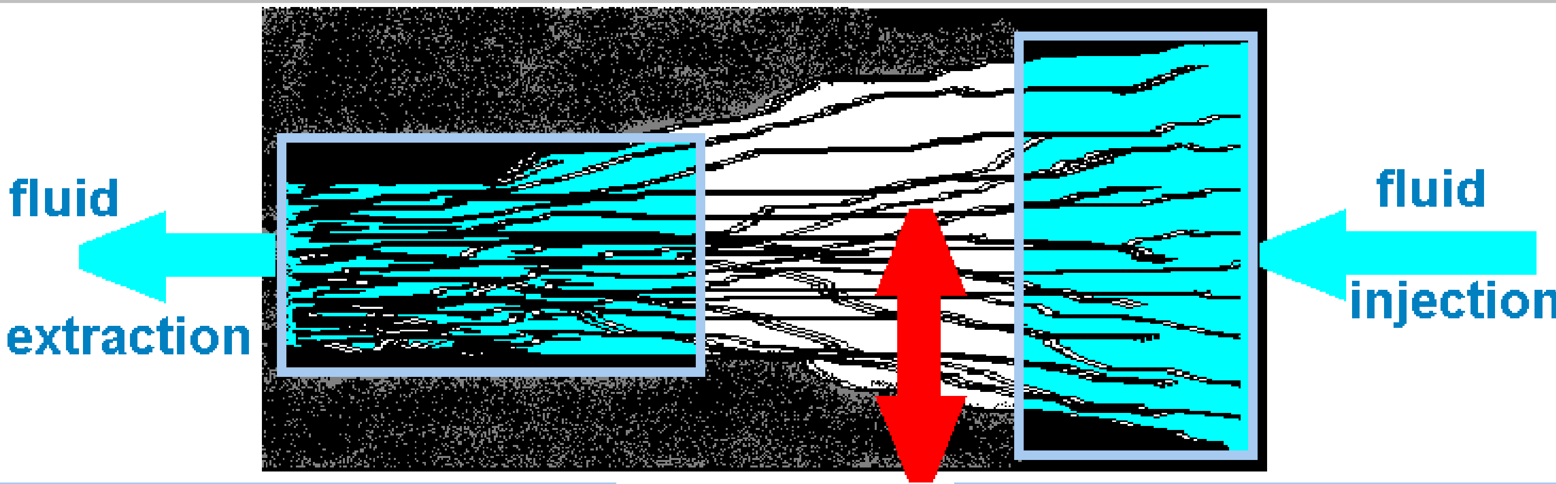








KTB push-pull tests: interpretation?



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

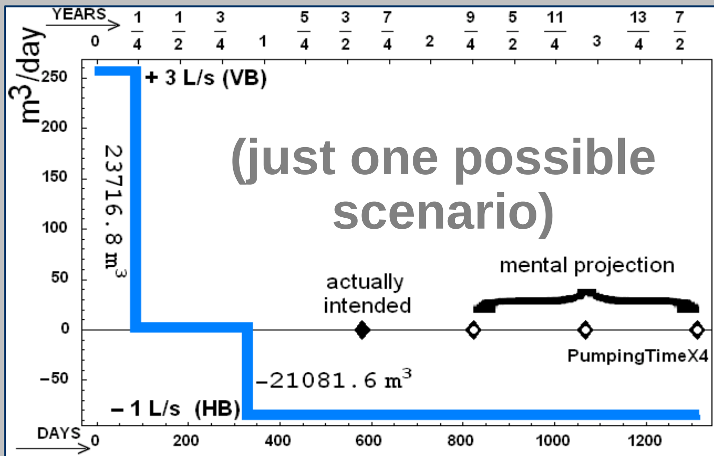
(the diagram was meant to be self-explaining)

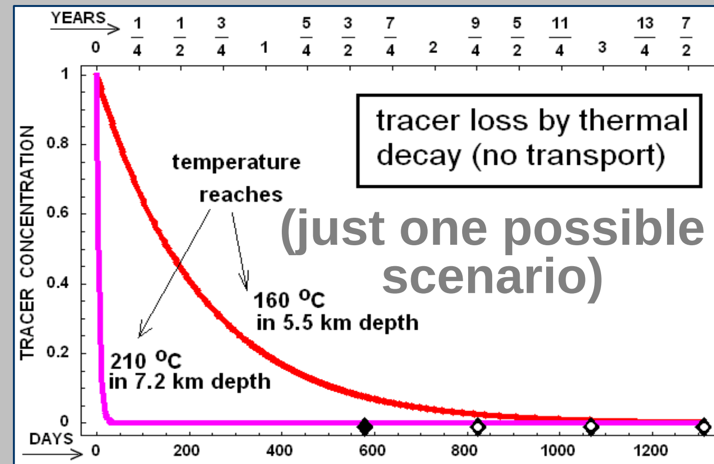
- Depletion *lowers* the apertures, and *increases* the spf. fracture area
- Stimulation *increases* the apertures, and *lowers* the spf. fracture area

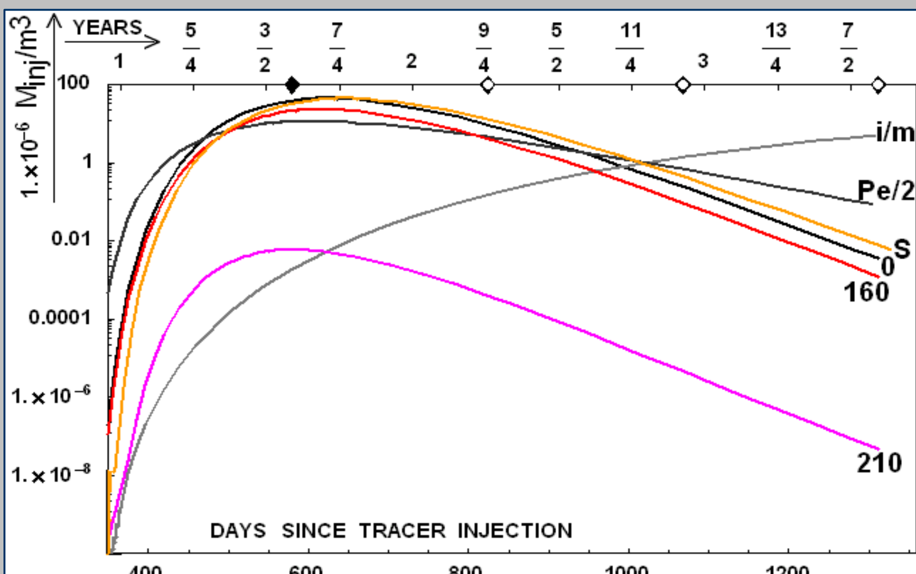
which implies that the *prevailing effect* of this massive fluid injection was to enlarge pre-existing fractures, rather than creating new ones

realize that since heat diffusivity exceeds solute diffusivities by >3 magnit.orders, temperature signals will always reflect a larger scale, complementary to the scale seen by the solute tracers

KTB, predictions for the flow-path tracing
pilot hole ----- main hole







0: conservative solute tracer (thermally-stable, no exchange with immobile phases), Pe = 100

Pe/2: doubled dispersivity (Pe = 50)

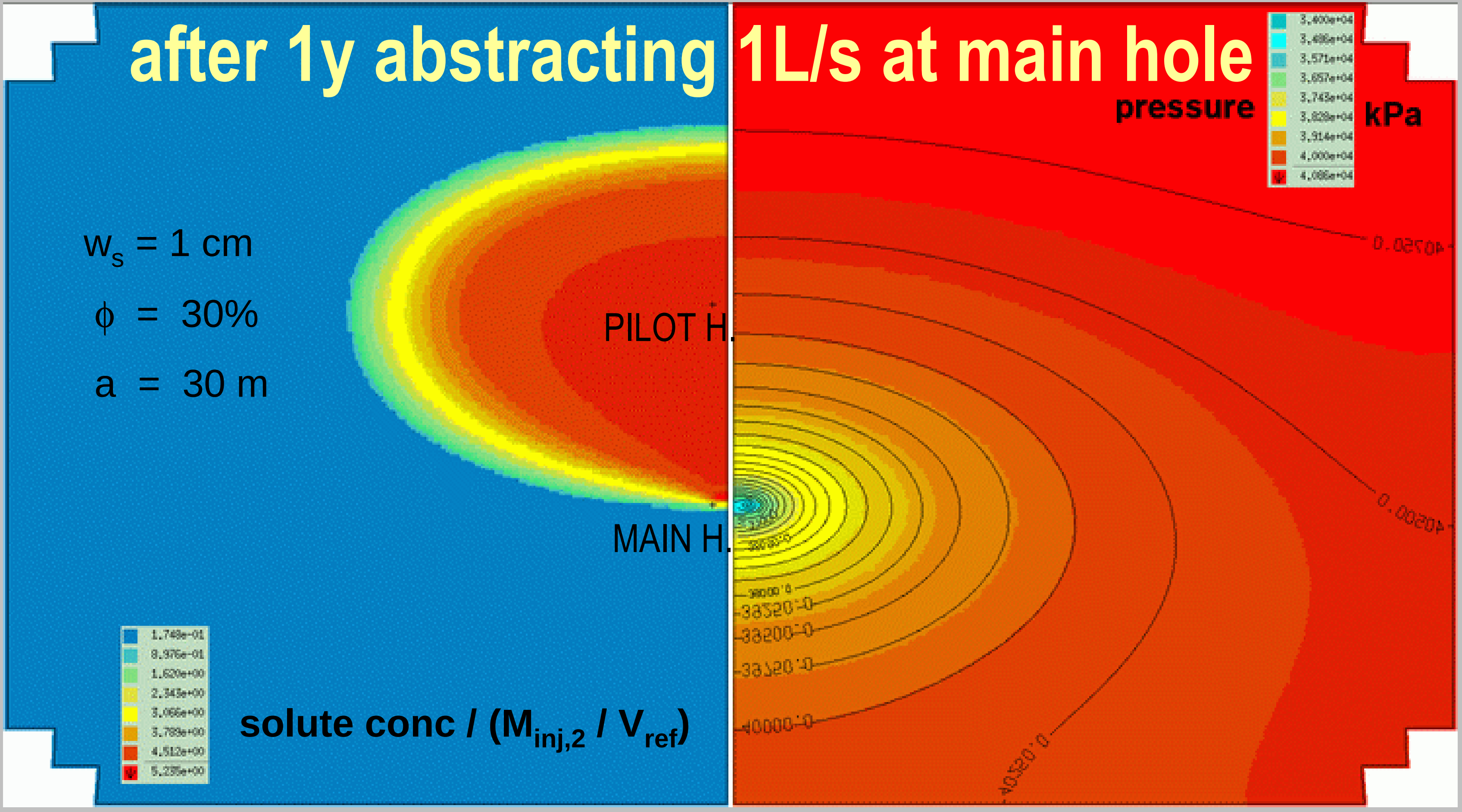
i/m: thermally-stable solute tracer, some exchange with immobile phases (K1=0.1d-1, K2=K1/2), Pe = 100

160: thermosensitive solute tracer, Pe = 100 temperature reaches 160 °C (in 5.5 km depth)

210: thermosensitive solute tracer, Pe = 100 temperature reaches 210 °C (in 7.2 km depth)

S: conservative solute tracer (thermally-stable, no exchange with immobile phases), return signal of a long-term push-pull test at the main hole, Pe = any (not a flow path tracing!)

KTB, prediction for the flow-path tracing pilot hole ----- main hole



Geothermics demonstration project *GenESys*: test at the Horstberg site

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 ~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.

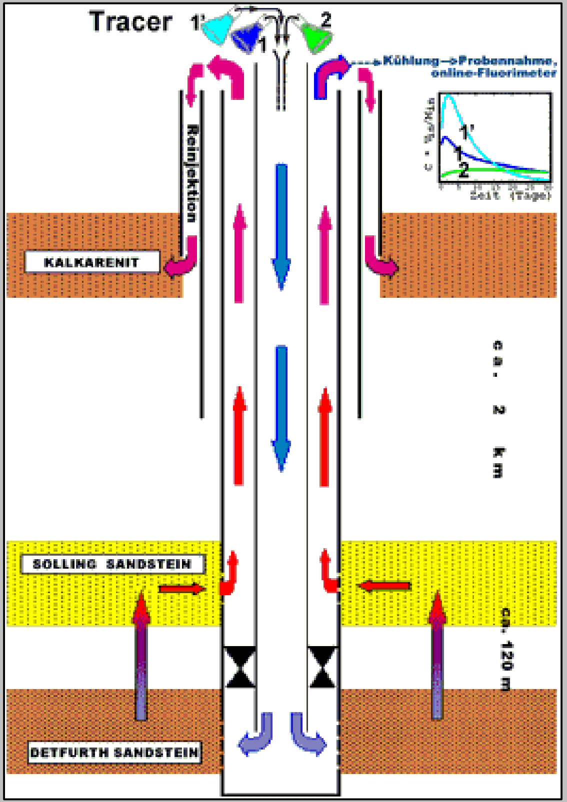
In order to better characterize the flow field in the induced fault, a tracer test was conducted.

Horstberg

schematic representation of the single-well, two-layer circulation scheme designed by Orzol, Jung, Junker (GGA)

and of the
flow-path tracing
conducted
in the induced fault

the hydro-frac in low-permeable clayey sandstone formation connects two better-permeable sandstone horizons

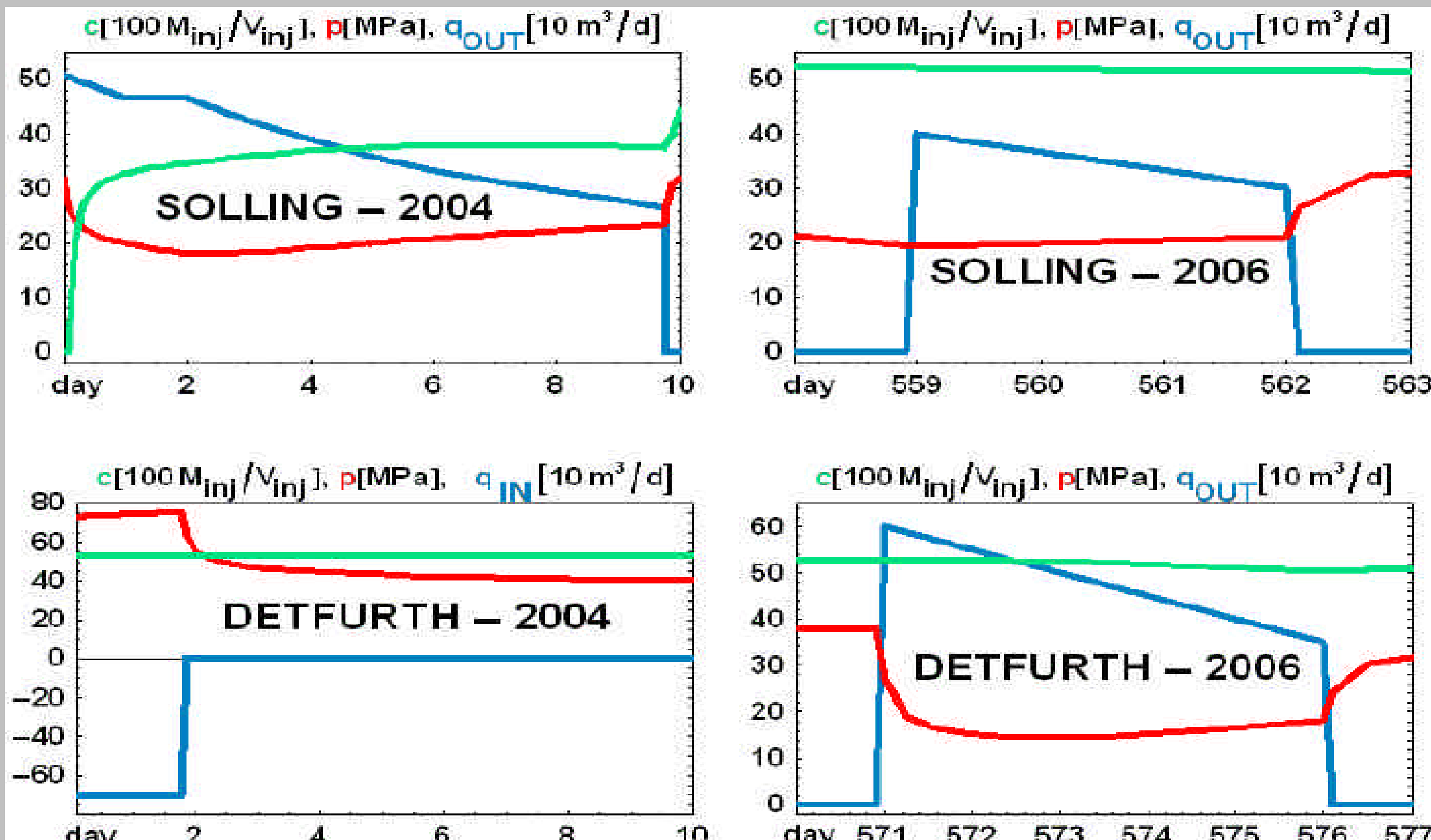


Horstberg

principle evolution of pressure and tracer concentration during the distinct test phases (*not* the measured signals)

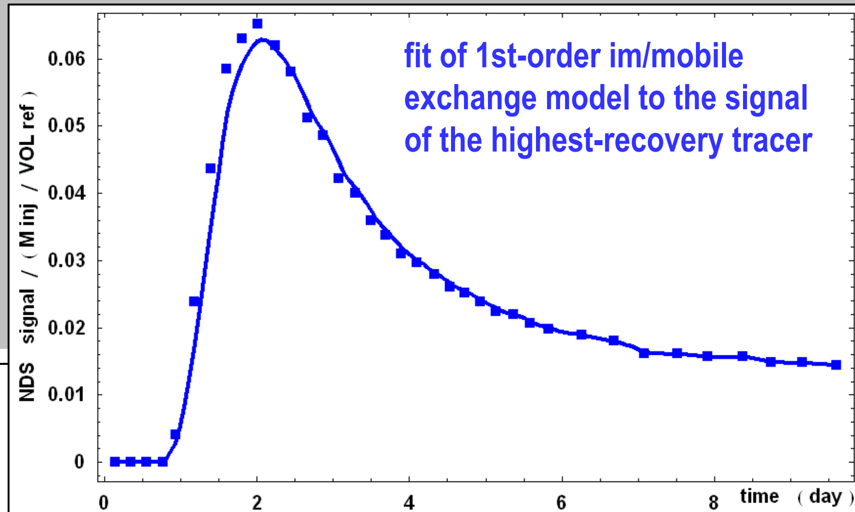
2004:
injection into **LOWER** horizon,
production from **UPPER** horizon

2006:
production from **UPPER**, followed by
production from **LOWER**

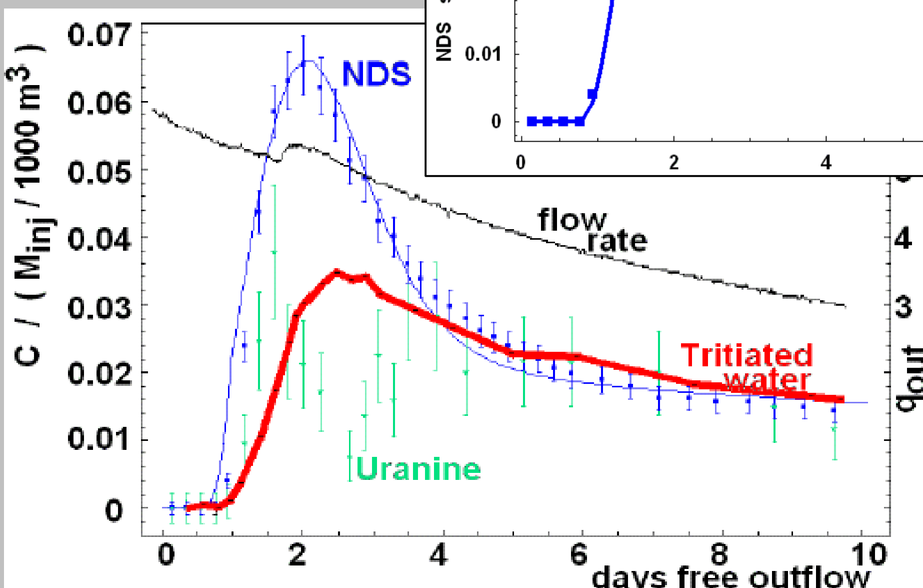


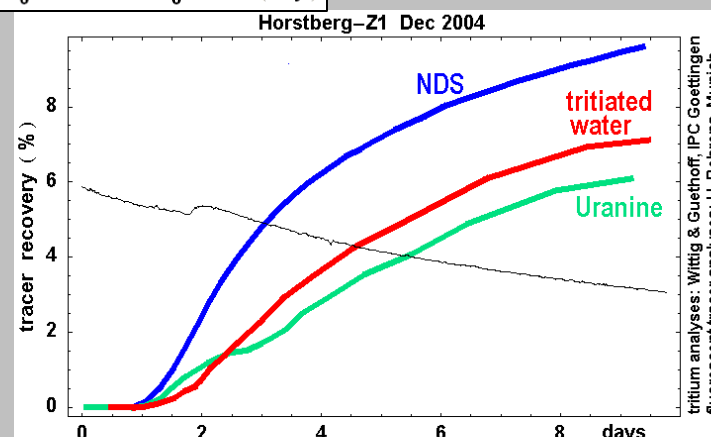
Horstberg

tracer BTCs and tracer recovery curves



extrapolated tracer recoveries show that up to 12% of the divergent flow field is focused to the production screen

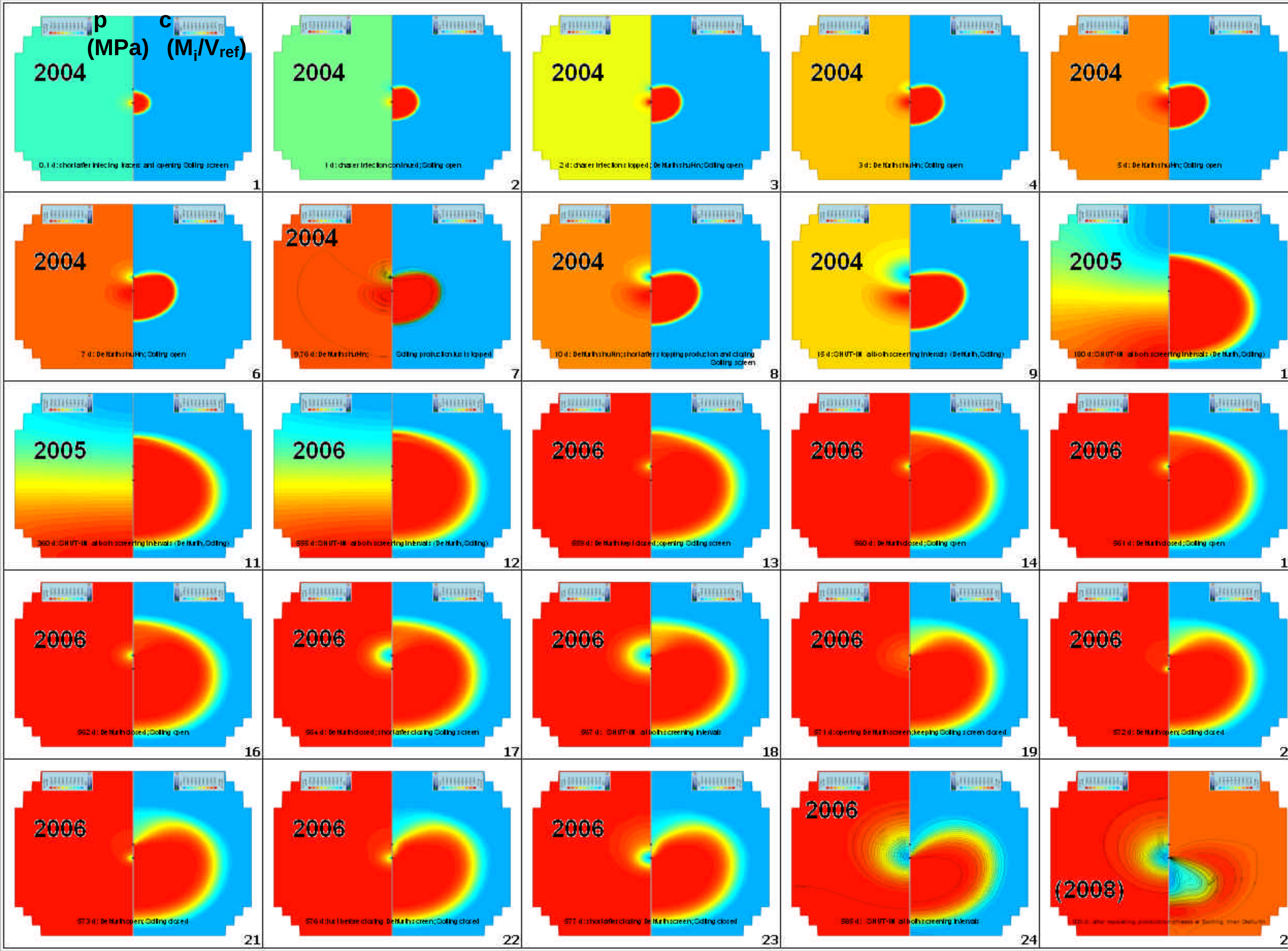




The following time sequence shows the evolution of pressure (*left half*) and tracer concentration (*right half*) fields in 2-D idealized frac projection

Horstberg

p,c evolution in 2-D frac projection

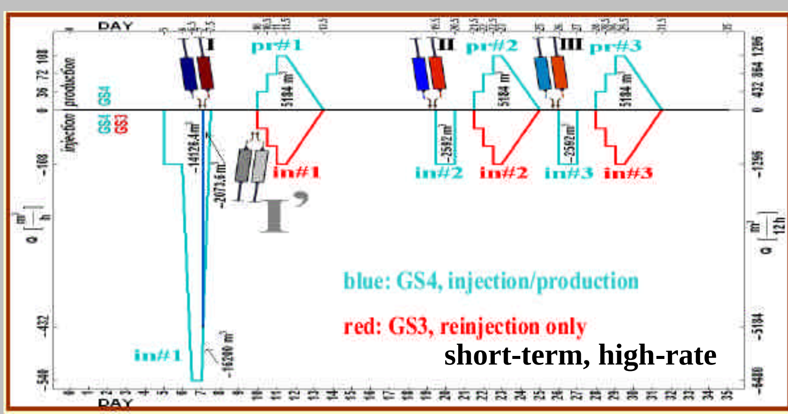


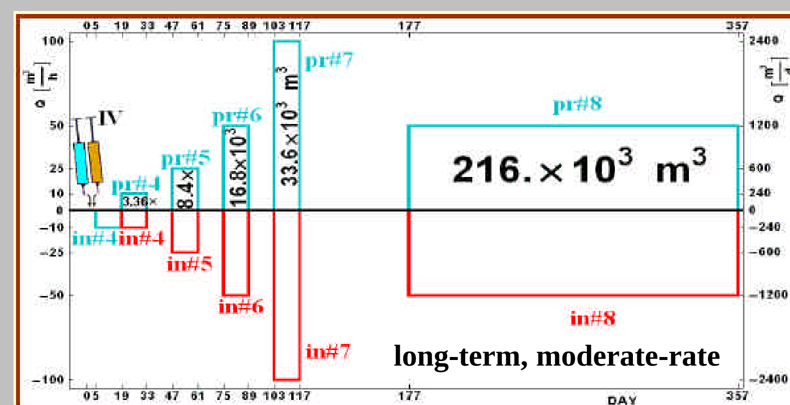
Großschönebeck, as of 2007:
test-sequence concept formulated by Zimmermann, Huenges et al., GFZ Potsdam

Two boreholes available:
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)

Intended test sequence:

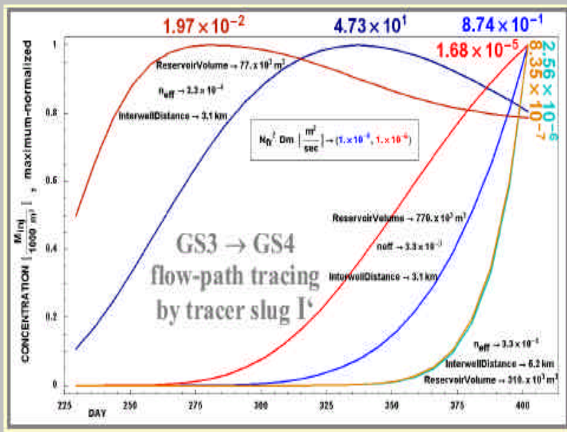
- **stimulations, spikings and production phases at GS4**,
  with (more or less simultaneous) **reinjection of produced fluids at GS3**
- additionally, single-time **spiking of reinjected fluids at GS3**

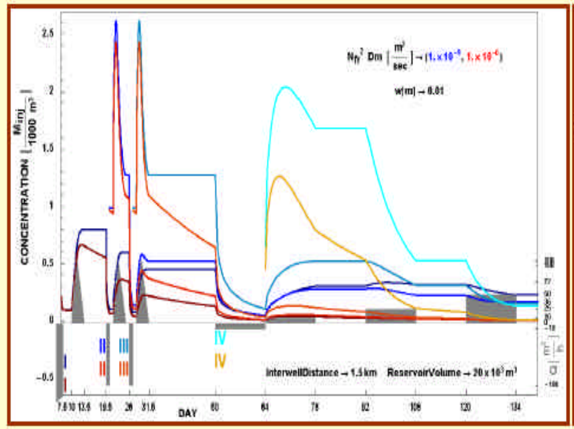


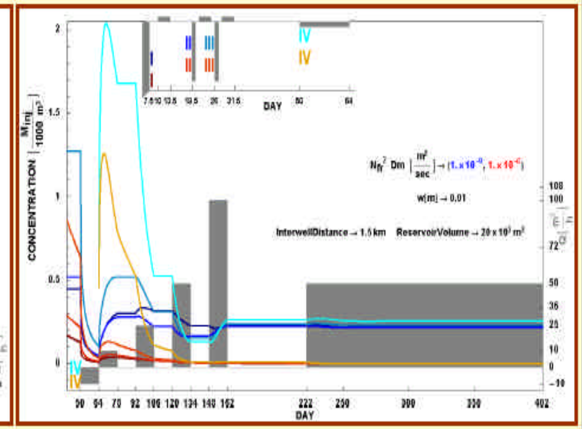


Our task: design and dimension 4 + 1 spikings at the boreholes GS4 + GS3 such that each individual spiking yields measurable signals during each of the subsequent outflow or abstraction phases

GS: some sensitivity analyses – to assist in dimensioning tracer slugs and sampling phases

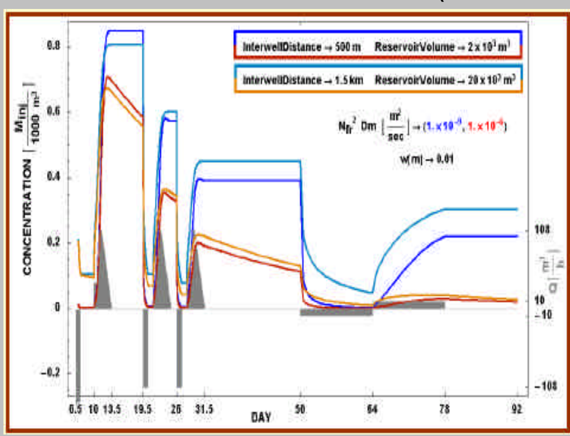


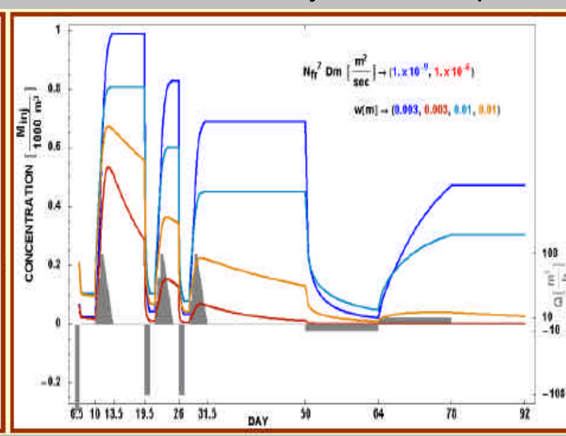


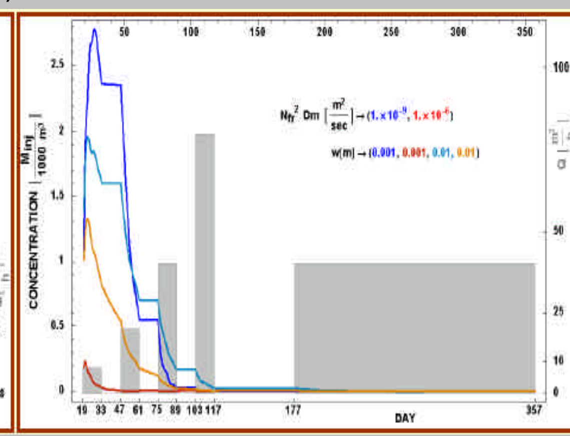


Tracer signals at GS4 originating from reinjection spiking at GS3 are very sensitive to reservoir size, and also to dispersion and surface/exchange parameters (fluid-rock contact-surface area, im/mobile exchange rates or alike).

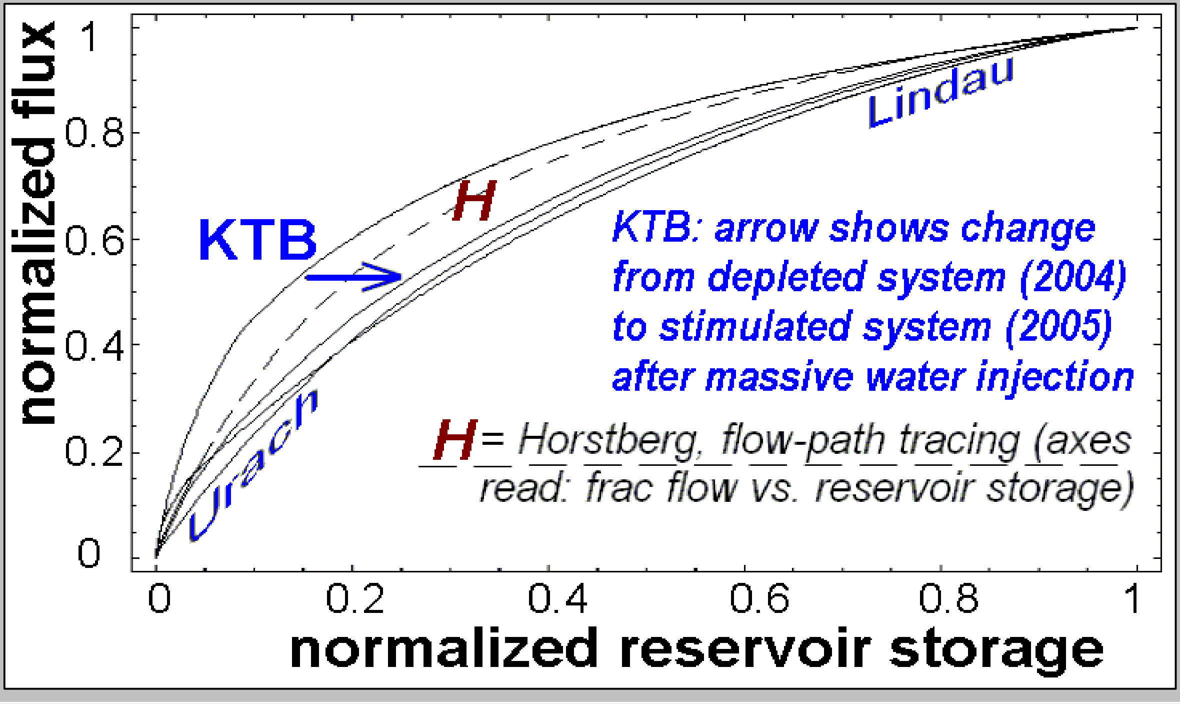
Tracer signals from flow-back (push-pull) tests at GS4 are more sensitive to effective aperture and specific contact-surface area (within the volume accessed by each test phase), than to total reservoir size.







normalized residence time distribution analysis



Flux-capacity analyses indicate

- what percentage of reservoir **flow** (if derived from flow-path tracings), or
- what percentage of solute or heat **exchange fluxes** (if derived from push-pull tests)

take place in a given fraction of the reservoir volume, in the form of a cumulative repartition function, sorted by fluid residence times.

Flow-capacity analyses (as known from reservoir hydraulics) have first been applied for interpreting tracer tests in geothermal systems in the USA by M. Shook (2003).

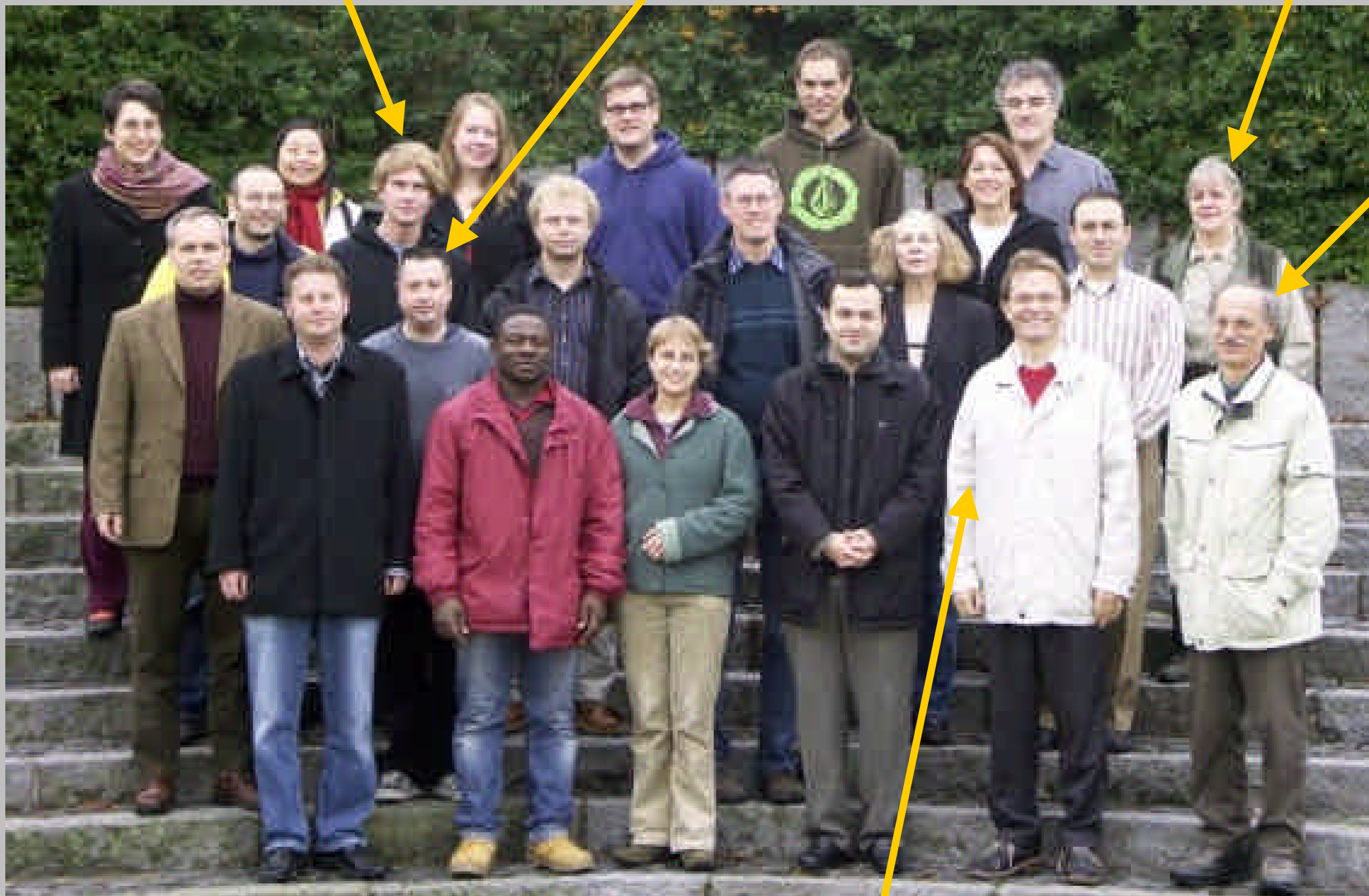
our team

Steffen Fischer,
technical implementation
of almost everything here

Tobias Licha,
Head of Chemical Laboratories

Manuela Lodemann,
KTB expert

Till Heinrichs: any difficult question – just ask him!



Prof. Martin Sauter, Hydrogeologist, Head of Department

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Questions, suggestions, corrections...

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