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Single-well tracer push-pull test sensitivity w. r. to fracture aperture and spacing

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Dealing with a parallel-fracture system of infinite lateral extension, four characteristic regimes of tracer signal sensitivity w. r. to fracture aperture and w. r. to fracture spacing s (whose reciprocal defines fracture density, or the fluid-rock interface area per volume) can be identified during the pull phase of a single-well push-pull test, also depending upon the ratio between push-phase duration T_{push} and a characteristic time scale T_s (defined by $s^2 / D = T_s$, with D denoting the tracer's effective diffusion coefficient):

- early-time regime: tracer signals are sensitive w. r. to fracture aperture, but insensitive w. r. to fracture spacing; sensitivity w. r. to fracture aperture first increases, then decreases with T_{push} / T_s (thus there will be an optimum in terms of to T_{push} / T_s , at early pull times);
- mid-time regime: tracer signals are sensitive w. r. to fracture spacing, but insensitive w. r. to fracture aperture; sensitivity w. r. to fracture spacing increases with T_{push} / T_s ;
- late-time regime: with increasing pull duration, tracer signals become increasingly insensitive w. r. to fracture spacing, while regaining sensitivity w. r. to fracture aperture;
- 'very late'-time regime: sensitivity w. r. to fracture aperture becomes independent upon T_{push} / T_s .

From these different regimes, some recommendations can be derived regarding the design and dimensioning of dual-tracer single-well push-pull tests for the specific purposes of geothermal reservoir characterization, using conservative solutes and heat as tracers.

EGU 2012 – ERE1.6: Deep geothermal energy
XL88 Mon, Apr 23 <EGU2012-4310.pdf>

gebo focus area **'Geosystem'**

Baker Hughes · Niedersächsisches Ministerium für Wissenschaft und Kultur

MOTIVATION : predict reservoir lifetime

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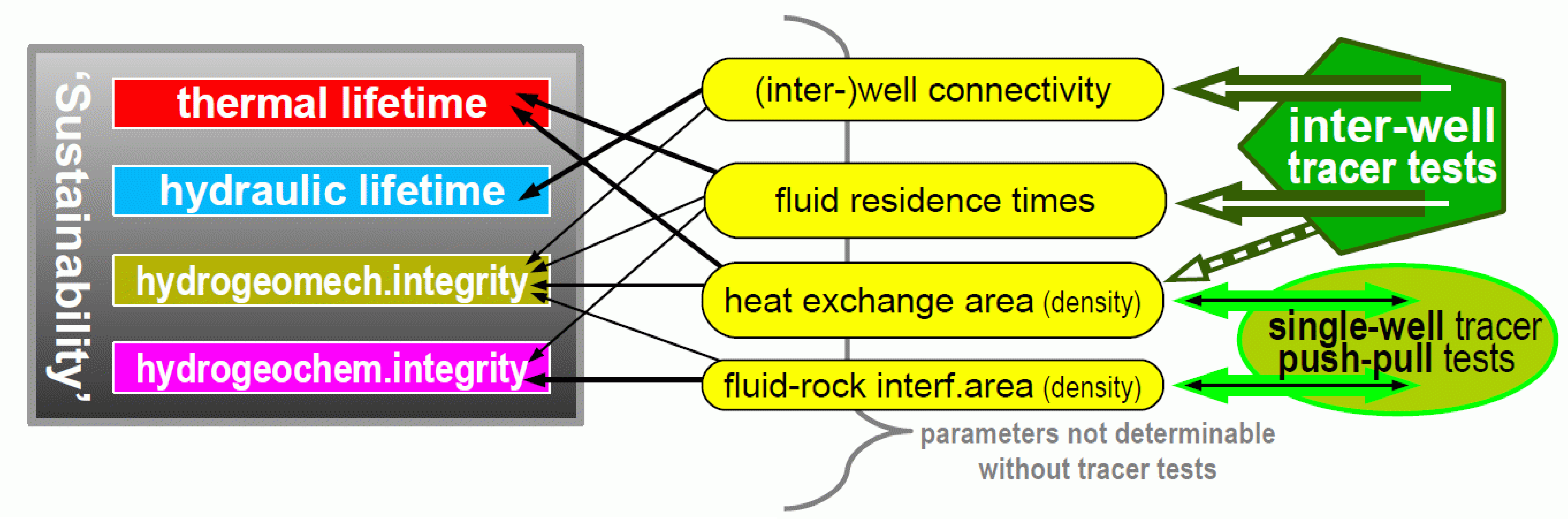
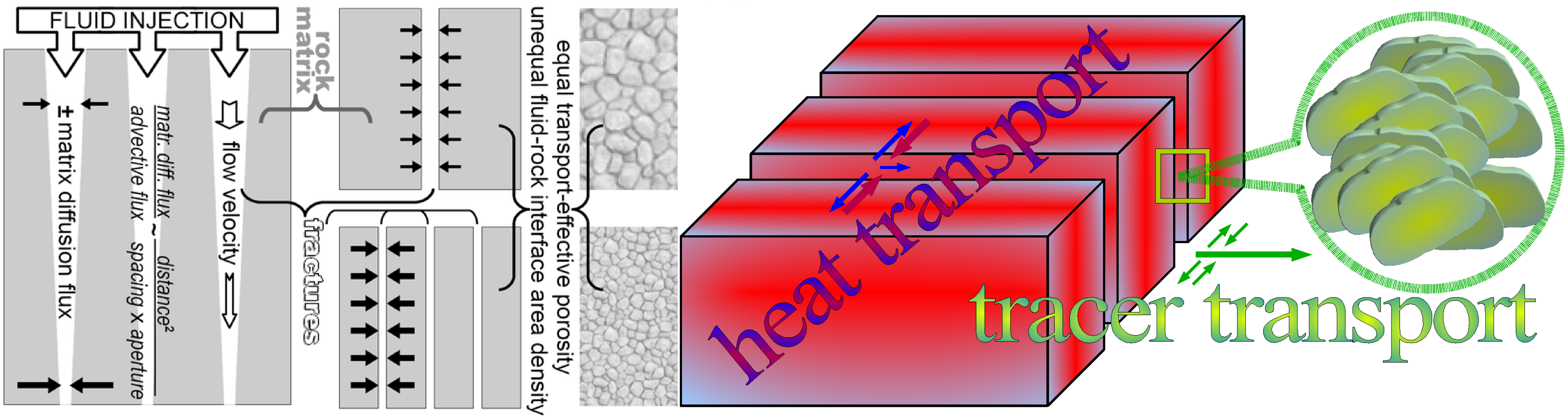
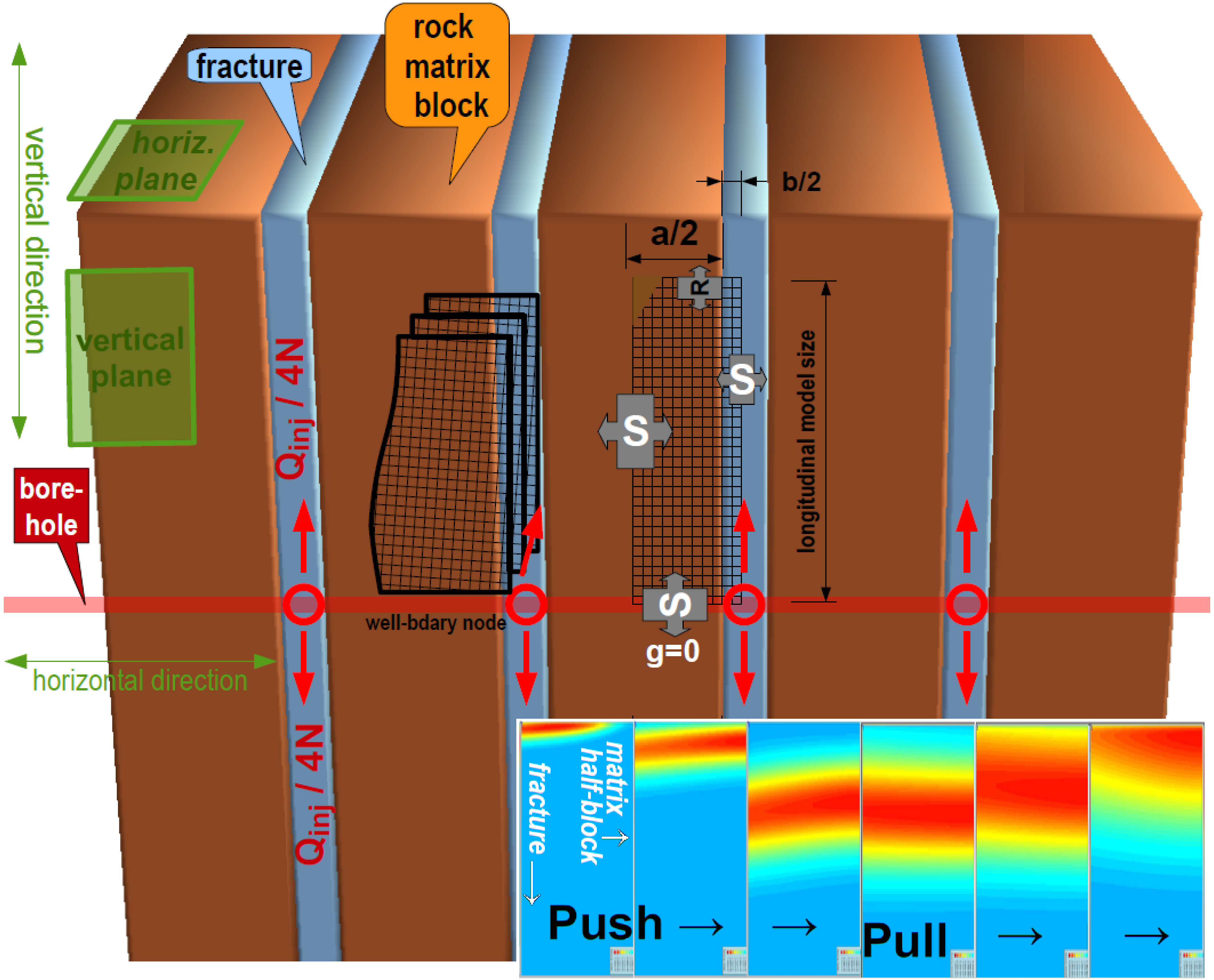
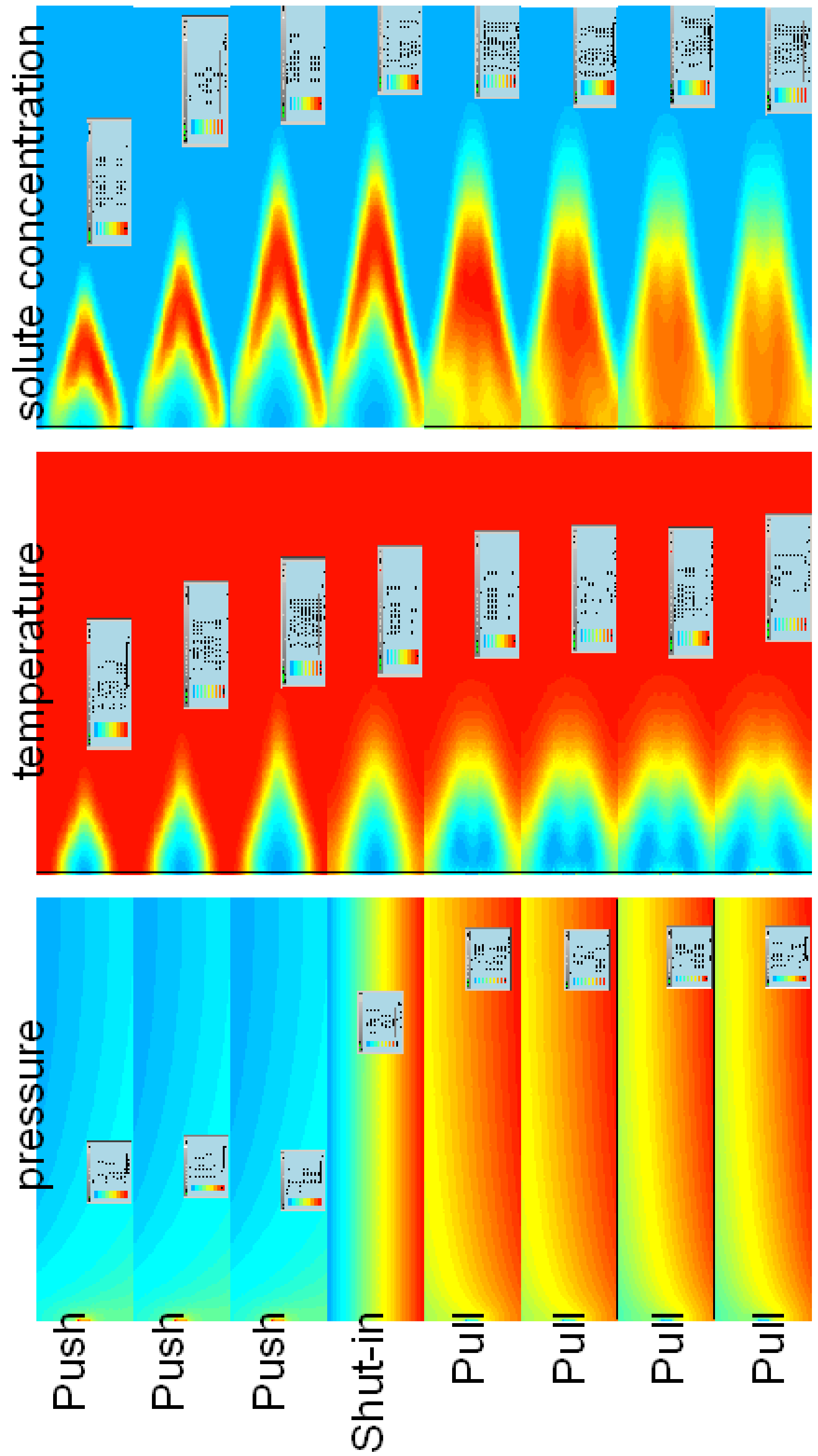




MODEL CONSTRUCTION





IBVP, SYMMETRIES, SCALING

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$$\frac{\partial C}{\partial t} + \frac{Q}{2\pi B_{\text{eff}}}\frac{1}{r}\frac{\partial C}{\partial r} - \frac{\alpha\,|Q|}{2\pi B_{\text{eff}}}\frac{1}{r}\frac{\partial^2 C}{\partial r^2} - \frac{\phi_m D_m}{b}\frac{\partial C}{\partial y}\Big|^{y=a} = 0 \quad (Source\ Terms)$$

$$\frac{\partial C_m}{\partial t} - D_m\frac{\partial^2 C_m}{\partial y^2} \underbrace{- D_m\frac{\partial^2 C_m}{\partial r^2}}_{\text{may choose to (not) neglect}} = 0$$

initial conditions: $C\,(t=0,r)=0 \ ,\ C_m\,(t=0,r,y)=0$

boundary conds.: $\mathbf{v}C - \mathbb{D}\cdot\nabla C|_{r=0^*} = InjTracerFlux(t)$

$$\mathbf{v}_m C_m + \mathbb{D}_m\cdot\nabla C_m|_{r=0} \approx 0$$

$$C\,(t, r\to\infty, y)\to 0 \ ,\ C_m\,(t=0, r\to\infty, y)\to 0$$

$$C_m(t,r,y=b) = C\,(t,r) \ ,\ \frac{\partial C_m\,(t,r,y)}{\partial y}\Big|^{y=a} = 0$$

$$\frac{\partial C}{\partial \tau} + \frac{\pm T}{2T_{\text{PUSH}}}\frac{1}{\rho}\frac{\partial C}{\partial \rho} - \frac{T}{2T_{\text{PUSH}}}\frac{1}{\text{Pe}_{\text{PUSH}}}\frac{1}{\rho}\frac{\partial^2 C}{\partial \rho^2} - \frac{\phi_m a}{b}\frac{\partial C}{\partial \eta}\Big|^{\eta=1} = 0$$

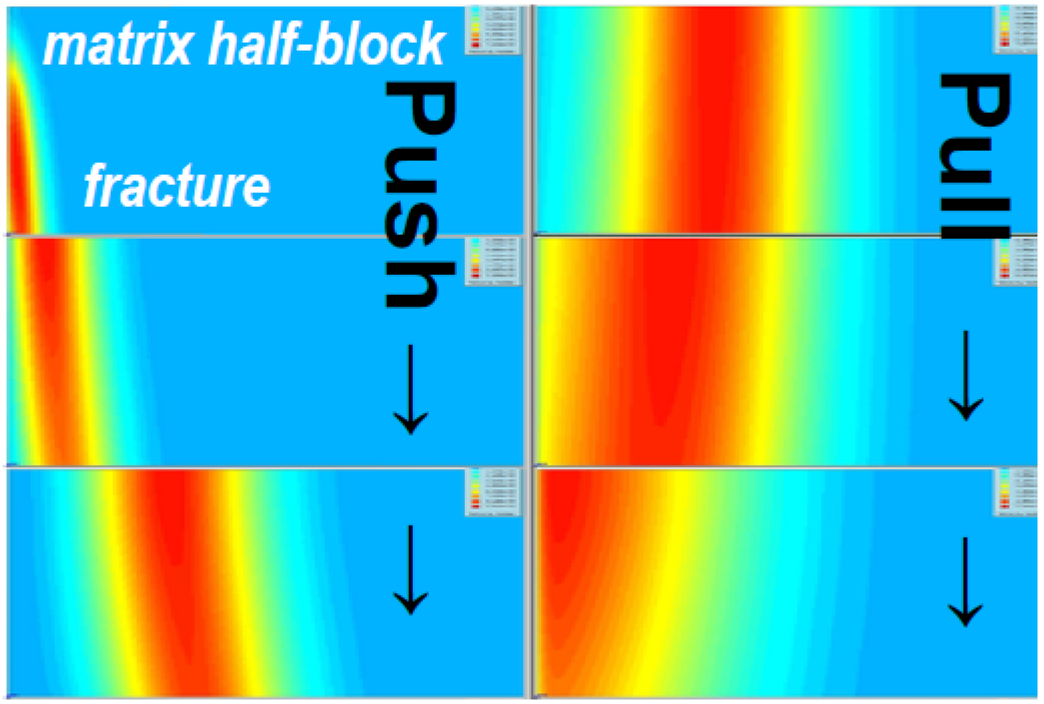
$$\frac{\partial C_m}{\partial \tau} - \frac{\partial^2 C_m}{\partial \eta^2} \underbrace{- \left(\frac{a}{R_{\text{PUSH}}}\right)^2 \frac{\partial^2 C_m}{\partial \rho^2}}_{\text{may choose to (not) neglect}} = 0$$

$$C_m\,(\tau,\rho,\eta=0) = C\,(\tau,\rho) \ ,\ \frac{\partial C_m\,(\tau,\rho,\eta)}{\partial \eta}\Big|^{\eta=1} = 0$$

scaled equations

Symmetries:

- axial (w.r.to well axis), neglecting the effects of gravity
- planar (w.r. to fracture plane)
- translational (along well axis)



asymptotic uncoupling of fracture spacing:

$$\frac{|\text{MxDiff}|}{|\text{Advect}|} = \frac{(\phi_m D_m)\,(\pi r^2 B_{\text{tot}})}{Q}\begin{cases}\frac{1}{a\cdot b}\ , & \text{'early'}\\ \frac{1}{a^2}\ , & \text{'late'}\end{cases}$$

MODEL PREDICTIONS
→ field test design requirements

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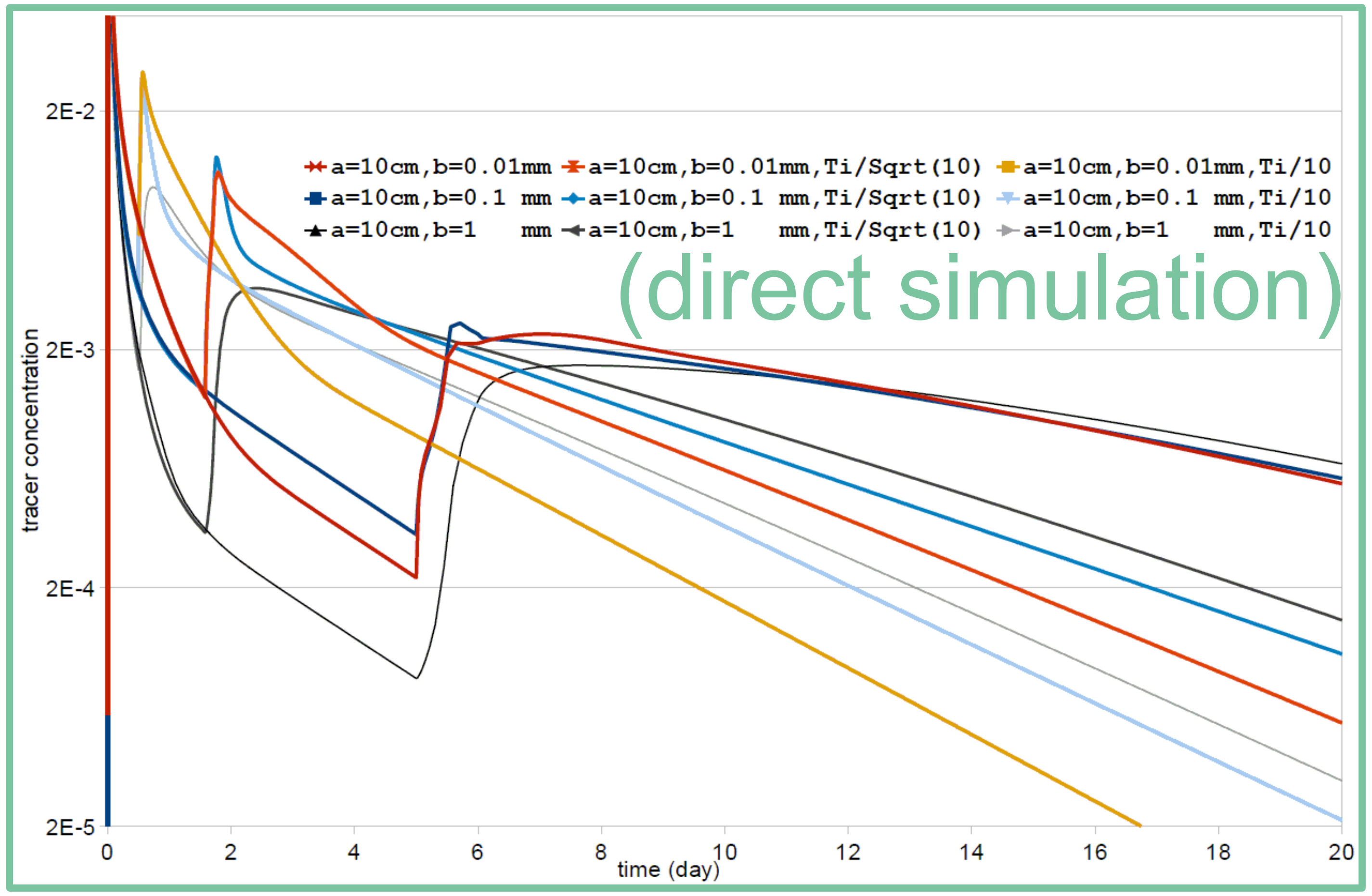
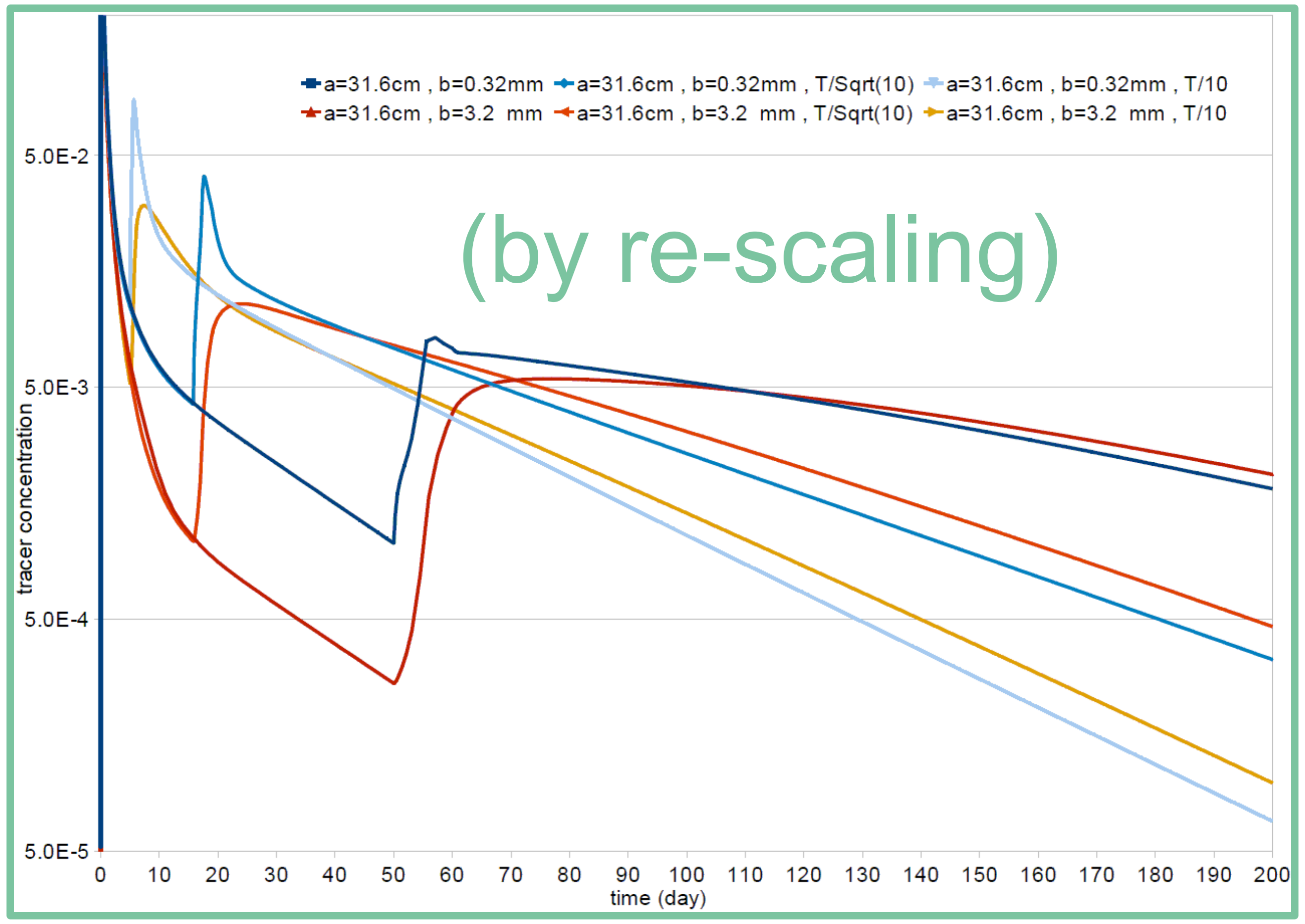
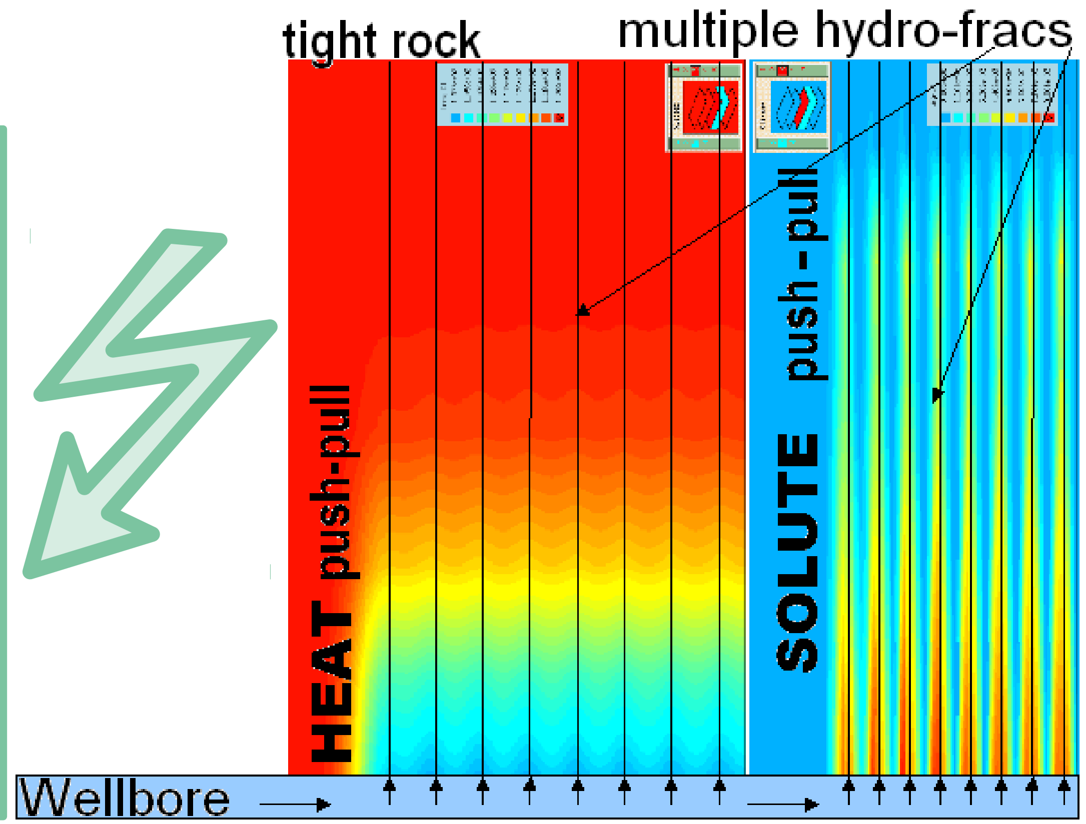




Fracture density in the range	***solute* push/pull** duration needed to determine		***heat* push/pull** duration needed to determine	
	fracture aperture	*fracture density*	*fracture aperture*	*fracture density*
1/cm	{push << 14h, pull < 14h}	{push<14h, pull>>14h} or {push>14h, pull<14h}	{push << 50s, pull < 50s}	{push<50s, pull>>50s} or {push>50s, pull<50s}
1/dm	{push << 58d, pull < 58d}	{push<58d, pull>>58d} or {push>58d, pull<58d}	{push << 1.4h, pull < 1.4h}	{push<1.4h, pull>>1.4h} or {push>1.4h, pull<1.4h}
1/m	{push << 16y, pull < 16y}	{push<16y, pull>>16y} or {push>16y, pull<16y}	{push << 6d, pull < 6d}	{push<6d, pull>>6d} or {push>6d, pull<6d}
1/(10m)	{push << 1600y, pull < 1600y}	{push<1600y, pull>>1600y} or {push>1600y, pull<1600y}	{push << 1.6y, pull < 1.6y}	{push<1.6y, pull>>1.6y} or {push>1.6y, pull<1.6y}
1/(30m)	{push << 16000y, pull < 16000y}	{push<16000y, pull>>16000y} or {push>16000y, pull<16000y}	{push << 16y, pull < 16y}	**{push<16y, pull>>16y} or {push>16y, pull<16y}**



SENSITIVITY w. r. to FRACTURE APERTURE and SPACING (density)

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duration of push, pull phases, compared to T [a] = a^2/D	short injection pulse $T_{inj} << T$ [a]	long injection pulse $T_{inj} > T$ [a]
early pull signals $t_{pull} << T$ [a]	• sensitive w. r. to 1/b • insensitive w. r. to a • single-fracture behavior like for isolated individual fractures	• sensitive w. r. to 1/(N a) • insensitive w. r. to b/a • single-fracture behavior for fracture bundle of total aperture (N a) and porosity (b/a)
late pull signals $t_{pull} \geq\approx T$ [a]	• sensitive w. r. to a • sensitive w. r. to 1/b • some ambiguity between parameters • parallel-fracture behavior like for $N \rightarrow \infty$	• sensitive w. r. to a and N • sensitive w. r. to 1/b • some ambiguity between parameters • parallel-fracture behavior like for finite N
very late pull signals $t_{pull} >> T$ [a]	• sensitive w. r. to 1/(N a) • insensitive w. r. to b/a • single-fracture behavior for fracture bundle of total aperture (N a) and porosity (b/a)	• sensitive w. r. to 1/b • insensitive w. r. to a • single-fracture behavior like for isolated individual fractures

$Tpull << T$: b–sensitive , a–insensitive
$Tpull \sim< T$: ambiguous inversion
$Tpull >\sim T$: a–sensitive , b–insensitive
$Tpull >> T$: b–sensitive , a–insensitive

Comparison with literature

approach	Małoszewski, Sudicky	Carrera et al.	Haggerty et al.	Kocabas, Horne	Pruess, Doughty	Kolditz	(this Report)
analytical / numerical	A	N	N	A, N	N	A , N	N
multiple- / single-fracture system	MF	MF	MF	SF	SF	SF	MF
inter-well / single-well	IW	IW	SW	SW	SW	IW	SW
dimensionality of fracture flow	1D parallel	1D parallel	1D radial	1D parallel	1D parallel	1D, 2D	1D radial (for scaling analysis), 2D (for numerical analysis)
dimensionality of matrix diffusion	1D	1D	1D	1D	1D	1D, 2D	3D
treatment of matrix diffusion	exact	exact, plus very accurate series approximation	like linear-sorption superpos.	exact	uses rough C_f / Sqrt(t) approximation	uses rough C_f / Sqrt(t) approximation	exact
asymptotic considerations	3 regimes	2 regimes	2 *regimes	n.a.	n.a.	n.a.	3 regimes