Single-well and *inter-well* dual-tracer test design for CCS pilot site assessment

MUSTANG EC FP7, Collaborative Large Scale Integrating Project

SEVENTH FRAMEWORK PROGRAMME

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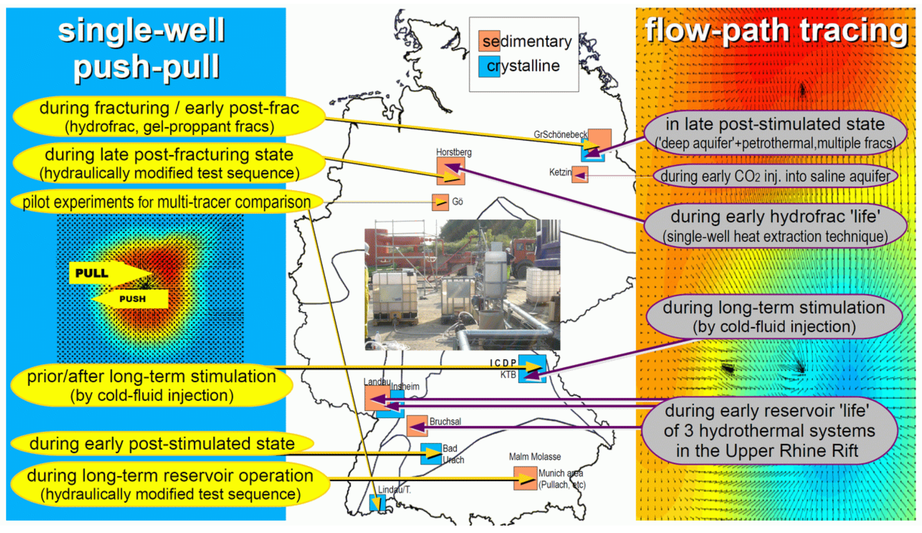
MOTIVATION for conducting tracer tests :
quantify or disambiguate relevant items that are not sufficiently determined from hydraulic and geophysical tests

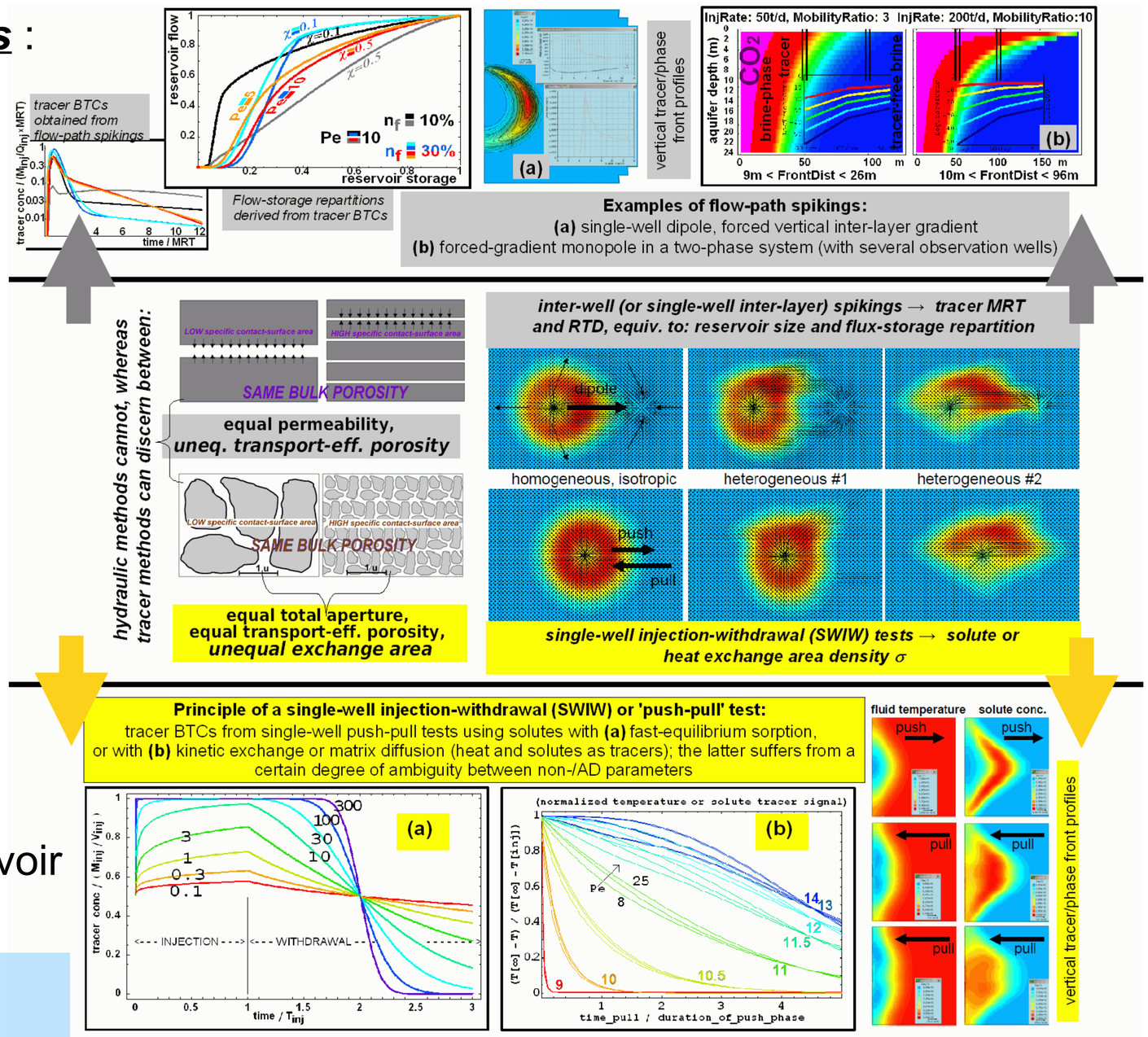


AIM of tracer tests within CCS :

- quantify single-phase and two-phase transport properties of storage formation
- diagnostic and monitor changes of reservoir state during / after CO_2 injection(s)

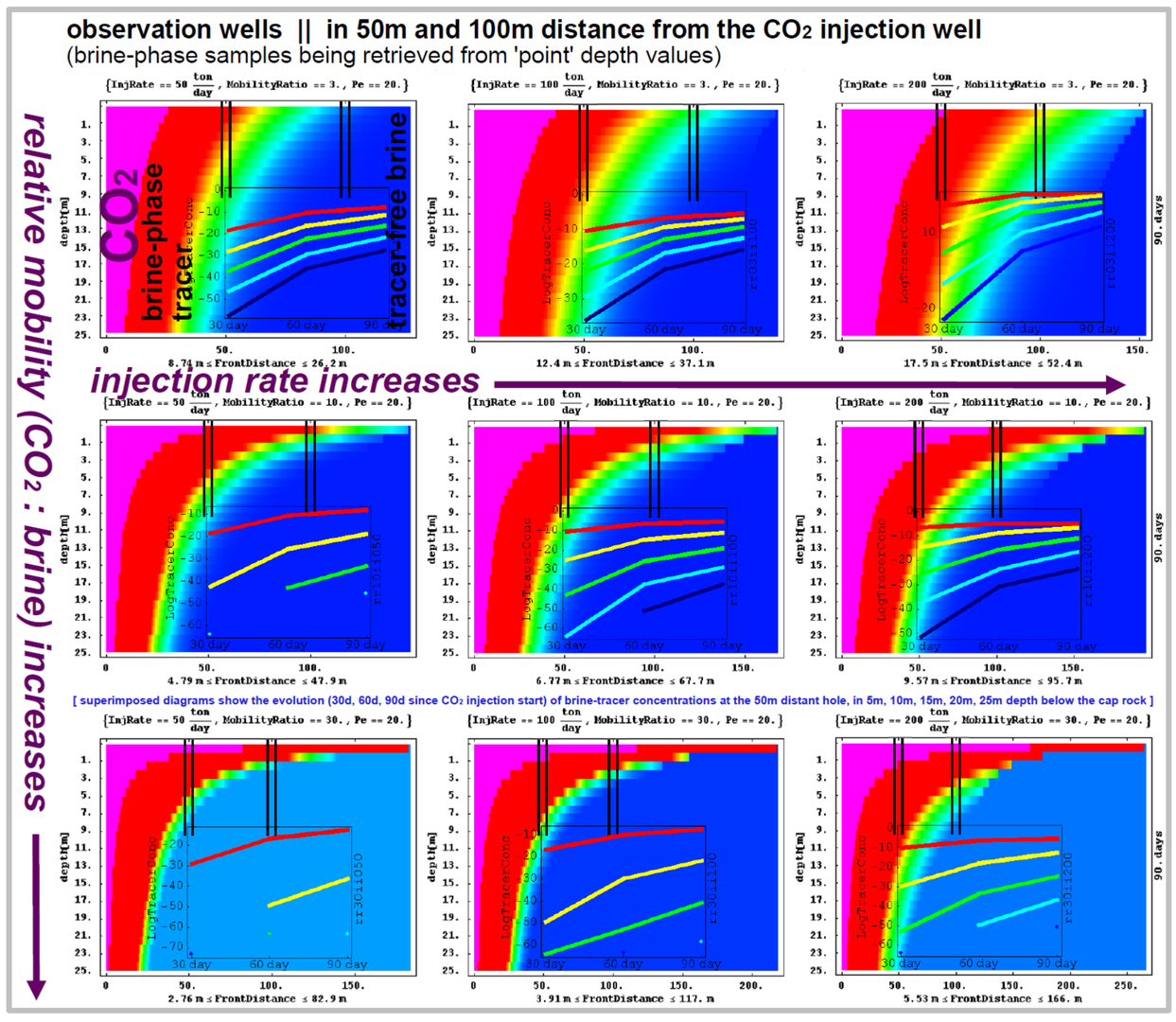
PRINCIPLES of tracer tests :

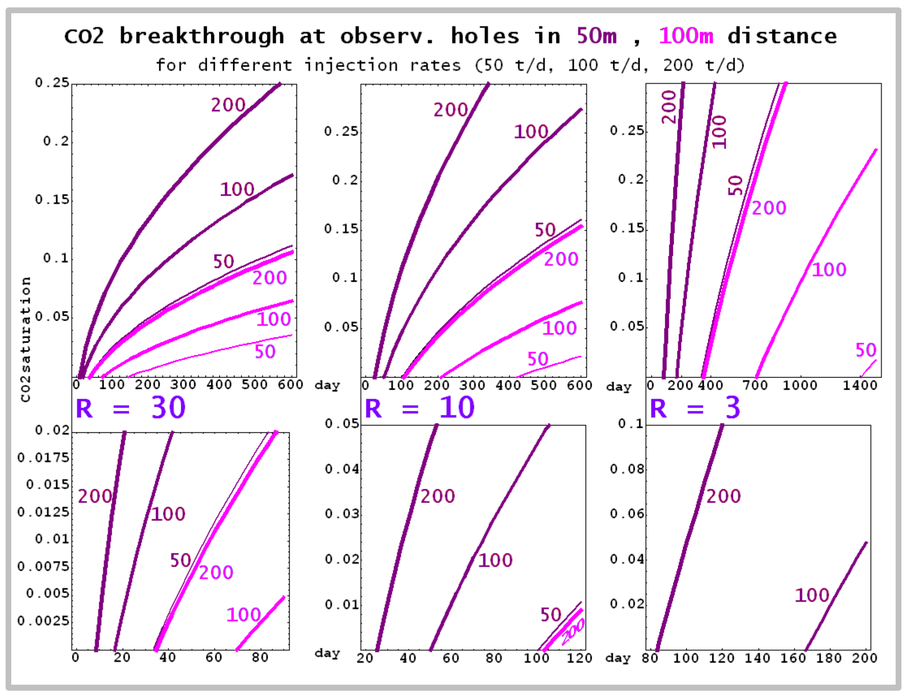
Inter-well tracings can be used to determine fluid residence time and flow-storage distribution (RTD, FSD). 'Statistical' RTD moments correlate with major reservoir features: ■ the 0th-order RTD moment can tell something about reservoir boundaries; ■■ the 1st-order RTD moment (MRT) represents a measure of reservoir size; ■■■ higher-order RTD moments (or FSR) provide information about reservoir heterogeneity. ***Single-well push-pull*** tracings can be used to quantify non-advective processes.



THEIR APPLICATION within CCS-MMV program at R&D pilot site Heletz in Israel :

1. prior to CO_2 injection: dual-tracer single-well push-pull test (monopole divergent followed by convergent flow field), using tracers with contrasting sorption and diffusion properties, aimed at characterizing flow-path apertures and fluid-rock interfaces
2. prior to CO_2 injection: brine-phase dual-tracer inter-well circulation test (forced-gradient, divergent-convergent dipole flow field), aimed at estimating storage reservoir size, determining brine RTD and FSR, characterizing reservoir-scale heterogeneity
3. during CO_2 injection: dual-tracer, inter-well injection-extraction test (forced-gradient, divergent-convergent dipole flow field), using single-phase and phase-partitioning tracers, aimed at quantifying the storage capacity, characterizing brine displacement processes, and determining RTD and FSR under two-phase flow conditions.





The research leading to these results has received funding from Baker Hughes (Celle) and from the Lower-Saxonian Science and Culture Ministry (MWK Niedersachsen) within the GEBO G6 project, and from the European Community's 7th Framework Programme FP7/2007-2013 under grant agreement n° 227286.

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Can tracer reactivity overcome the insensitivity of SWIW methods w.r. to rapid-equilibrium processes?

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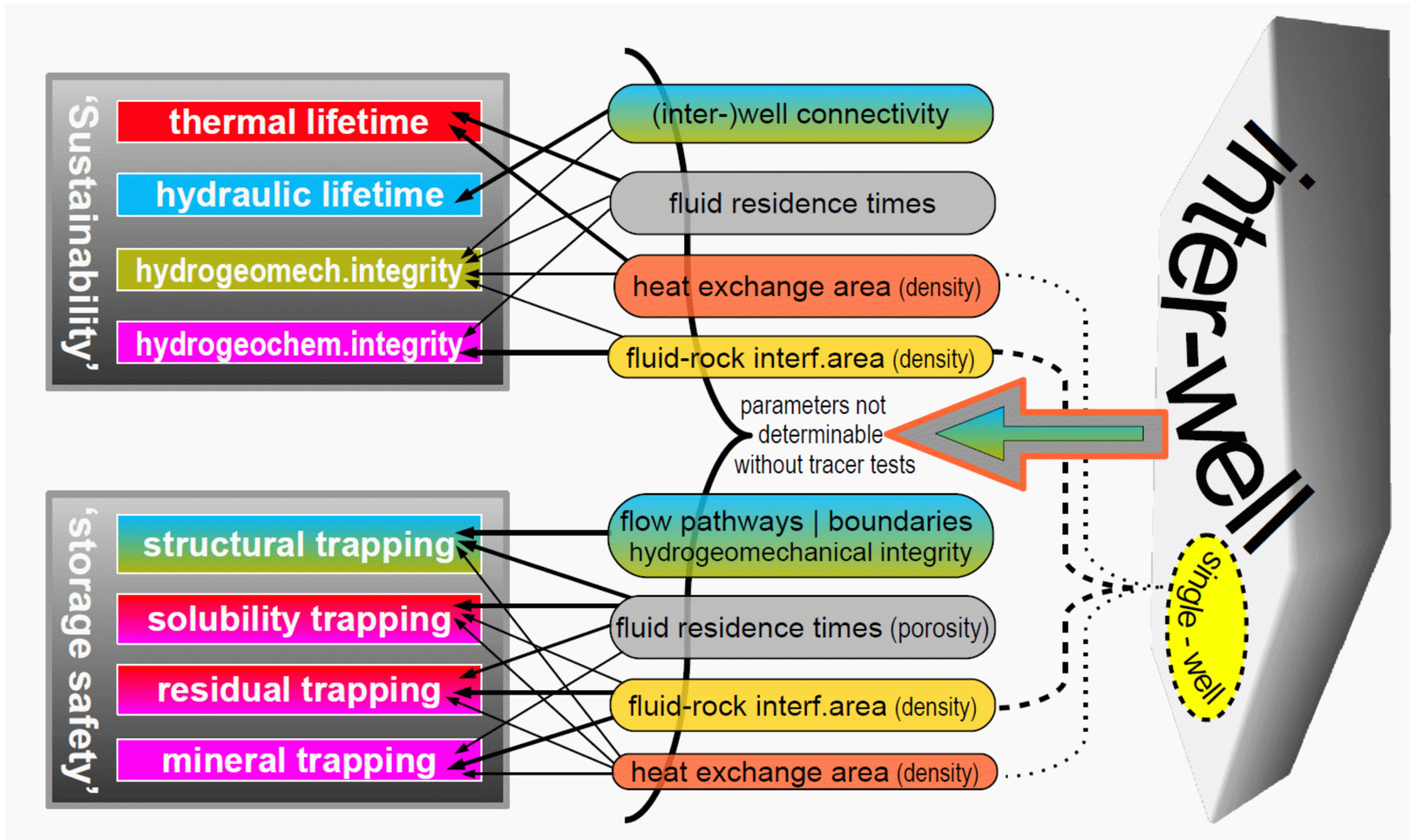
MOTIVATION :
Single-well injection-withdrawal (SWIW or 'push-pull') tests appear attractive for practical reasons, but suffer from poor sensitivity towards rapid-equilibrium exchange of tracer between fluid phases or between fluid and rock. This makes parameters such as phase volume (saturation) and phase interface area difficult to invert from 'pull' signals of phase-partitioning or sorptive tracers.



A promising sensitivity improvement is examined, exploiting the time-dependent, in-situ release of a second tracer, from the originally injected tracer, with contrasting partitioning or sorption properties :

tracer species	reactivity	exchange process (retardation factor)	test type	injection at	plot style
'ester'	reactive $T_{1/2} = T_{push}$	phase-partitioning or sorptive $R - 1 = \{0^*, 0.2, 0.4\}$	SW	$t = 0$, $r = 0$	thick dashed black*/blue/red
'alcohol'	stable	non-partitioning, non-sorptive ($R = 1$)	SW	(not being injected, but produced in-situ from #1)	thick full black*/blue/red
ref. for reactivity	stable	phase-partitioning or sorptive $R - 1 = \{0.2, 0.4\}$	SW	$t = 0$, $r = 0$	thin dashed blue/red
ref. for partitioning or sorption	stable	non-partitioning, non-sorptive ($R = 1$)**	SW	$t = 0$, $r = 0$	thin full grey/blue**/red**
ref. for SW vs. IW	stable	phase-partitioning or sorptive $R - 1 = \{0.2, 0.4\}$	IW	$t = 3 \times T_{push}$ (beginning of Pull) $r = R_{push}$	faded thick dashed blue/red
	stable	non-partitioning, non-sorptive ($R = 1$)**			faded thick full grey/blue**/red**

Here, retardation factors R stand for
– either partitioning of tracer between the mobile fluid and the immobile fluid phase: $R = 1 + KD \times s / (1 - s)$
– or sorption of tracer from the mobile fluid phase to the rock surface: $R = 1 + \sigma \times W \times (KD / \rho) \times (1 - n) / n$
with : s = immobile-phase saturation, σ = fluid-rock interface area density,
W = thickness of screened reservoir formation, n = transport-effective porosity,
ρ = bulk rock density, KD = partitioning or sorption distribution coefficient.

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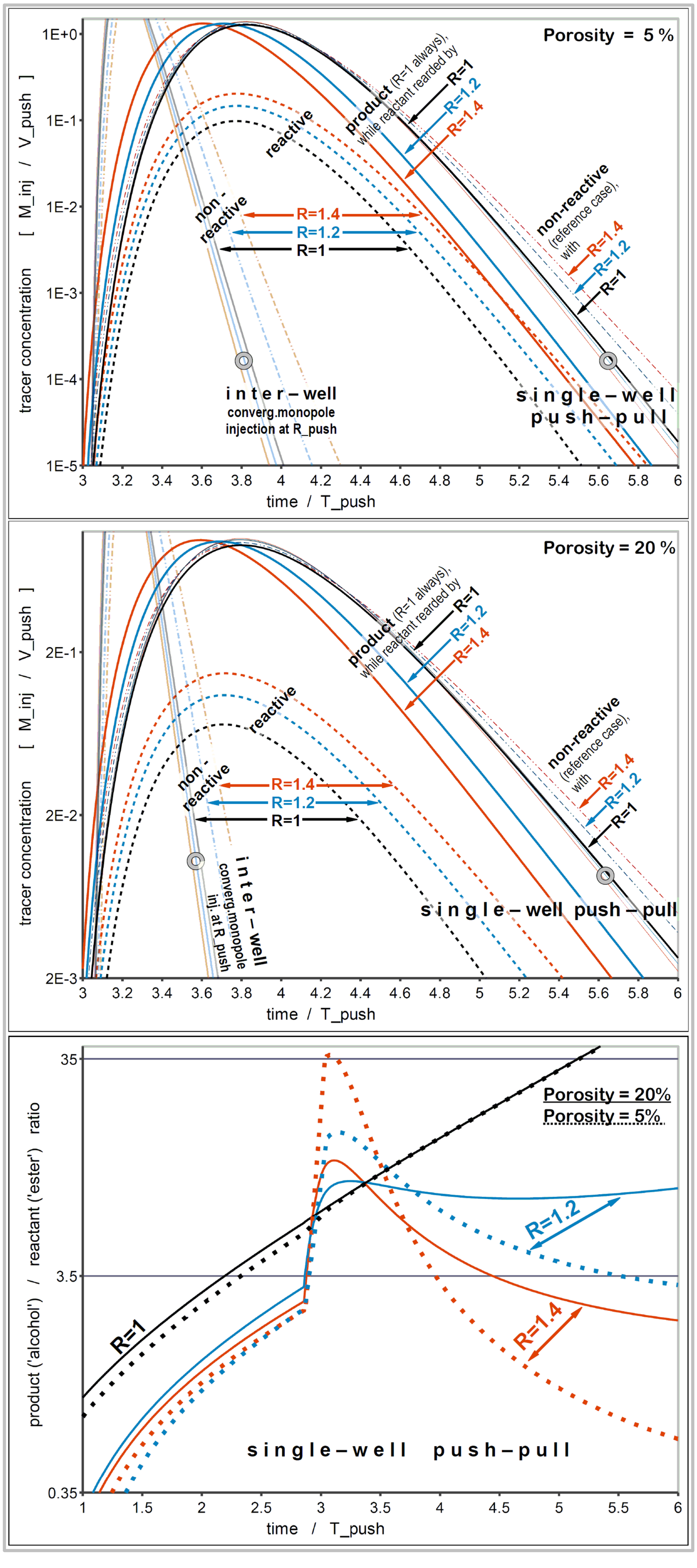
RESULTS :

- Non-reactive tracers with different sorptivity or partitioning yield almost identical signals during SW pull stages; they are insensitive towards the target parameters of the SW test; in this respect, IW tests perform better than SW tests.
- The time-dependent release of a 'daughter' tracer from a reactive 'source' tracer allows to regain sensitivity towards target parameters in SW tests.
- Changes in *R* values produce opposite responses of 'daughter' and 'source' signals; this enhances their joint sensitivity towards *R*.
- In the low-*R* range, a SW test using reactive tracers is more sensitive w.r. to *R*, than a IW test using non-reactive tracers with the same *R* values; in this sense, SW tests indeed perform a 'sensitivity enhancement', compared to IW tests.
- If one of the species {'source', 'daughter'} happens to be difficult to measure (i. e., to detect and quantify), then it would also suffice to measure only one of them, alongside with a reference tracer; higher sensitivity, however, is obtained from the ratio 'daughter'/'source' (which requires measuring both).
- The sensitivity of tracer BTCs towards the respective target parameter (immobile-phase saturation *s*, or fluid-rock interface area density σ) is equivalent to their sensitivity towards the retardation factor *R*. This equivalence is linear for σ, but heavily non-linear for *s*. When *R* is close to 1 and *KD* lower than ~0.3, small uncertainties in *R* or *KD* lead to large uncertainties in *s* determination.
  — In the case of fluid-fluid partitioning (not sorption), different of values of *R* (1, 1.21, 1.43) are associated with different values of immobile-phase saturation *s* (0, 4%, 8%, for the assumed *KD* = 5).
  — It is not a prerequisite that the 'daughter' tracer always has to be a non-partitioning tracer, in contrast to the 'source' tracer (the alcohol produced in Tomich et al. 1973 was soluble only into the brine phase, while the ester partitioned between brine and oil). What actually matters, is only the *relative retardation* between 'source' and 'daughter' tracer (i. e., only the ratio between their *KD* values). In this study, relative retardation factors <2 were purportedly considered, because a sensitivity enhancement is particularly interesting for such low values.



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Dual-tracer push-pull tests for quantifying residual CO_2 saturation and interface area

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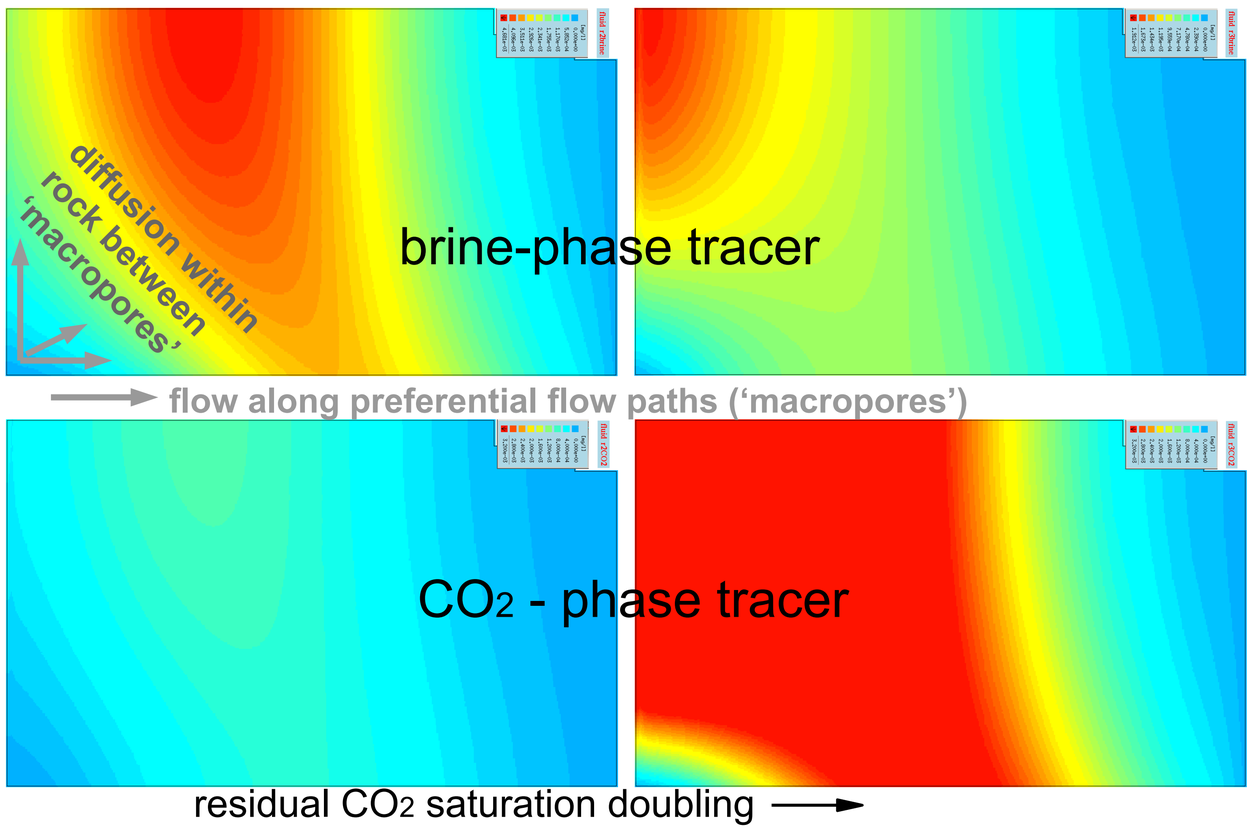
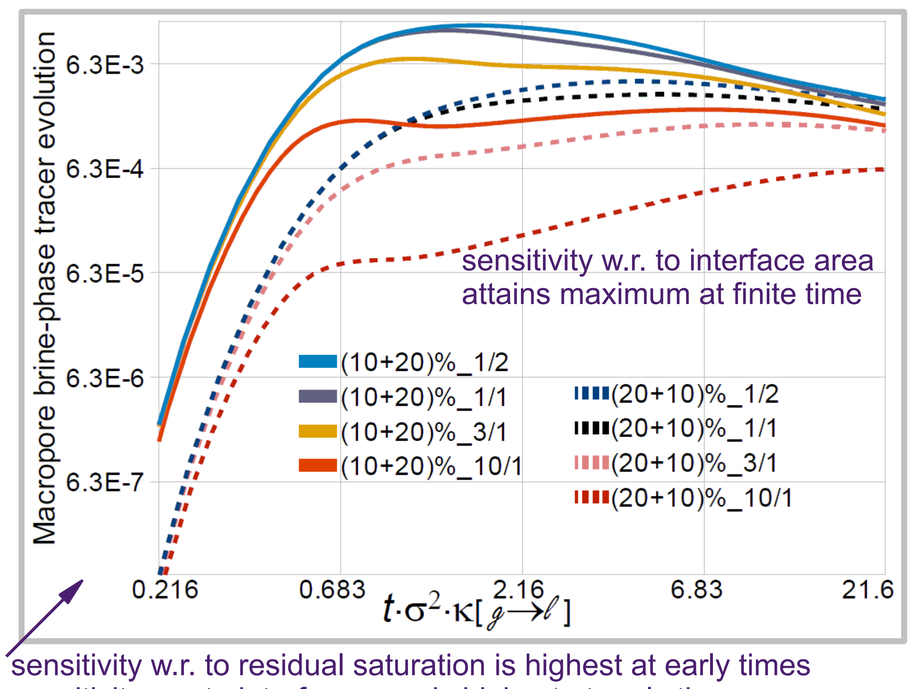
MOTIVATION :
residual trapping plays important part in mid- to long-term storage safety

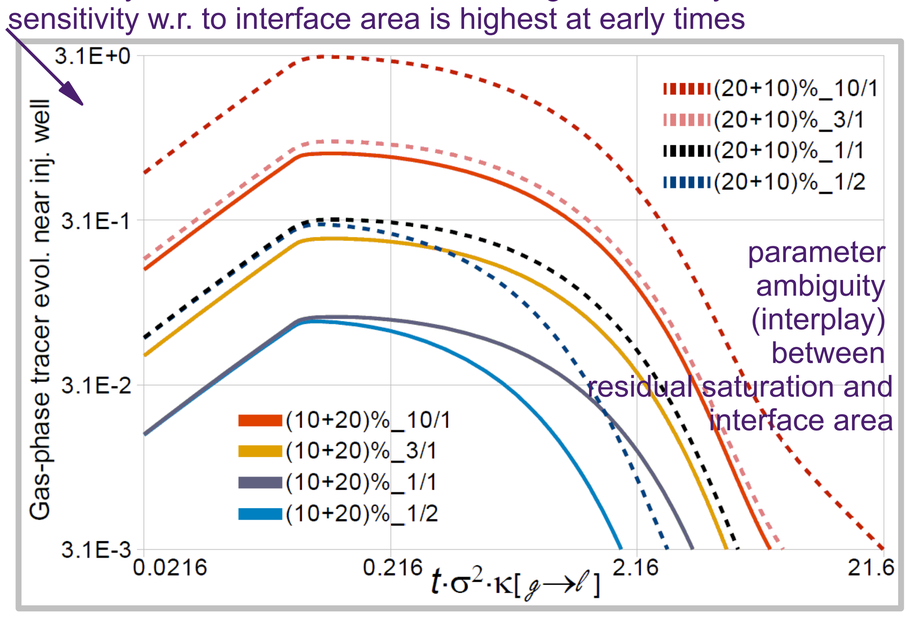
GOAL :
quantify *residual CO_2 distribution* (vol. fraction, CO_2 – brine interface area), alongside with parameters controlling solute *transport* (preferential-flow-path aperture, mobile-fluid – rock interface area).

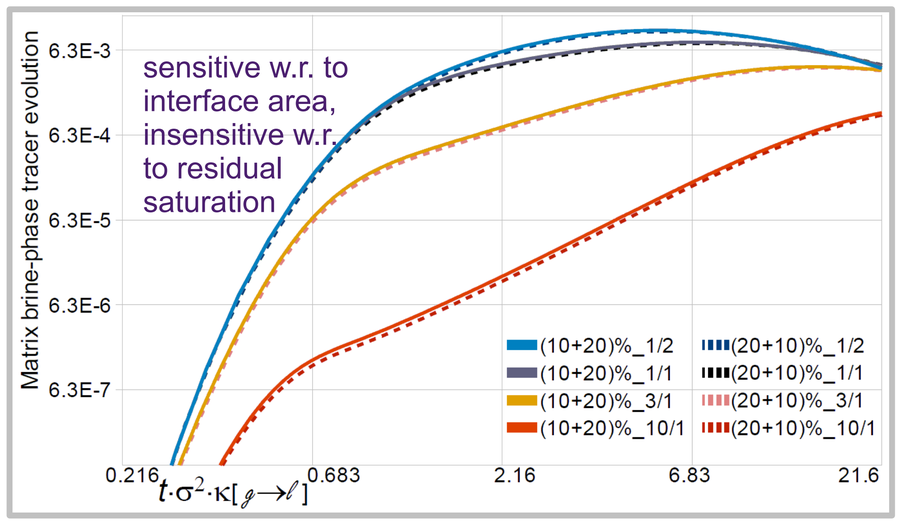
These parameters cannot be inverted unambiguously from hydraulic or geophysical test results. → *Need for tracer tests !*





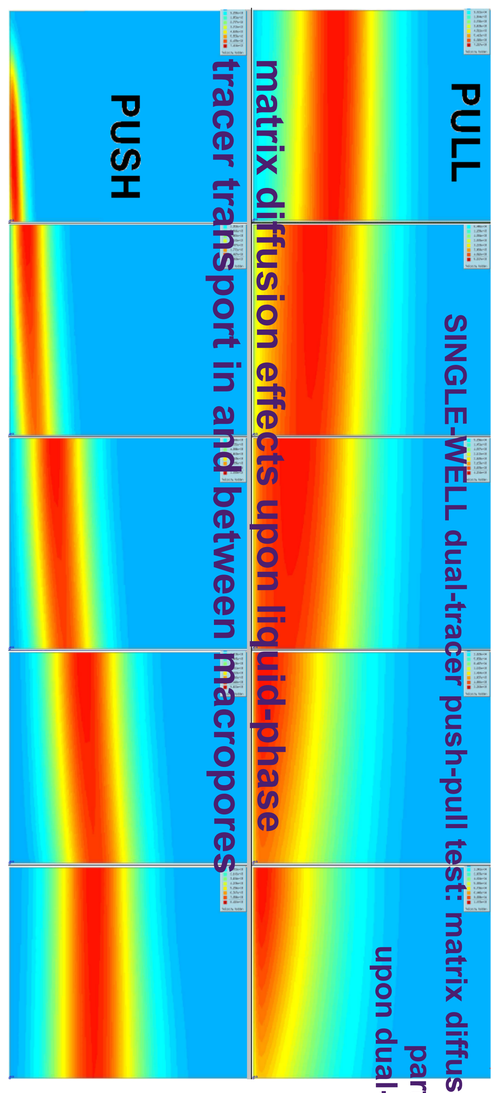
sensitivity w.r. to residual saturation is highest at early times
sensitivity w.r. to interface area is highest at early times

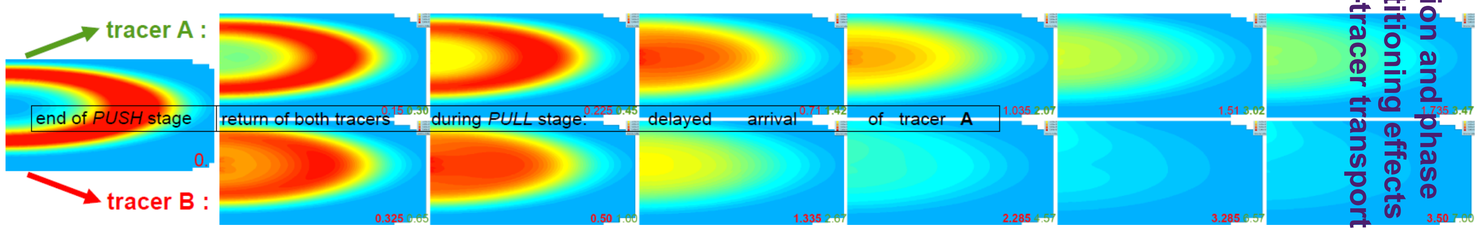




PROPOSED METHODS :

- use single-well methods to reduce the sensitivity of tracer signals w. r. to advective-macrodispersive parameters, and to enhance their sensitivity w. r. to non-advective parameters
- use brine-phase tracers with high diffusivity to quantify macropore density (consider using DTS for measuring heat as a tracer!)
- use partitioning tracers with rapid exchange to quantify residual saturation
- use partitioning tracers with slow exchange, or (slow) chemical reactions at interfaces to quantify interface areas





We gratefully acknowledge three intellectual sources for this study:

- *Carrera et al. 1998* : major ideas for efficient treatment of matrix diffusion (with interface area as a distributed parameter);
- *Tomich et al. 1973* : oilfield use of in-situ hydrolysis of oil-&brine-soluble ester (A), to form brine-only-soluble alcohol (B);
- *Licha, Nottebohm 2009* : identification of suitable esters undergoing hydrolysis at CO_2-brine interfaces.
  Schaffer, Sauter

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