Upscaling “dissolution” mechanisms in porous media

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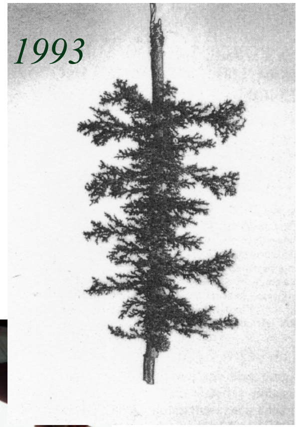
Outline

- Background
- Pore-scale model and effective surface
- Darcy-scale models
- Stability
- Large-scale models?
- Conclusions

Introduction

- **Dissolution: geochemistry, karsts, salt mines, NAPL, petrol. Engng, aerospace industry…**
- **Problems:**
  - Multiple-scale analysis
  - History effects
  - Instabilities

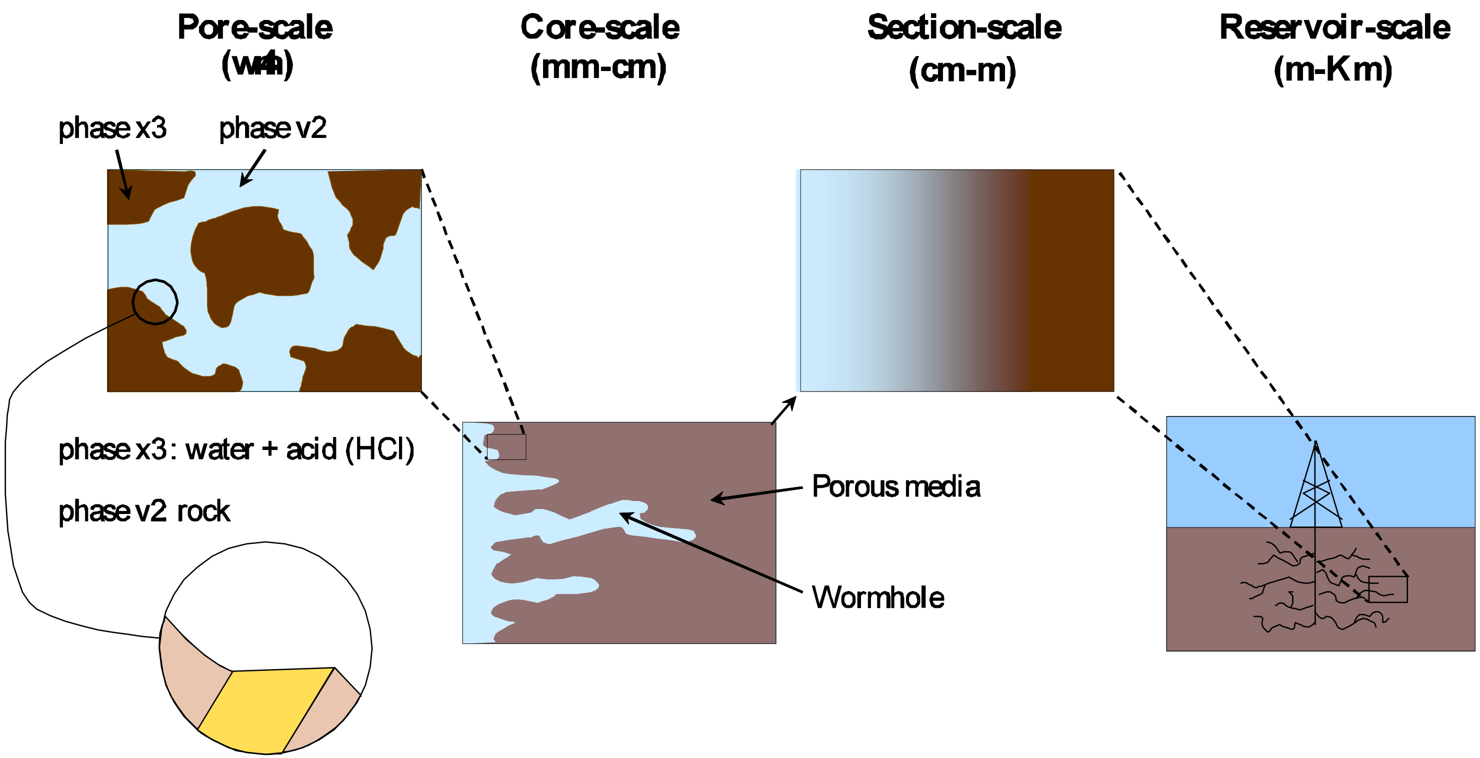
Daccord et al., 1993



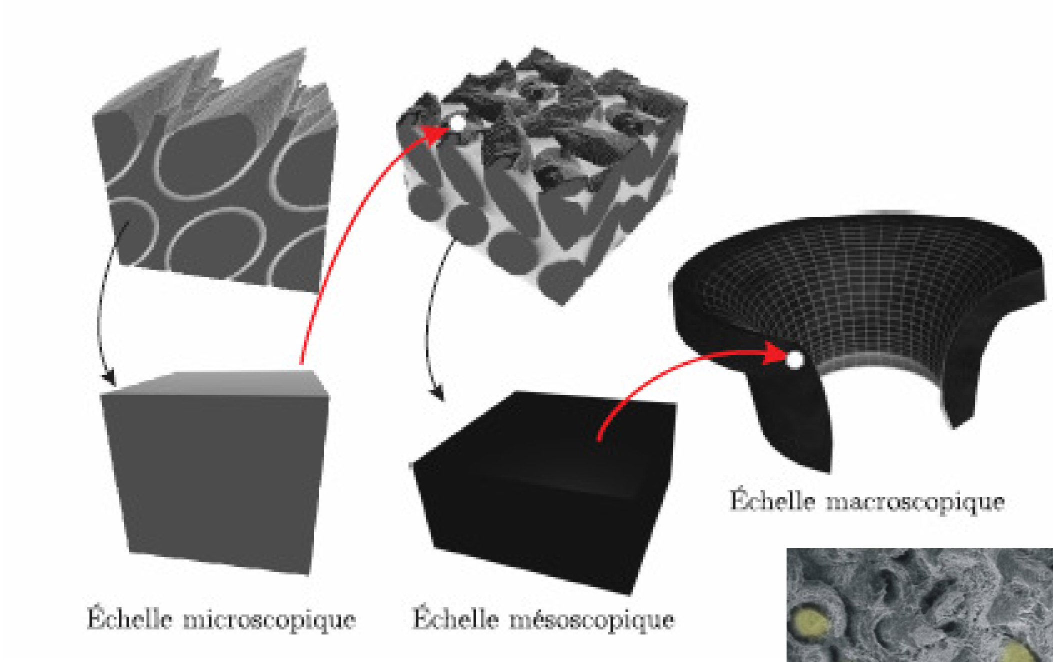
Ha Long Bay

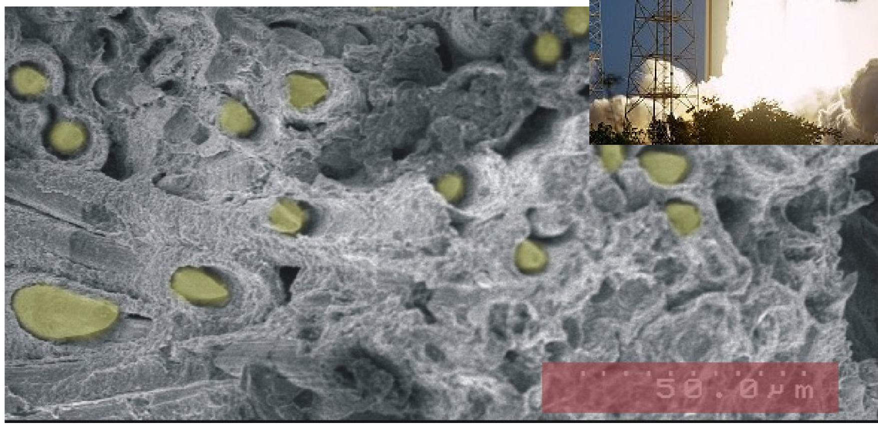
Igue de Planagrèze

Example 1: acidizing treatment

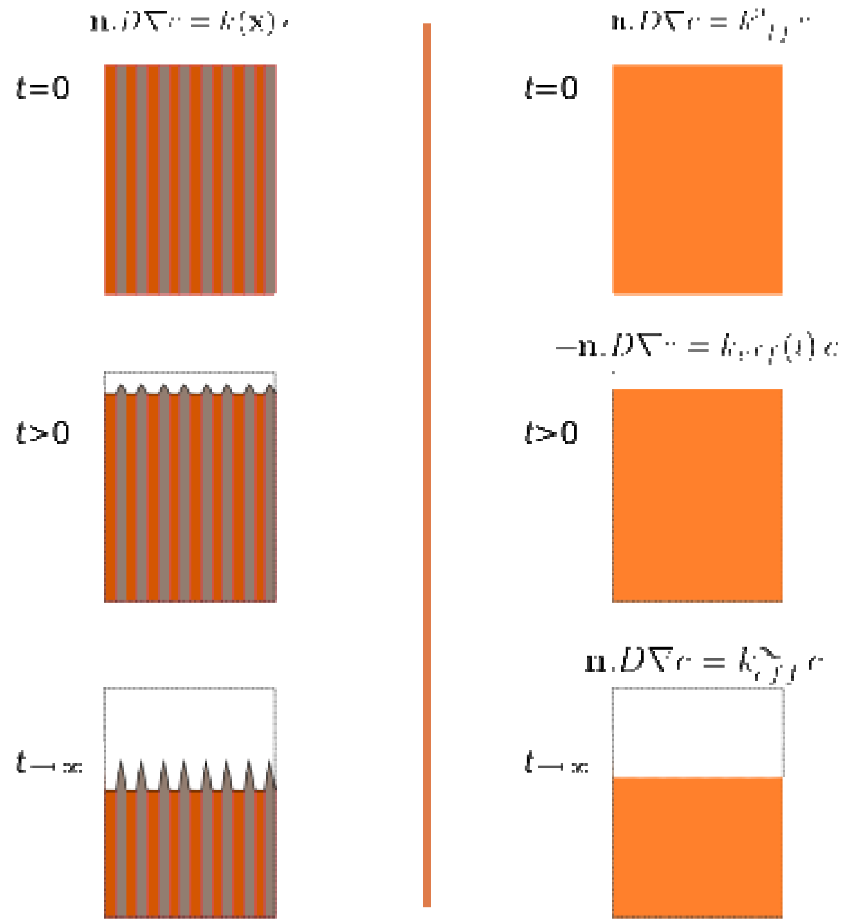


Example 2: ablation of composite structures

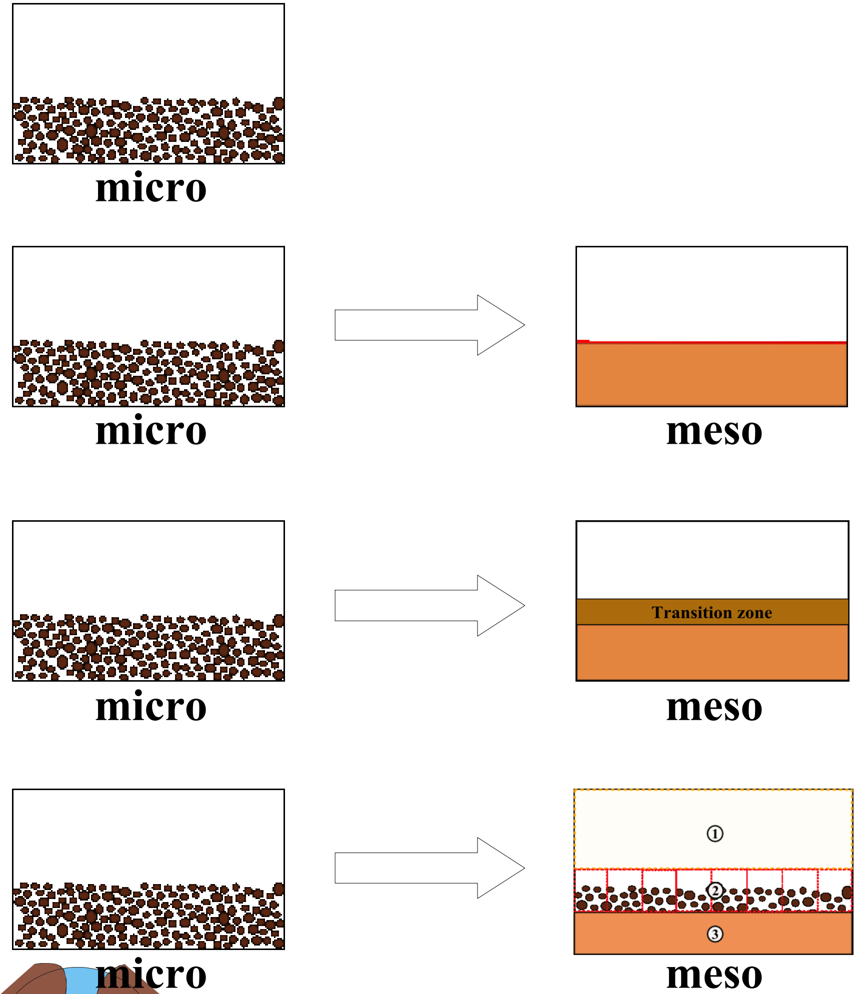




Upscaling Surface Heterogeneities: The concept of Effective Surface



Non-ablative case: various approaches



Direct Simulation

$\langle c \rangle + \tilde{c}$ → **Effective surface, effective BC (jump conditions)**

Eg : Ochoa et al., Wood et al., Valdès-Parada et al.

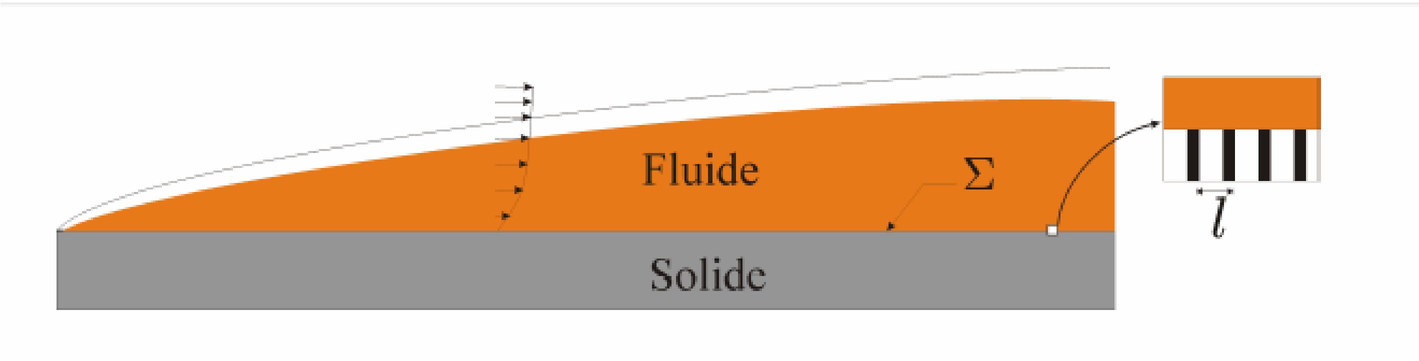
Meso-scale modelling, GTE → Effective surface, effective BC

Eg : Chandesris et al., Goyeau et al.

Domain decomposition

Achdou et al., Jäger and Mikelic, …

Extension of Wood et al. (2000)



Flow: Blasius

$$\mathbf{u}.\nabla c = \nabla . D \nabla c \quad \text{in the fluid domain}$$

$$-\mathbf{n}_{\gamma\kappa} . D \nabla c = k(\mathbf{x})\, c \quad \text{at} \quad \Sigma$$

$$c(y = h) = C_0 \quad \text{at top of B.L.}$$

$$c(x = x_0) = c(x = x_0 + l)$$

Extension of Wood et al. (2000)

$$c = \langle c \rangle + \tilde{c}$$

with

$$\mathbf{u}.\nabla \langle c \rangle = \nabla.D\nabla \langle c \rangle \quad \text{in the fluid domain}$$

$$-\mathbf{n}_{\gamma\kappa}.D\nabla \langle c \rangle = \langle k(\mathbf{x})\, c \rangle_{\Sigma} \quad \text{at} \quad \Sigma$$

and

$$\mathbf{u}.\nabla \tilde{c} = \nabla.D\nabla \tilde{c} \quad \text{in the fluid domain}$$

$$-\mathbf{n}_{\gamma\kappa}.D\nabla \tilde{c} = k\,\tilde{c} + \tilde{k}\,c - \langle k\,\tilde{c} \rangle_{\Sigma} \quad \text{at} \quad \Sigma$$

Extension of Wood et al. (2000)

$$\tilde{c} = s(\mathbf{x})\langle c \rangle + \ldots$$

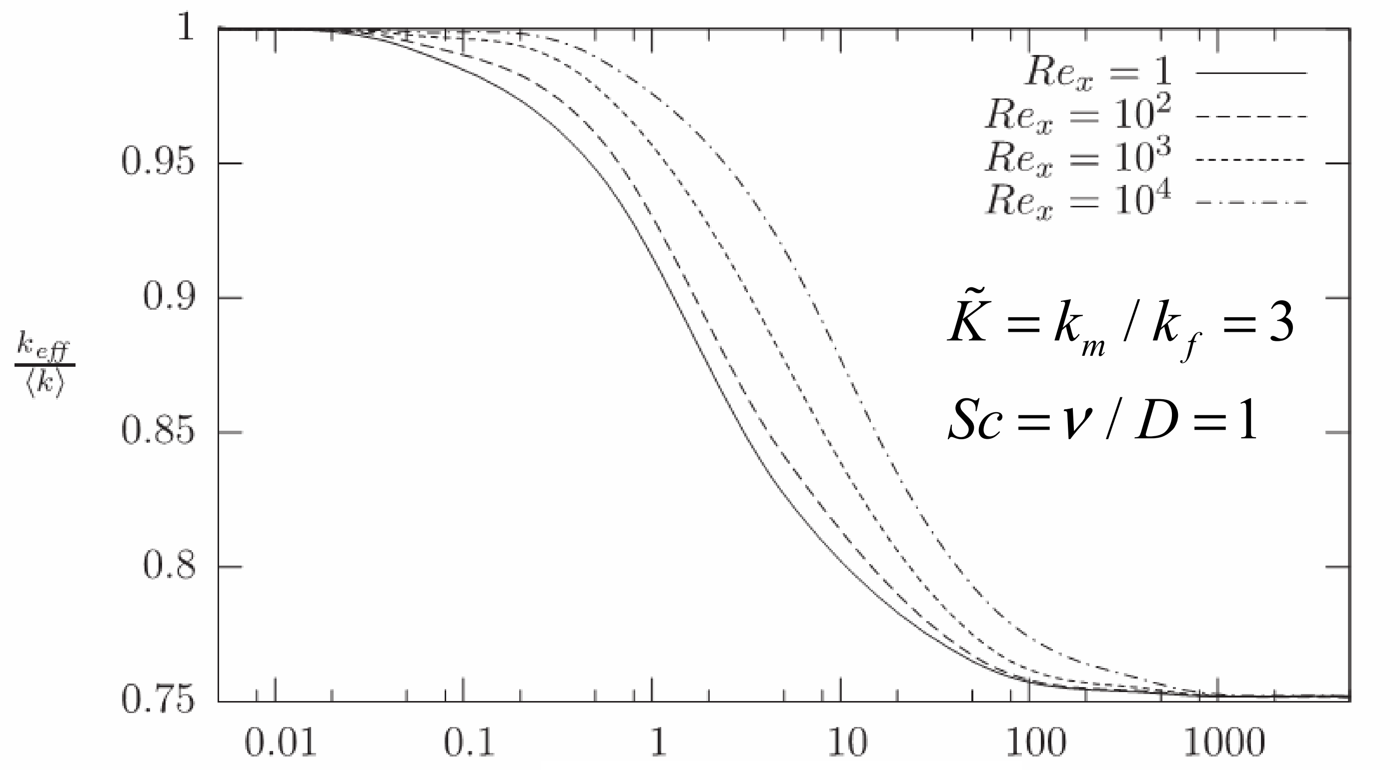
with

$$\mathbf{u}.\nabla s = \nabla.D\nabla s \quad \text{in the fluid domain}$$

$$-\mathbf{n}_{\gamma\kappa}.D\nabla s = k\,s + \tilde{k} - \left\langle \tilde{k}\,s \right\rangle_{\Sigma} \quad \text{at} \quad \Sigma$$

$$k_{eff} = \langle k \rangle_{\Sigma} + \left\langle \tilde{k}\,s \right\rangle_{\Sigma}$$

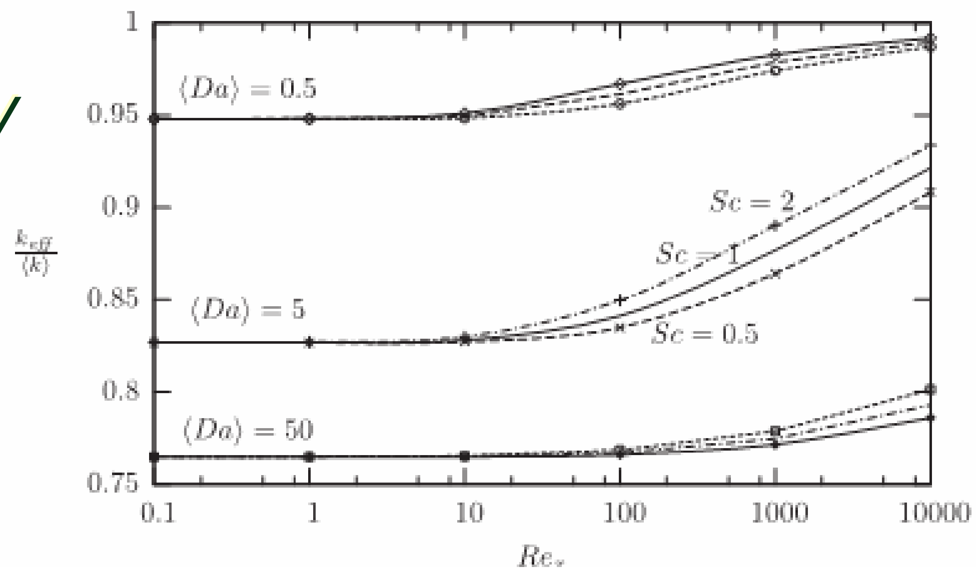
Results for circular patches (far from entrance region)



$$Da = kl / D$$

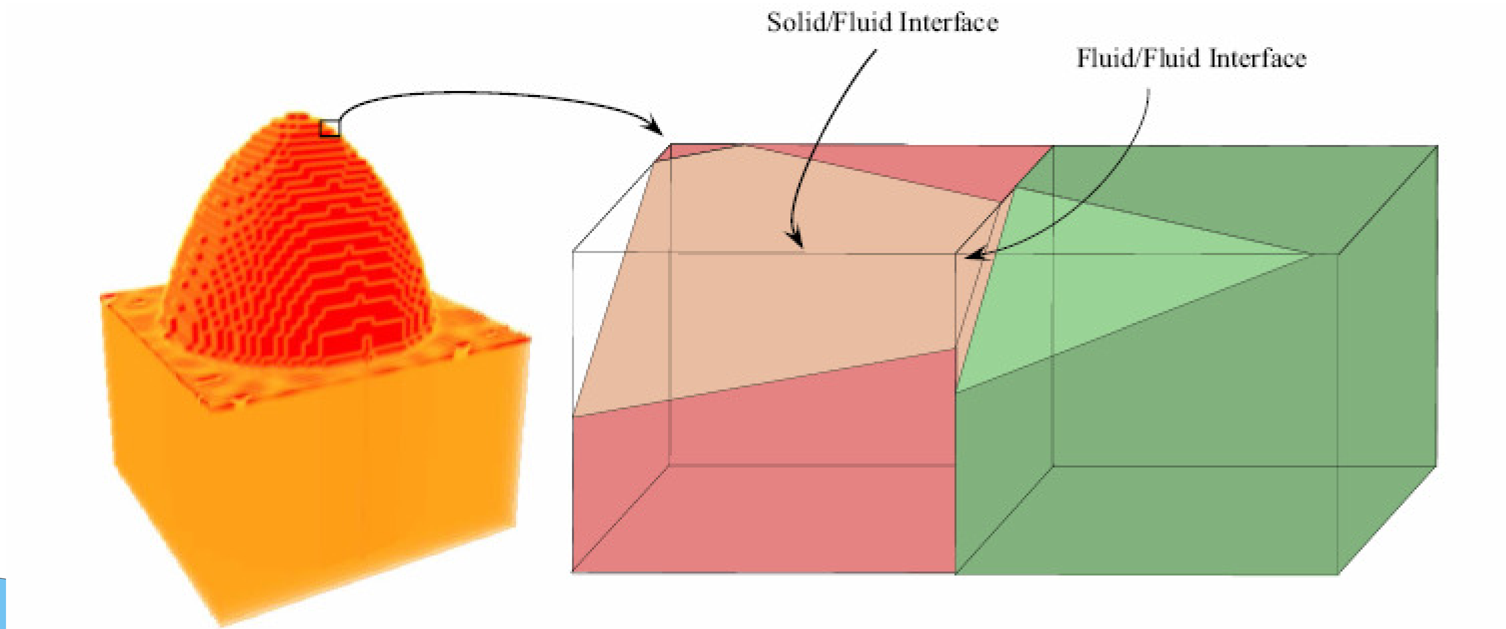
Results

- **two limit cases**
  - Da <<1, $c(x) = C_0$ → $k_{eff} = \langle k \rangle$
  - Da >>1, $k_{eff} = k^*$ (harmonic mean of the reactivities)
- **general case**
  - *influence of geometry*
  - *slight influence of Re (for low Re…)*

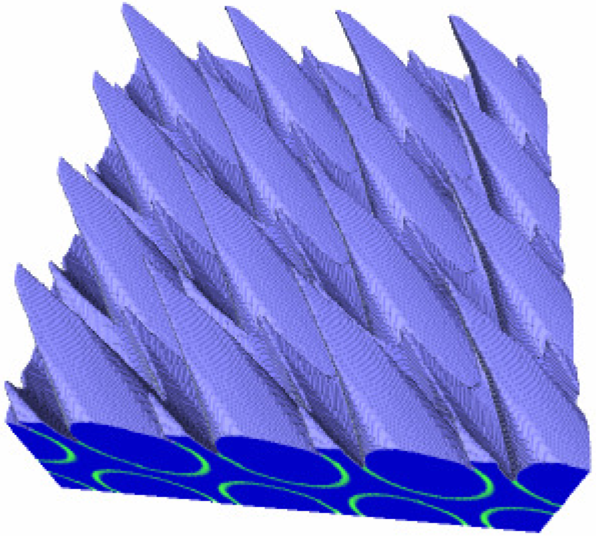


Ablative case: transient → DNS

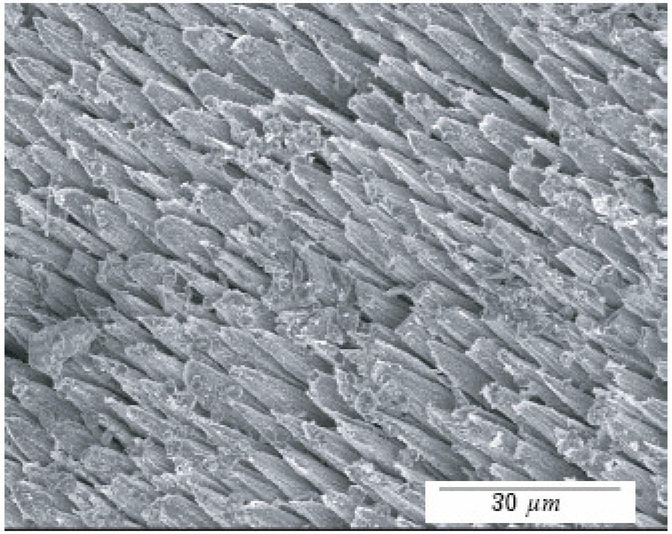
- Ablation leads to non-differentiable surfaces
- Limits of ALE and phase field methods → adapted VOF method (Aspa, 2006)



Example 1: steady-state surface



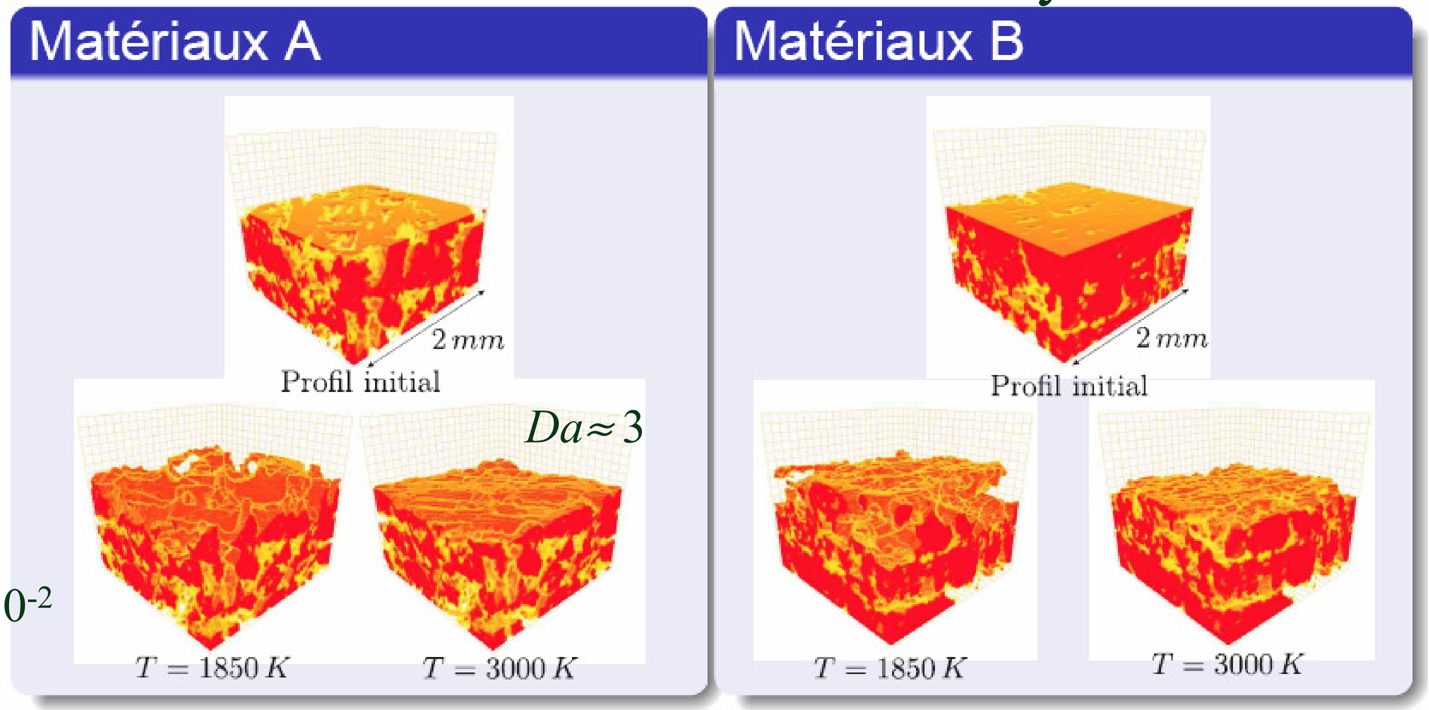
(a) Simulation avec $k_f = k_m = 0.4\,m/s$ et $k_i = 3.2\,m/s$



(b) Observation

Example 2: porous composites

Weaved Layered



$Da \approx 6\ 10^{-2}$

Note: *T* changes the “diffusion” coefficient

K_{eff} ? case Da<<1

- Projected Areas: $A_{m,p}$ and $A_{f,p}$
- Steady-state ablation: uniform velocity implies

$$\xi k_f \cos(\theta_f) = \xi k_m \cos(\theta_m) \Rightarrow$$

$$k_f \frac{A_f}{A_{f,p}} = k_m \frac{A_m}{A_{m,p}} \Rightarrow \frac{A_f}{A_{f,p}} = \tilde{k}$$

$$k_{eff} = \langle k \rangle \approx k_m$$

$$\neq \langle k \rangle_{t=0}$$

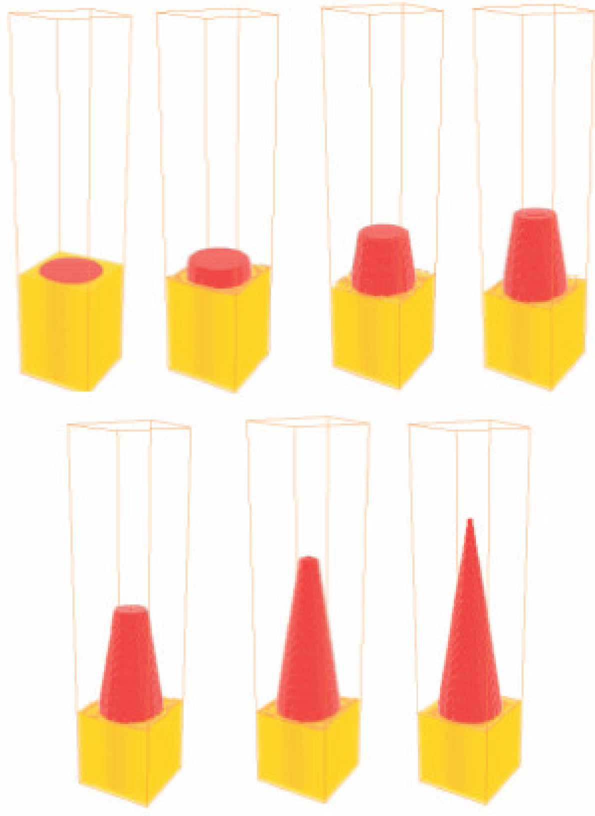
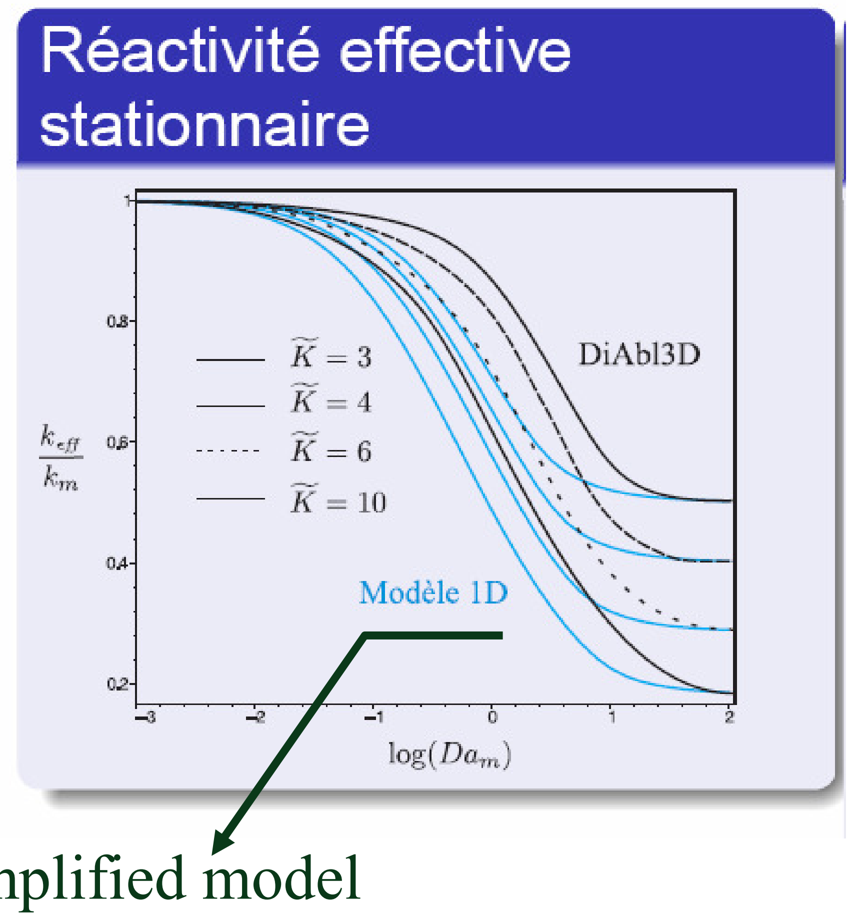


Fig. 1 – Évolution Morphologique d'une cellule avec $\tilde{k} = 7$

K_{eff} ?

- **Limit Cases: simple models**
  - **Da<<1, max(*k*)**
  - **Da>>1, *k*-harmonic mean**
- **Intermediate Da → complex simulations**

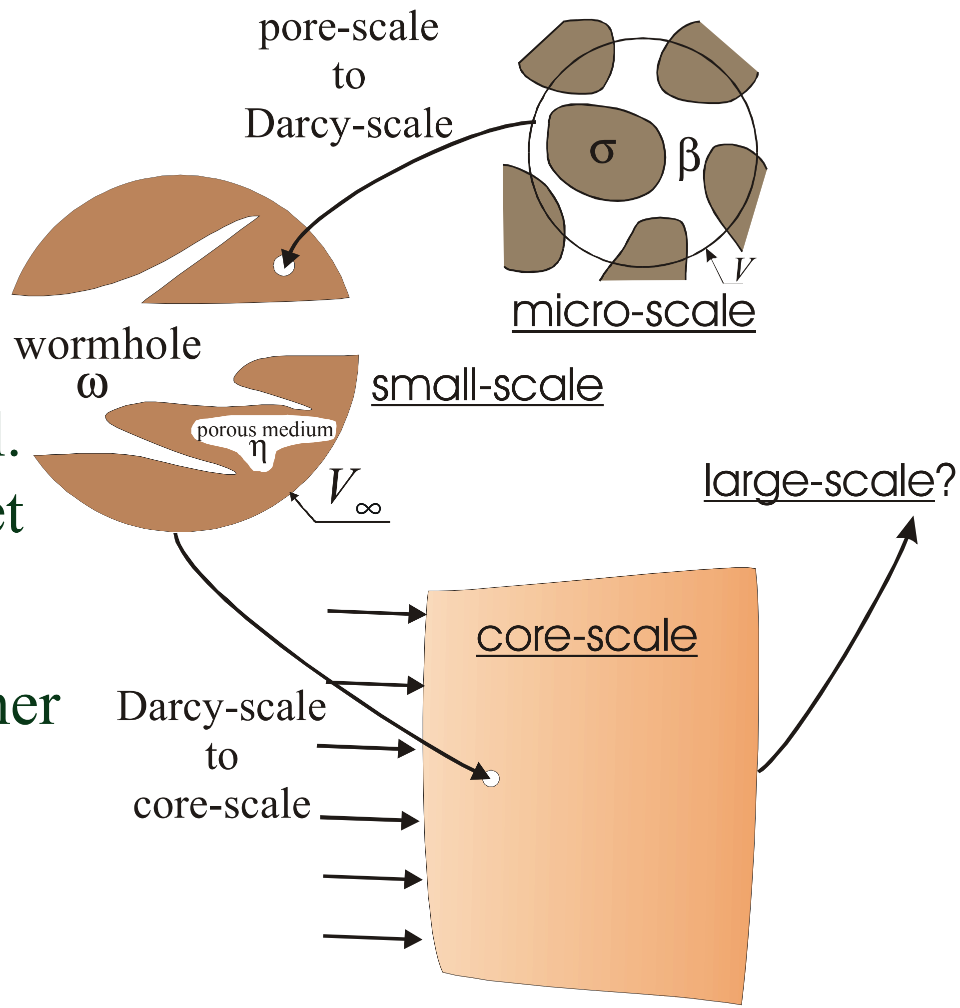


Dissolution: Darcy-scale (core-scale) models?

- **Pore-scale: non-local effects (space and time)**

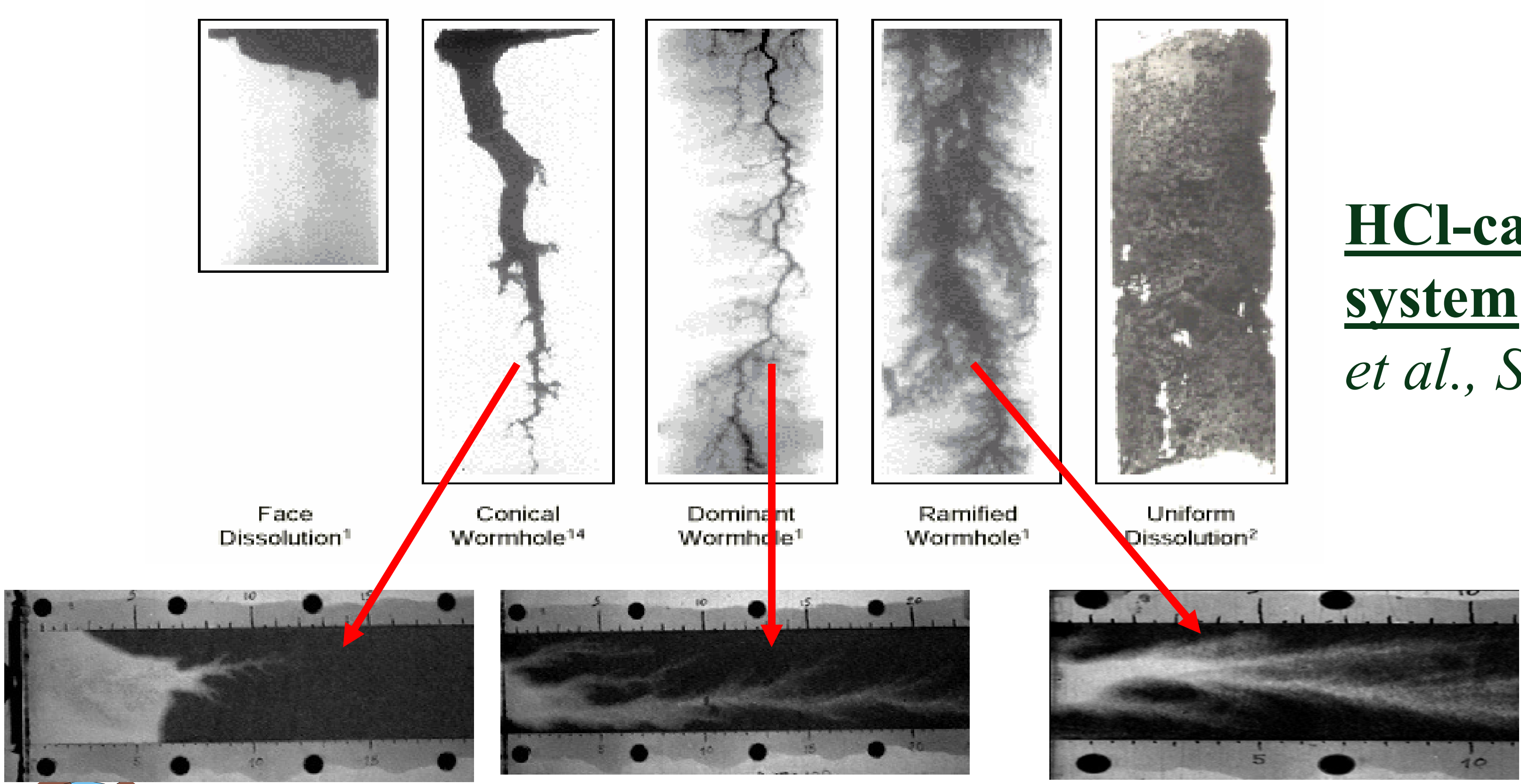
• *Direct Simulation* : Bekri et al. (1995), Mercet (2000), Zhang et Smith (2001), …

•*Network models* (Fredd, Hoefner et al.)



Target 1: Dissolution Instabilities (Wormholing)

FLOW RATE



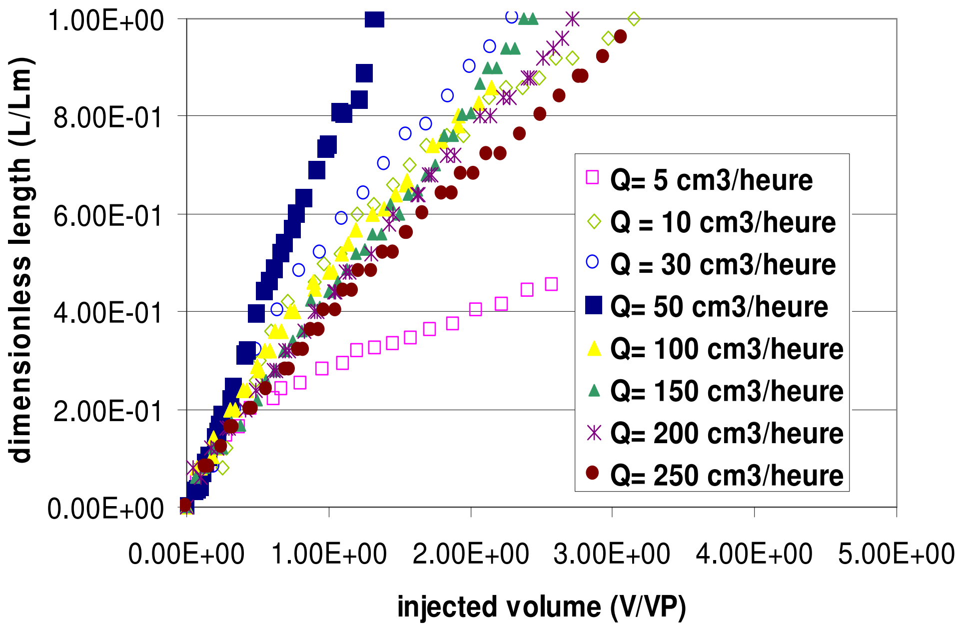
HCl-calcite system *(Fredd et al., SPE)*

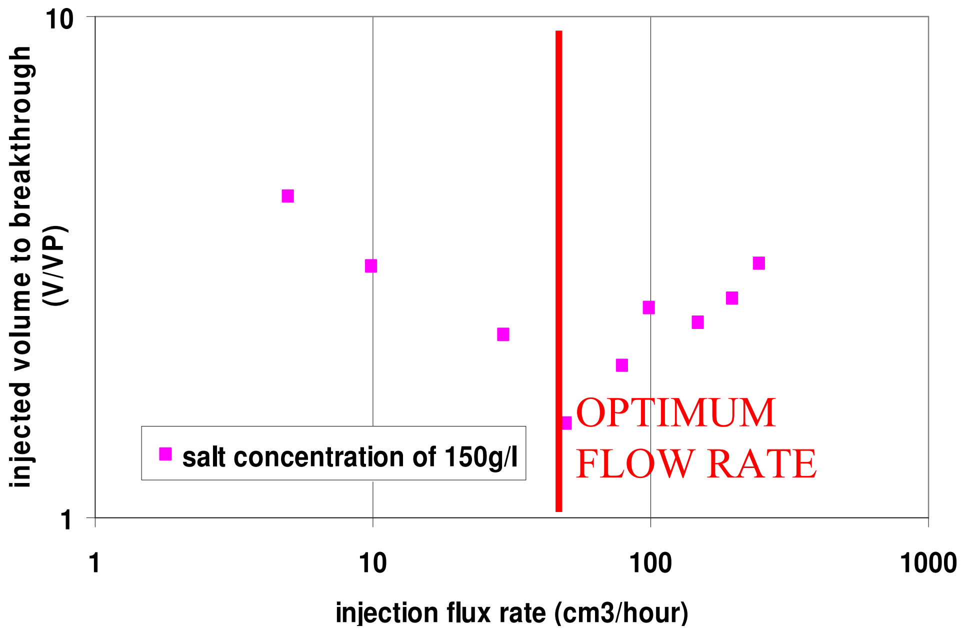
water-NaCl system *(Zarcone et al.)*

Target 2: “Optimum flow rate”

Optimum injection rate: minimum injected acid volume to breakthrough

$$Q_{opt} = f\,(\text{length core}, C_{NaCl} \ldots)$$





NaCL Concentration of 150 g/l

Simplified Pore-scale problem

$$N.-S.$$

$$+$$

$$\frac{\partial c}{\partial t}+\nabla.\left(\mathbf{v}c\right)=\nabla.\left(D\nabla c\right) \quad \text{in the fluid domain}$$

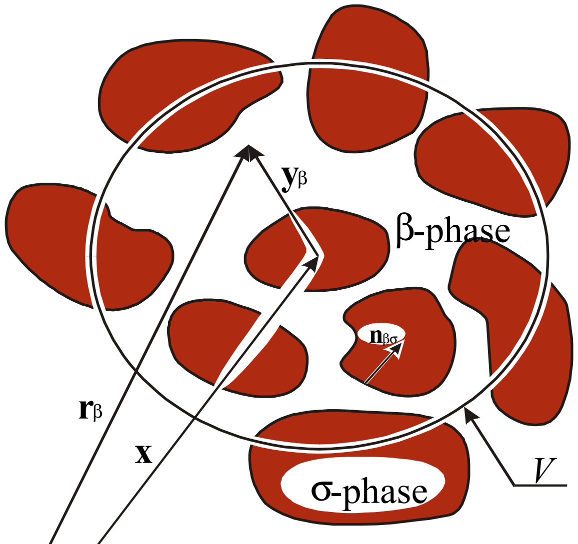
$$c=C_{eq} \quad \text{at } A_{\beta\sigma}$$

Note (binary case):

$$-\mathbf{n}.D\nabla c=kc \quad \Leftrightarrow \quad c=C_{eq}\approx 0 \;\; \text{at } A_{\beta\sigma} \;\; \text{if } Da>>1$$

Darcy-scale: Local Non-Equilibrium Models

- **Local equilibrium dissolution:** $C_{A\beta} = \langle c_{A\beta} \rangle^{\beta} = C_{eq}$ **produces sharp fronts**
- **LNE: Heuristic model classically used in Chemical Engineering (discussion in Quintard & Whitaker, 1994, 1999)**



$$C_{A\beta} = \langle c_{A\beta} \rangle_{\mathbf{x}}^{\beta} = \frac{1}{V_\beta} \int_{V_\beta} c_{A\beta}(\mathbf{x}+\mathbf{y}) dV$$

$$\varepsilon \frac{\partial C}{\partial t} + \mathbf{V}.\nabla C = \nabla.\left(\mathbf{D}^{*}.\nabla C\right) - \alpha C$$

$+$ additional terms

$+$ other macro-scale equations

Upscaling (framework)

(Quintard and Whitaker, 1999; Golfier et al., 2001)

- **Deviations** $\mathbf{v}_\beta = \varepsilon_\beta^{-1}\mathbf{V}_\beta + \tilde{\mathbf{v}}_\beta \qquad c_{A\beta} = C_{A\beta} + \tilde{c}_{A\beta}$
- **Coupled pore-scale and averaged equations**

$$\frac{\partial\left(\varepsilon_\beta C_{A\beta}\right)}{\partial t} + \nabla\cdot\left(\mathbf{V}_\beta C_{A\beta}\right) + \frac{1}{V}\int_{A_{\beta\sigma}} \mathbf{n}_{\beta\sigma}\cdot c_{A\beta}\left(\mathbf{v}_{A\beta} - \mathbf{w}\right) dA = \nabla\cdot\left[D\left(\varepsilon_\beta \nabla C_{A\beta} + \frac{1}{V}\int_{A_{\beta\sigma}} \mathbf{n}_{\beta\sigma}\tilde{c}_{A\beta} dA\right)\right] - \nabla\cdot\left\langle \tilde{\mathbf{v}}_\beta \tilde{c}_{A\beta}\right\rangle$$

$$+$$

$$\frac{\partial \tilde{c}_{A\beta}}{\partial t} + \tilde{\mathbf{v}}_\beta\cdot\nabla C_{A\beta} + \mathbf{v}_\beta\cdot\nabla\tilde{c}_{A\beta} - \underbrace{\varepsilon_\beta^{-1}\nabla\cdot\left\langle\tilde{\mathbf{v}}_\beta\tilde{c}_{A\beta}\right\rangle}_{\ll \mathbf{v}_\beta\cdot\nabla\tilde{c}_{A\beta}} = \nabla\cdot\left(D\nabla\tilde{c}_{A\beta}\right) - \underbrace{\varepsilon_\beta^{-1} D\nabla\cdot\left[\frac{1}{V}\int_{A_{\beta\sigma}} \mathbf{n}_{\beta\sigma}\tilde{c}_{A\beta} dA\right]}_{\ll \nabla\cdot\left(D\nabla\tilde{c}_{A\beta}\right)} - \frac{\varepsilon_\beta^{-1}}{V}\int_{A_{\beta\sigma}} \mathbf{n}_{\beta\sigma}\cdot D\nabla\tilde{c}_{A\beta} dA$$

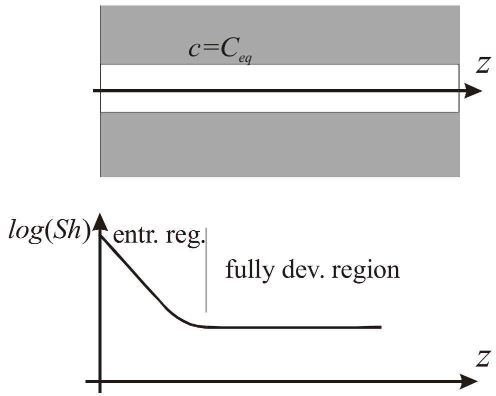
$+ \ldots\ldots$

Upscaling : problems

- Quasi-steady dissolution: terms like $\mathbf{n}_{\beta\sigma}\cdot\left(\mathbf{v}_{A\beta}-\mathbf{w}\right)$ may be neglected in the problem for the deviations
- "Closure"= approximate solution of the coupled equations
  - Quasi-steady solution?
  - *But…historical effect remains through the interface evolution*

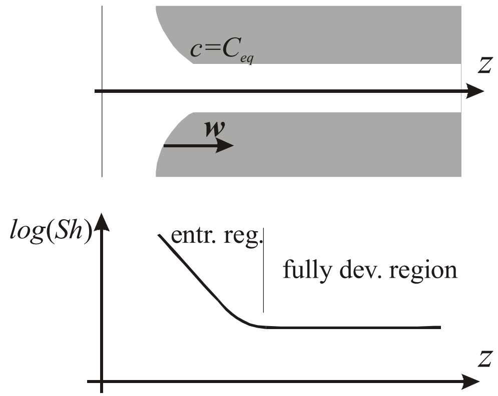
A simple example: the tube problem (Graetz's problem, Pe>>1)

- **Classical Problem**



$$\alpha(\mathbf{x}, V, D..)$$

- **Dissolution**



$$\alpha(\mathbf{x}, t, V, D..)$$

Non-local in space and time?

…see Golfier et al. (2001), Pierre et al. (2005)

2D and 3D cases (MQ & SW, 94, 99, FG et al., 2002)

- **Representation of the deviations:**

$$\tilde{c}_{A\beta} = c_{A\beta} - \left\langle c_{A\beta} \right\rangle^{\beta} = \mathbf{b}_{\beta} \cdot \nabla \left\langle c_{A\beta} \right\rangle^{\beta} - s_{\beta} \left\langle c_{A\beta} \right\rangle^{\beta} + \ldots$$

- **Darcy-Scale equation:**

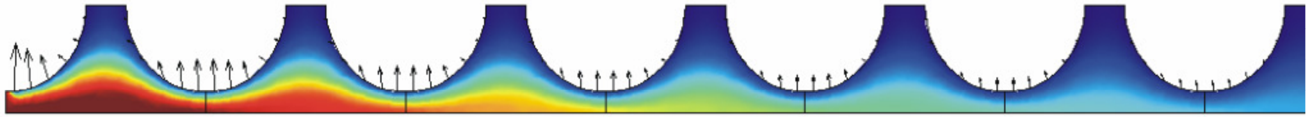
$$\frac{\partial}{\partial t}\left(\varepsilon_{\beta} \langle c_{A\beta} \rangle^{\beta}\right) + \nabla \cdot \left(\langle \mathbf{v}_{\beta} \rangle \langle c_{A\beta} \rangle^{\beta}\right) - \nabla \cdot \left[\mathbf{d}_{\beta} \langle c_{A\beta} \rangle^{\beta}\right] - \mathbf{u}_{\beta} \cdot \nabla \langle c_{A\beta} \rangle^{\beta}$$

$$= \nabla \cdot \left(\mathbf{D}^{*}_{\beta} \cdot \nabla \langle c_{A\beta} \rangle^{\beta}\right) - \alpha \langle c_{A\beta} \rangle^{\beta}$$

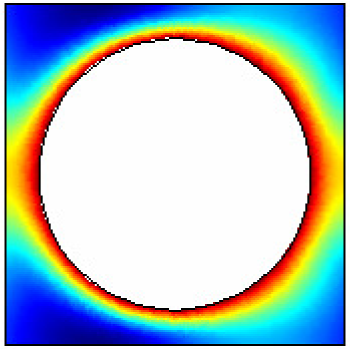
- **+ cell problems→"effective" properties**

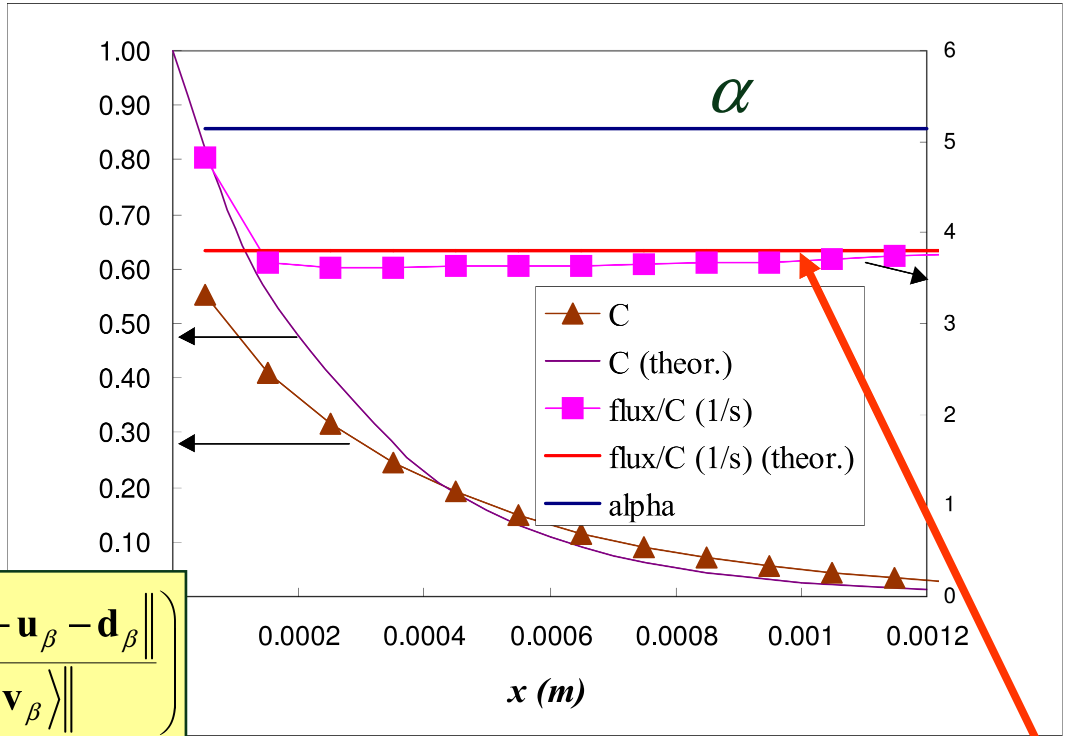
Comparison with numerical experiments

Pe=185



- numerical experiments over several unit cells
- solution of the closure problems over a unit cell





$$\alpha^* = \alpha \Bigg/ \left(\frac{\left\| \langle \mathbf{v}_\beta \rangle - \mathbf{u}_\beta - \mathbf{d}_\beta \right\|}{\left\| \langle \mathbf{v}_\beta \rangle \right\|} \right)$$

→ need the additional convective transport terms!

Problem with evolving geometry : Effective Coefficients (α, D_β, K)

- **Effective coefficients as a function of the time evolution of the interface (example of direct simul.: Bekri et al.)?**
  - ε (t)
  - α(t, Pe, …) → $\alpha(\varepsilon,Pe)$
  - D_β(t, Pe, …) → $D_\beta(\varepsilon,Pe)$
  - K(t) → K(ε)

Correlations obtained using: numerical simulation, closure pbs, experiments, …

Transport and Dissolution: numerical model

- Dimensionless equations

$$\varepsilon_\beta \frac{\partial C'_{A\beta}}{\partial t'} + \mathbf{V}'_{A\beta} . \nabla C'_{A\beta} = \frac{1}{Pe} \nabla \cdot \left(\mathbf{D}' \cdot \nabla C'_{A\beta} \right) - Da\, C'_{A\beta}$$

$$\frac{\partial \varepsilon_\beta}{\partial t'} = \frac{\left(1-\varepsilon_\beta\right)}{\varepsilon_\beta} Da\, N_{ac}\, C'_{A\beta}$$

+ **Darcy-Brinkman**

- Dimensionless numbers

$$F = \frac{L_1}{L_2} \qquad N_D = \frac{\mathbf{K}}{L_1^2}$$

$$Da = \frac{\alpha\, l}{\left|\mathbf{v_0}\right|}$$

Damköhler

$$Pe = \frac{\left|\mathbf{v_0}\right| l}{D}$$

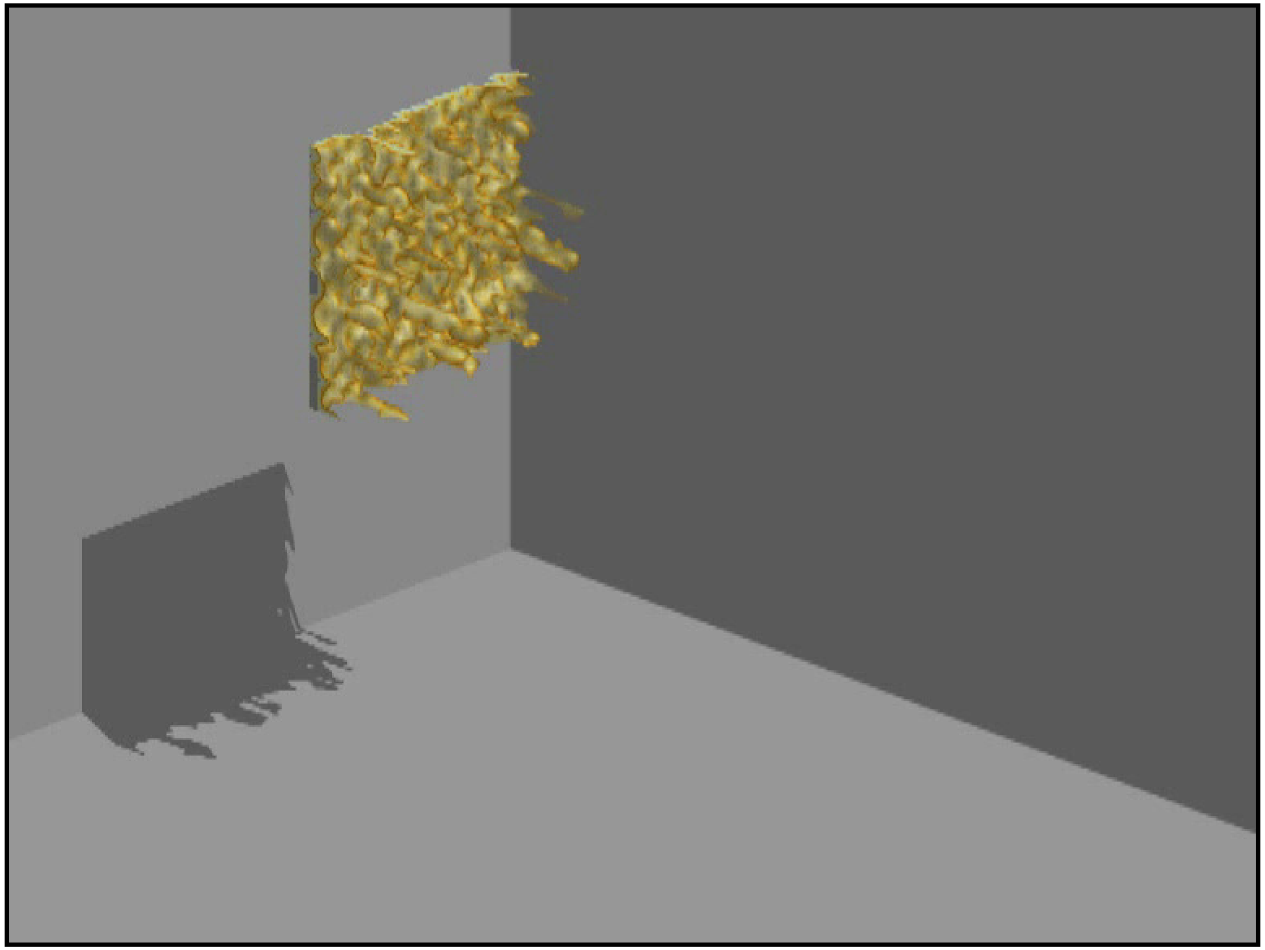
Péclet

$$N_{ac} = \frac{\varepsilon_\beta\, C_0\, \beta}{\left(1-\varepsilon_\beta\right)\rho_\sigma}$$

Acid capacity number

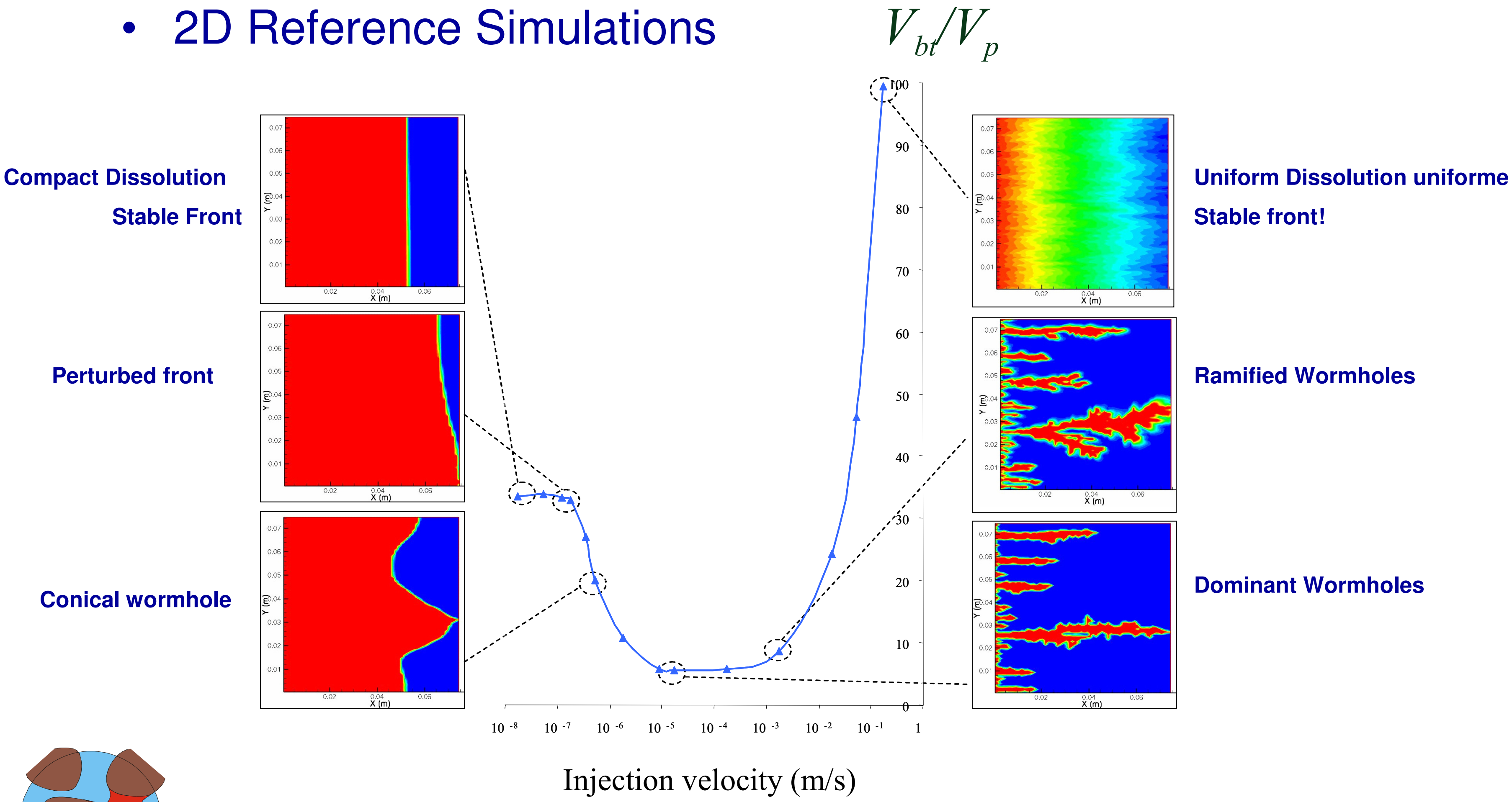
3D example

I.C.: random permeability field



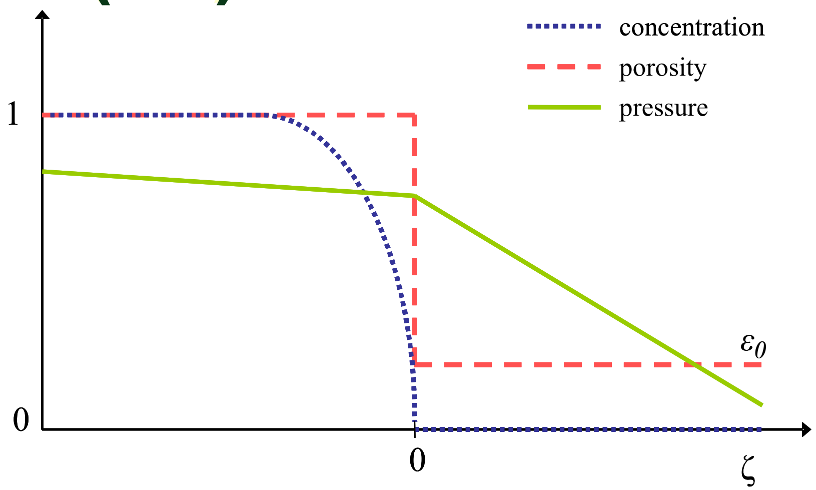
Stability Analysis

- 2D Reference Simulations



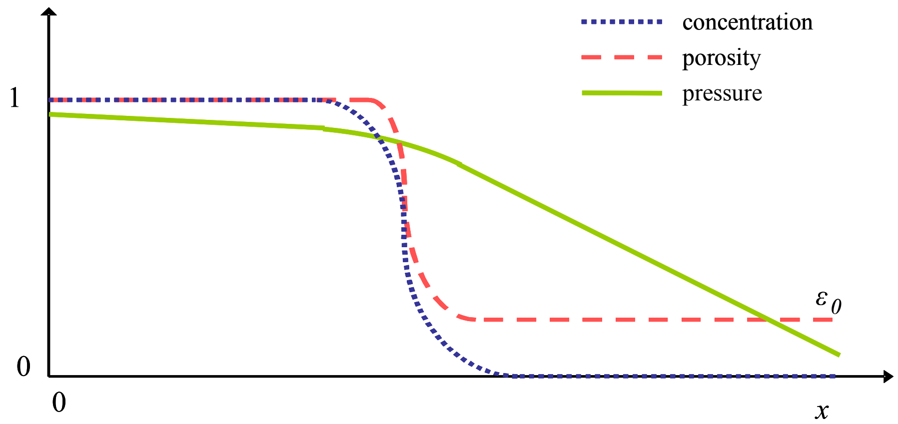
Stability of the linearised problem (Cohen, 2006)

- **Compact Front (LE)**



Autonomous Case

- **LNE**

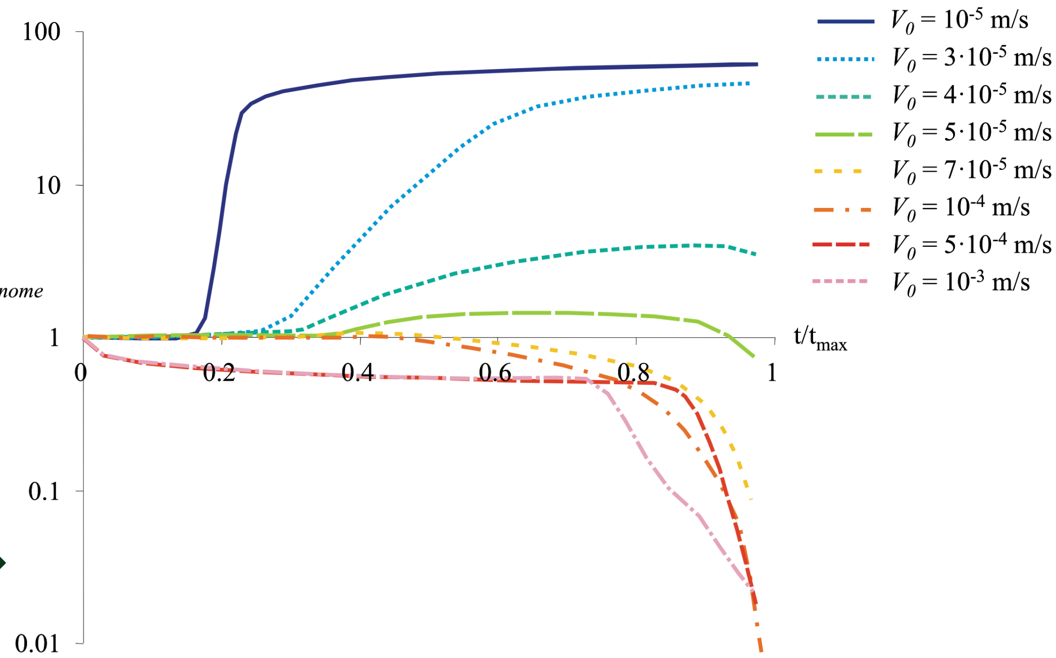


2 Cases: autonomous and non-autonomous

Case LNE

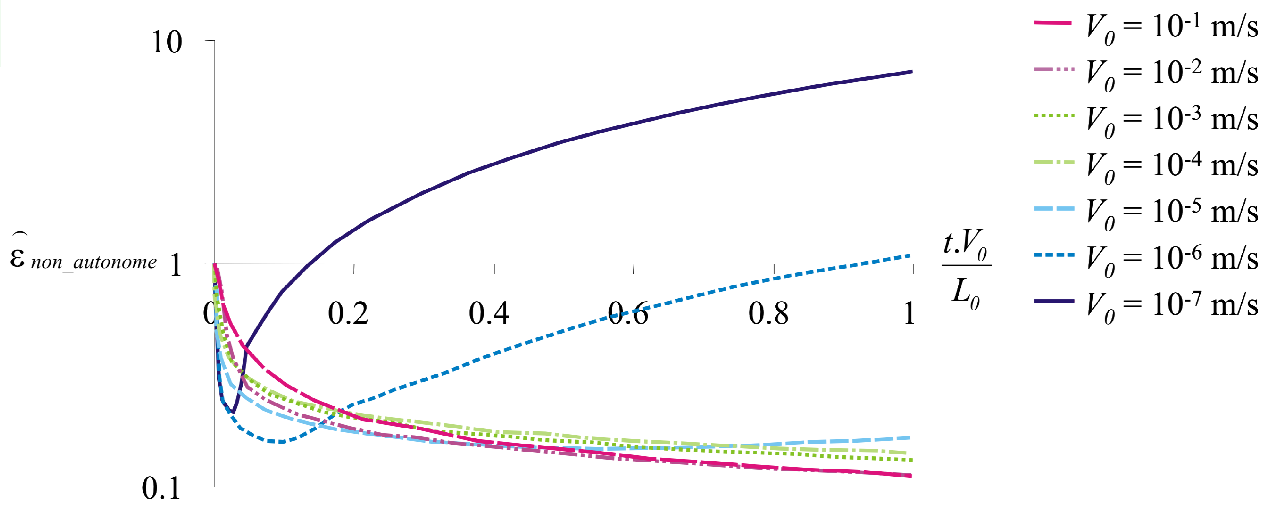
Amplitude Coefficient

$$\widehat{\varepsilon}_{autonome}(t) = \left(\frac{\int_\Omega f_\varepsilon^{\,2}(t)\,dz}{\int_\Omega f_\varepsilon^{\,2}(0)\,dz} \right)^{1/2}$$

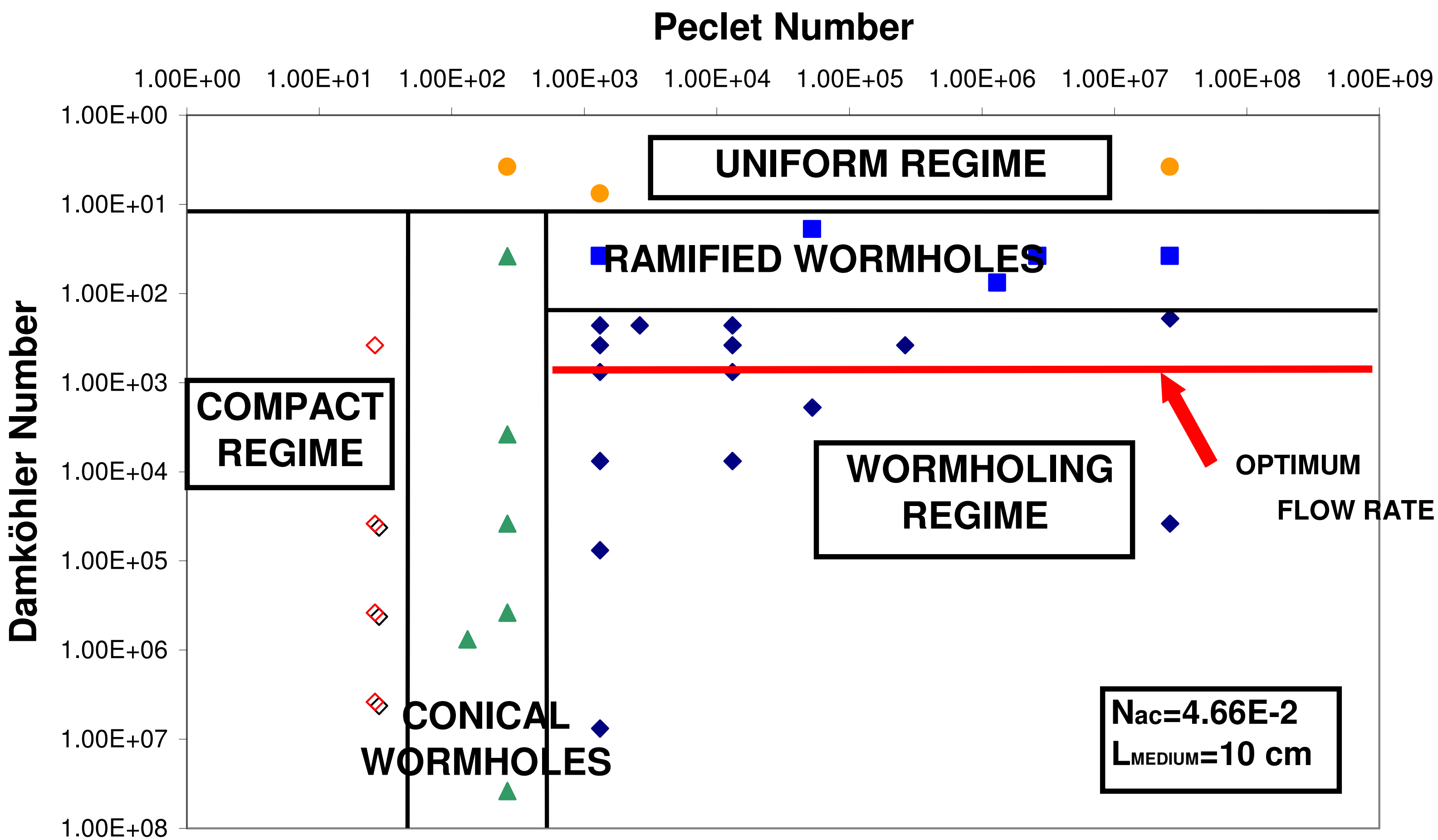


Front thickness growth → stabilizing effect

Non-autonomous Case



Dissolution Diagram (Golfier et al., 2001)



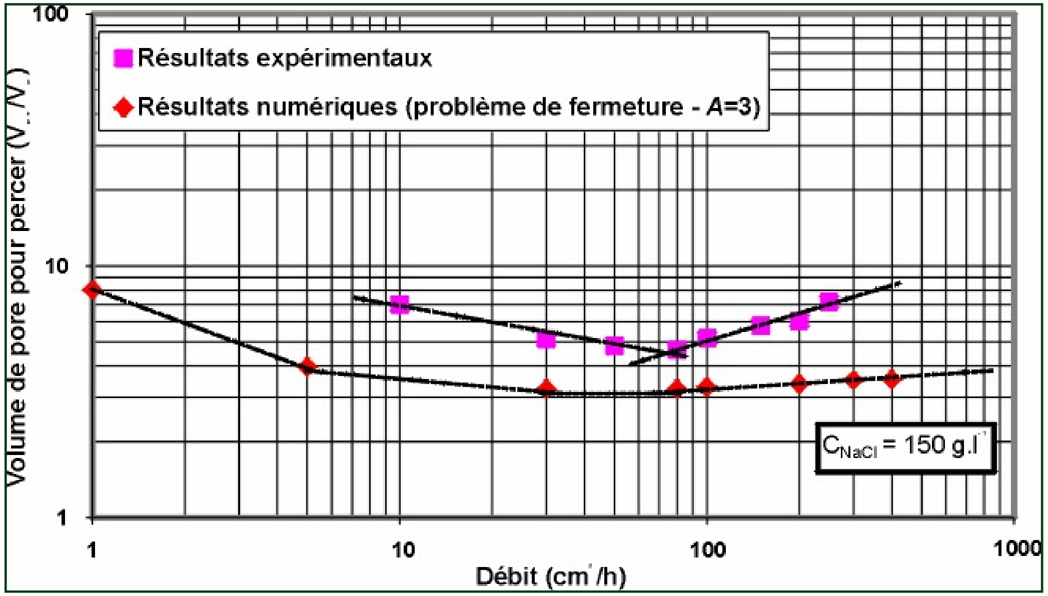
Peclet -Damköhler Diagram

"Optimum flow rate"

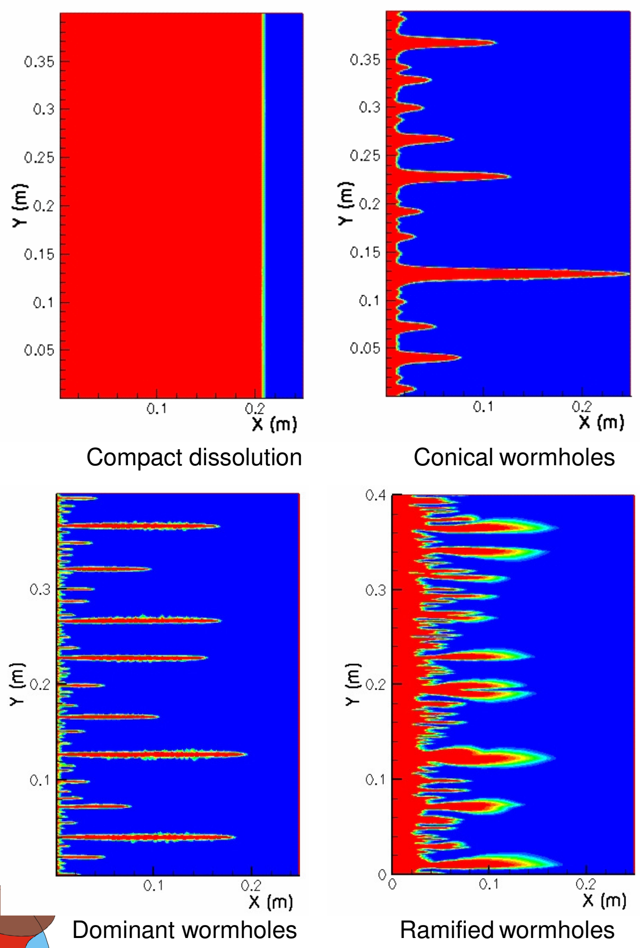
- **Need "mainly" to calibrate α**

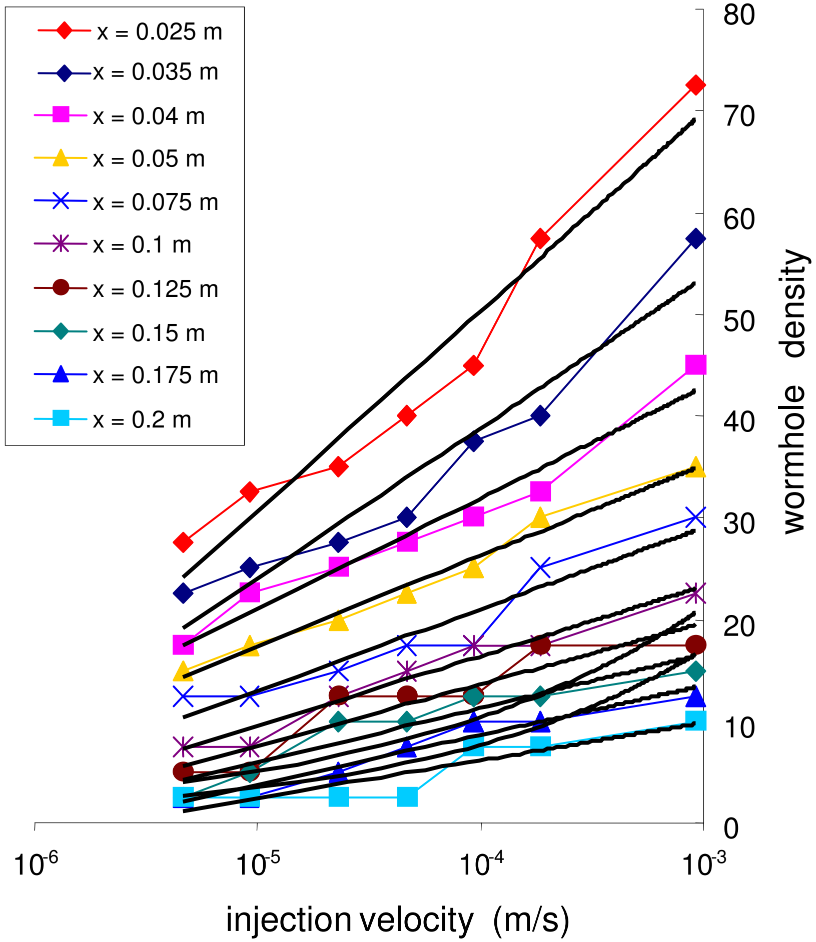
$$\alpha = A\alpha_0$$

where α_0 is the correlation obtained from the closure problem + simple unit cell

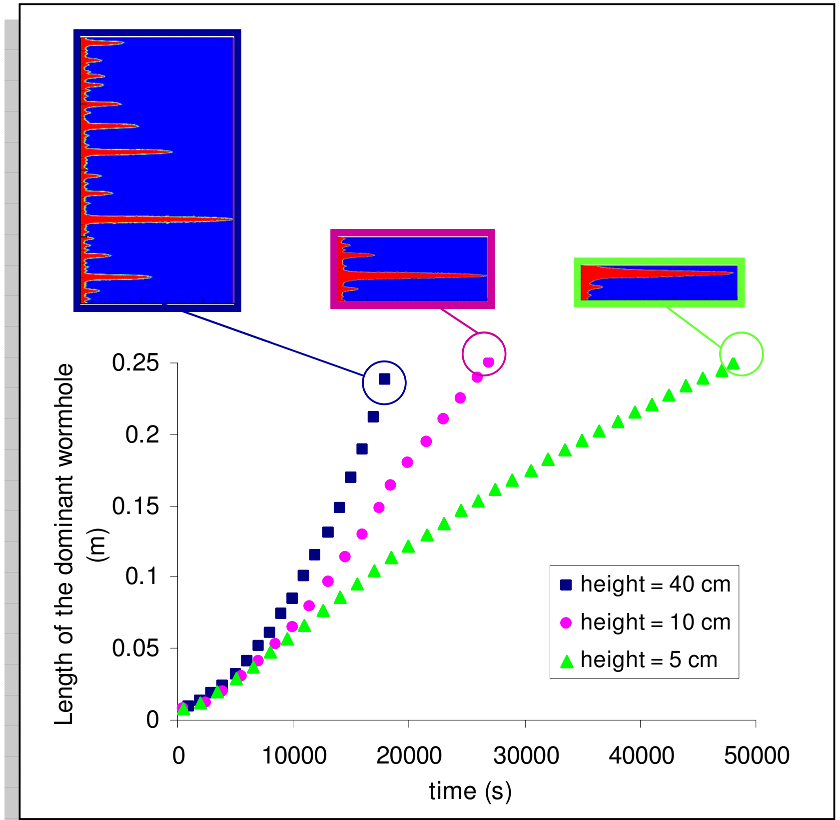


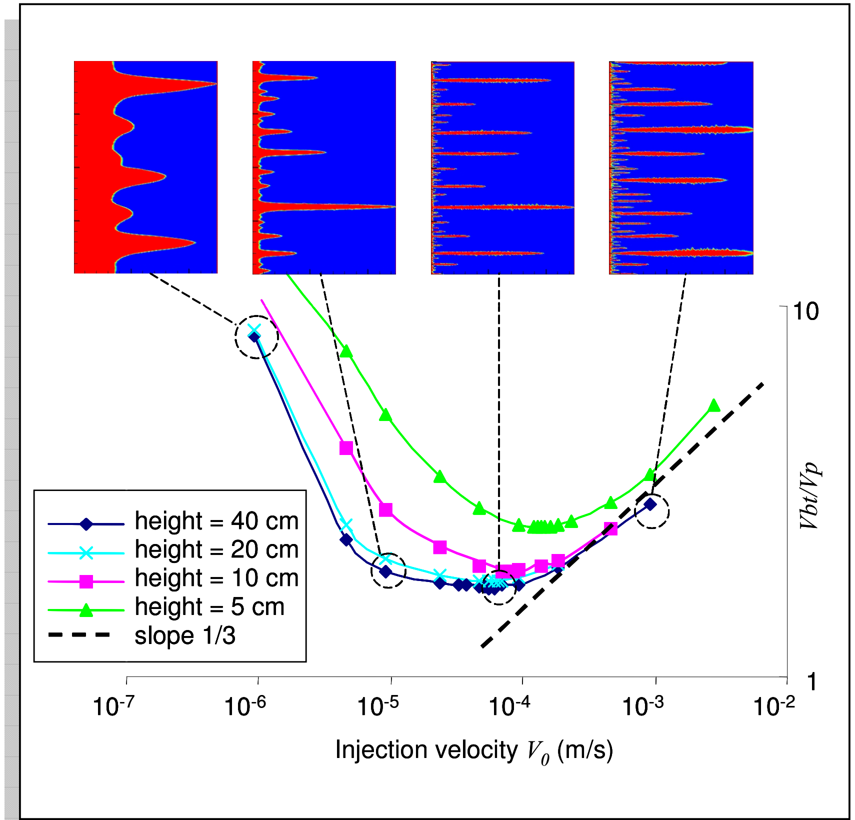
Confinement Effect: « wormhole competition », Cohen et al. (2007)





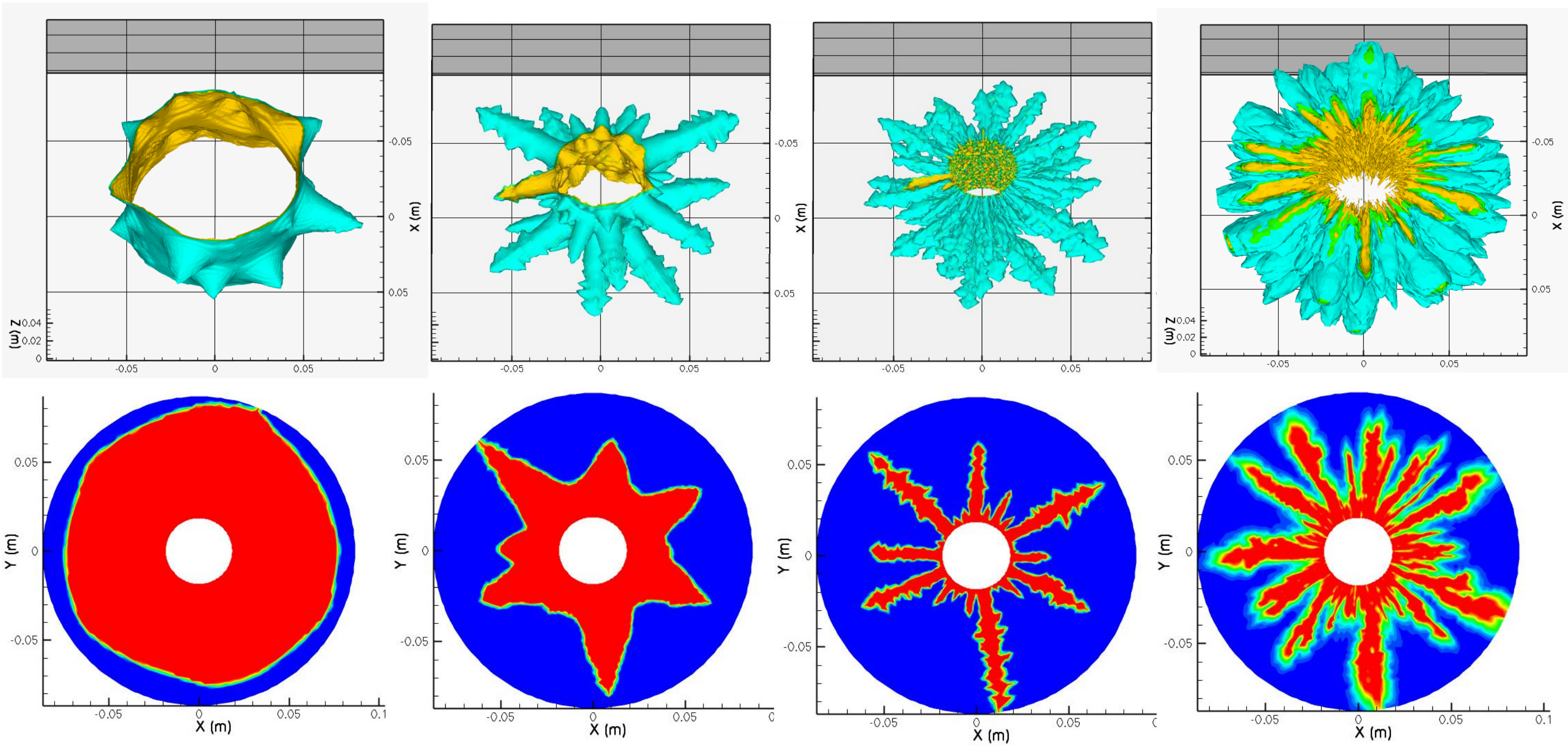
Confinement (cont.)





- **Dominant wormhole growth rate increases with domain height**
- **Optimum injection velocity increases with height decreasing**

Effect of geometry: ex. radial



$V_0 = 4.96 \cdot 10^{-7}$ m/s
$Pe = 1.57 \cdot 10^{-5}$
$Da = 6.37 \cdot 10^{-2}$

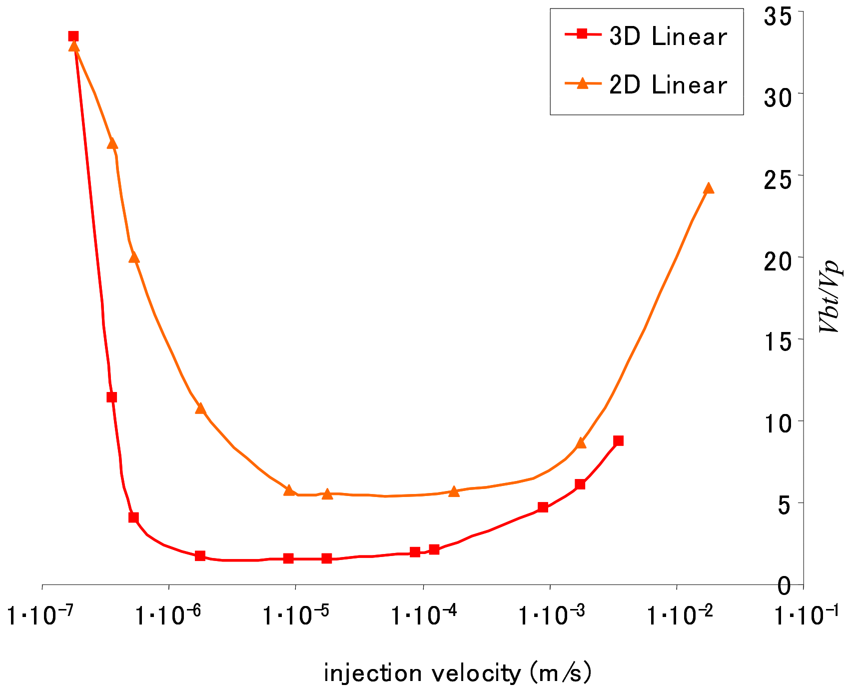
$V_0 = 1.65 \cdot 10^{-6}$ m/s
$Pe = 5.23 \cdot 10^{-5}$
$Da = 1.91 \cdot 10^{-2}$

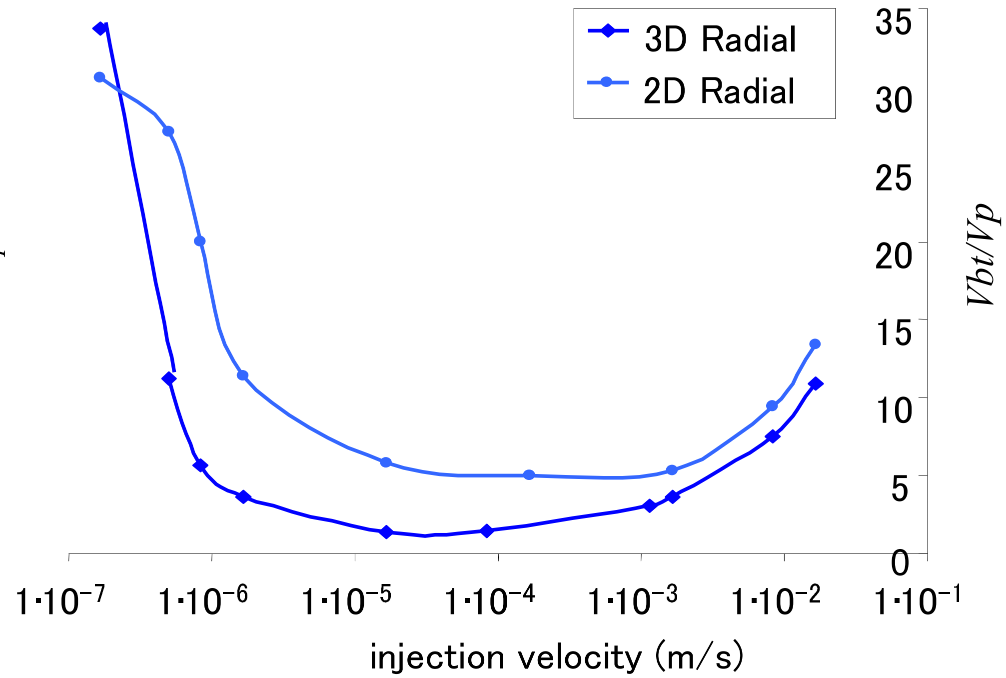
$V_0 = 1.65 \cdot 10^{-4}$ m/s
$Pe = 5.23 \cdot 10^{-4}$
$Da = 1.91 \cdot 10^{-3}$

$V_0 = 1.65 \cdot 10^{-2}$ m/s
$Pe = 5.23 \cdot 10^{-1}$
$Da = 1.91 \cdot 10^{-6}$

see Cohen, 2007

Effect of geometry on optimum flowrate





Extension of LNE models to complex phase diagrams, and multicomponent systems

- **Equilibrium conditions at $A_{\beta\sigma}$**

$$\begin{bmatrix} \vdots \\ \mu_{\beta i}\left(..,\left\langle c_{\beta j}\right\rangle^{\beta}+\tilde{c}_{\beta j},...\right) \\ \vdots \end{bmatrix} = \begin{bmatrix} \vdots \\ \mu_{\sigma i}\left(..,\left\langle c_{\sigma j}\right\rangle^{\sigma}+\tilde{c}_{\sigma j},...\right) \\ \vdots \end{bmatrix}$$

$$\begin{bmatrix} \vdots \\ \mu_{\beta i}\left(..,\left\langle c_{\beta j}\right\rangle^{\beta},...\right) \\ \vdots \end{bmatrix} + \begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & \left.\dfrac{\partial \mu_{\beta i}}{\partial c_{\beta j}}\right|_{\left\langle c_{\beta}\right\rangle^{\beta}} & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix} \begin{bmatrix} \tilde{c}_{\beta} \end{bmatrix} = \begin{bmatrix} \vdots \\ \mu_{\sigma i}\left(..,\left\langle c_{\sigma j}\right\rangle^{\sigma},...\right) \\ \vdots \end{bmatrix} + \begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & \left.\dfrac{\partial \mu_{\sigma i}}{\partial c_{\sigma j}}\right|_{\left\langle c_{\sigma}\right\rangle^{\sigma}} & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix} \begin{bmatrix} \tilde{c}_{\sigma} \end{bmatrix}$$

Expression for the mass exchange terms

$$\begin{bmatrix} \cdot \\ \mu_\beta\big|_{\langle c_\beta\rangle^\beta} \\ \cdot \end{bmatrix} + J_\beta \begin{bmatrix} \tilde{c}_\beta \end{bmatrix} = \begin{bmatrix} \cdot \\ \mu_\sigma\big|_{\langle c_\sigma\rangle^\sigma} \\ \cdot \end{bmatrix} + J_\sigma \begin{bmatrix} \tilde{c}_\sigma \end{bmatrix}$$

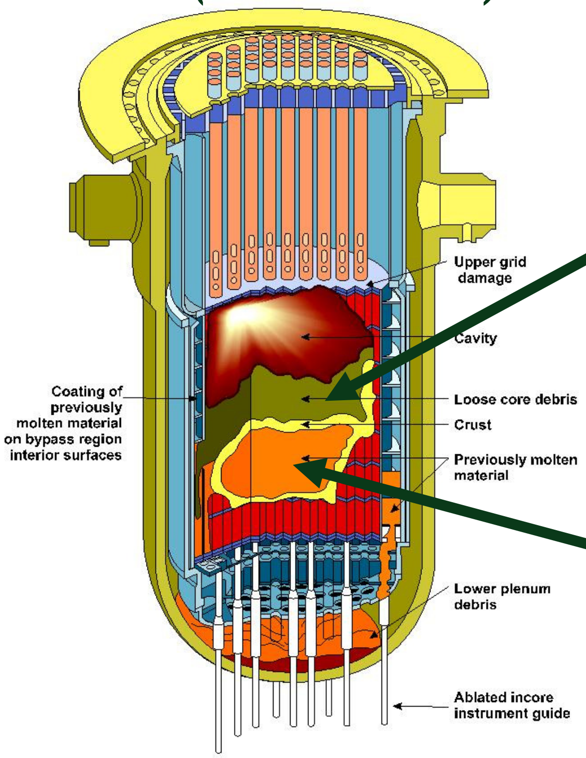
- **Case 1: diagonal J_β and J_σ**

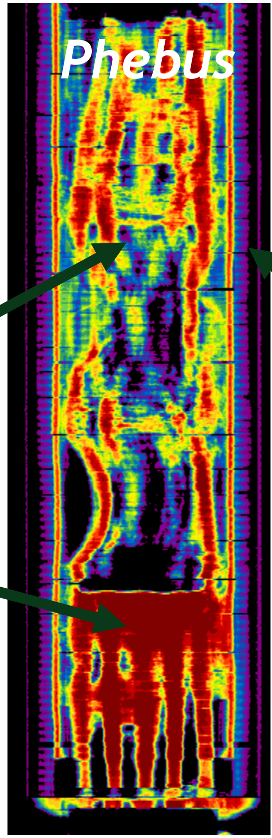
$$\text{exchange term for species } i \div \mu_{\beta i}\big|_{\langle c_\beta\rangle^\beta} - \frac{J_{\sigma i}}{J_{\beta i}} \mu_{\sigma i}\big|_{\langle c_\sigma\rangle^\sigma}$$

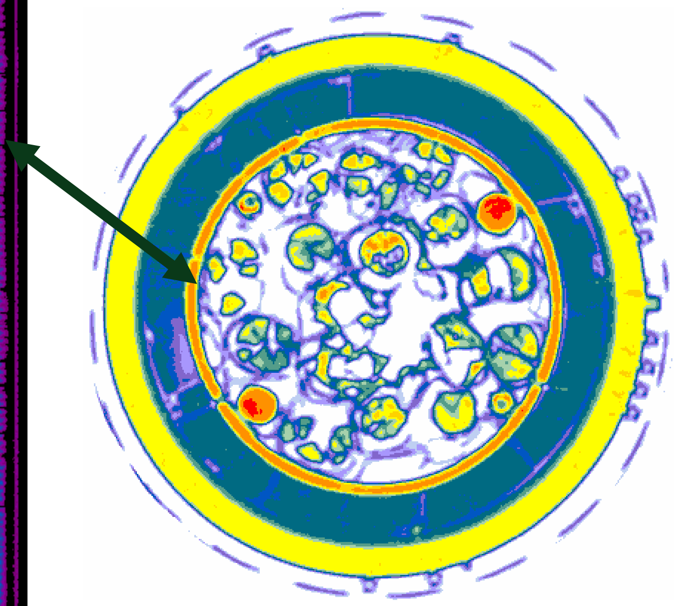
- **General case?**

Example: ZrO_2 / Zr (Belloni, 2008)

TMI-2 (28 mars 1979)







Example: ZrO_2 / Zr **(Belloni, 2008)**

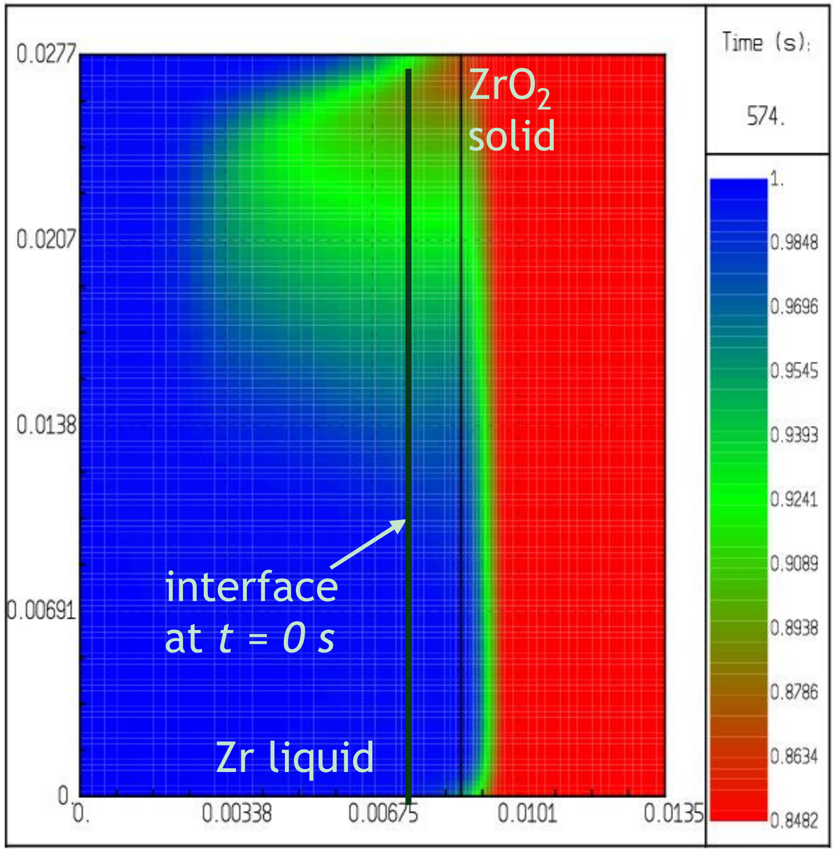
$$\frac{\partial}{\partial t}\left(\varepsilon_l\rho_l\langle C_l\rangle^l\right)+\nabla.\left(\varepsilon_l\rho_l\langle C_l\rangle^l\langle \mathbf{v}_l\rangle^l\right)$$
$$+C_l^*\frac{\partial}{\partial t}(\varepsilon_s\rho_s)=$$
$$\nabla.\left(\varepsilon_l\rho_l\mathbf{D}_l.\nabla\langle C_l\rangle^l\right)+\rho_l h_{ml}(C_l^*-\langle C_l\rangle^l)$$

+ similar equation for s

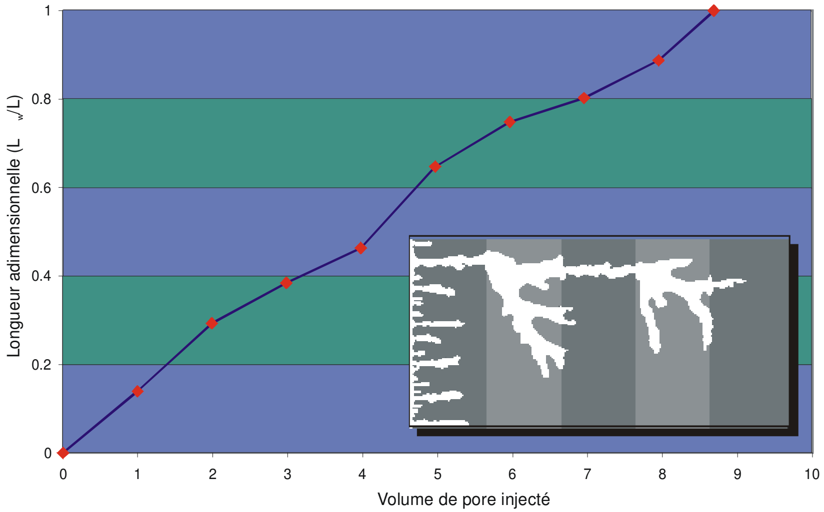
+ Averaging of the mass balance BC at A_{ls}:

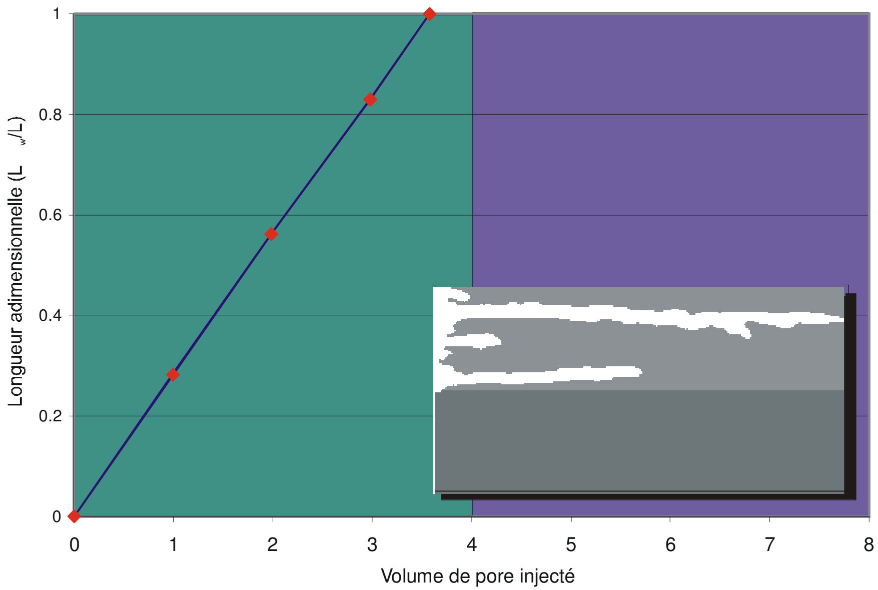
$$\frac{\partial}{\partial t}(\varepsilon_s\rho_s)=\frac{1}{C_l^*-C_s^*}(\rho_s h_{ms}(C_s^*-\langle C_s\rangle^s)$$
$$+\rho_l h_{ml}(C_l^*-\langle C_l\rangle^l))$$

Zr mass fraction (2373K , 574s)

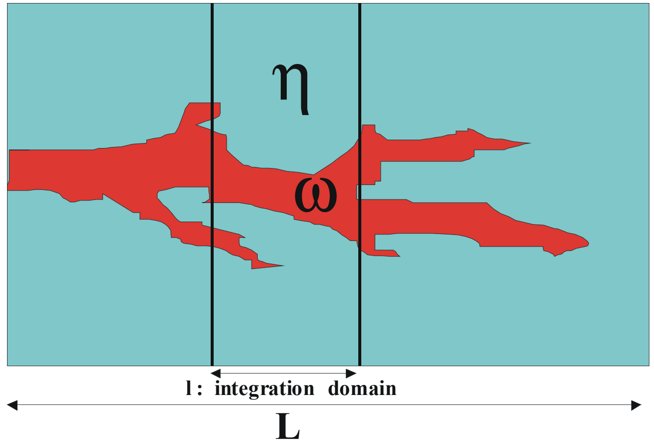


Flow in Heterogeneous Systems





Core-scale description



- fluid zone/porous zone

  ➔ 1D effective medium

- 1- equation model?
  - 1 single equation
  - easy to implement
  - loss of information
- 2- equation or “double-porosity” model?
  - 1 equation for each zone
  - *Darcy-scale problem is similar to the pore-scale problem in the case of equilibrium dissolution*

pb. with non-locality and history effects

Core-Scale Volume Fractions: Definitions

- **Wormhole volume fraction:** φ_ω
- **Core-scale porosity**

$$\varepsilon^* = \frac{1}{V_\infty} \int_{V_\infty} \varepsilon \, dV$$

if Local Equilibrium dissolution:

$$\varepsilon^* = \varphi_\omega + (1 - \varphi_\omega)\,\varepsilon$$

Ex.: 2-equation model (Golfier et al., 2004, 2006)

- Flow :

$$\nabla . \mathrm{V}_{\beta}^{\varpi} = 0$$
$$\nabla \mathrm{P}_{\beta}^{\varpi} = -\mu_{\beta} \left(\mathrm{K}^{\varpi} \right)^{-1} \cdot \mathrm{V}_{\beta}^{\varpi}$$

$$\nabla . \mathrm{V}_{A\beta}^{\eta} = 0$$
$$\nabla \mathrm{P}_{\beta}^{\eta} = -\mu_{\beta} \left(\mathrm{K}^{\eta} \right)^{-1} \cdot \mathrm{V}_{A\beta}^{\eta}$$

pb. with regional velocities?

- Transport and Dissolution :

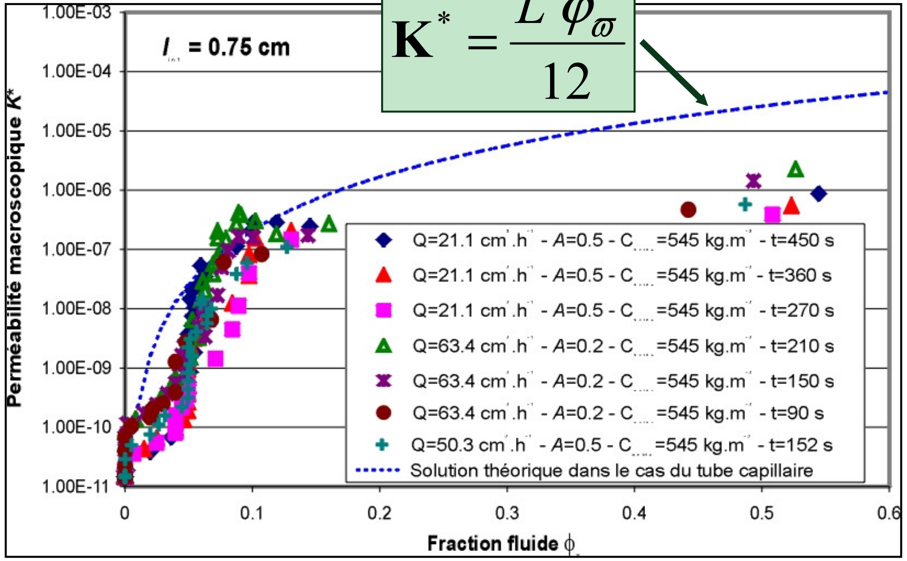
$$\varphi_{\varpi} \frac{\partial C^{\varpi}{}_{A\beta}}{\partial t} + \mathbf{V}^{\varpi}{}_{\beta} . \nabla C^{\varpi}{}_{A\beta} = \frac{1}{Pe} \nabla \cdot \left(\mathbf{D}^{**} \cdot \nabla C^{\varpi}{}_{A\beta} \right) - \alpha^{*} \quad C^{\varpi}{}_{A\beta}$$

$$\frac{\partial \varphi_{\varpi}}{\partial t} = \frac{\beta}{\rho_{\sigma}} \alpha^{*} \quad C^{\varpi}{}_{A\beta}$$

$$C^{\eta}{}_{A\beta} = 0 \quad \text{in } \eta\text{-region}$$

need Darcy-scale local equilibrium!

Obtained Correlations: permeability



$$K^* = \frac{L^2 \varphi_{\varpi}^3}{12}$$

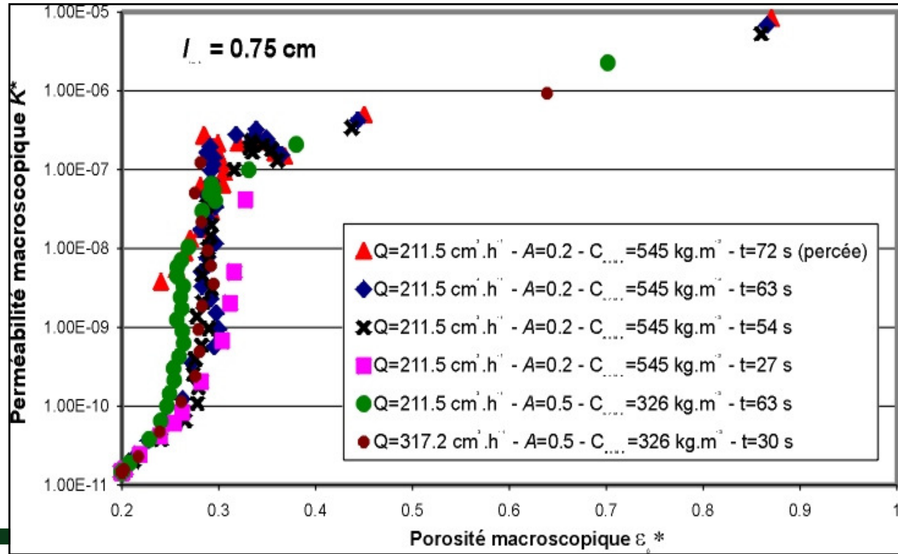
Wormholing regime

$$K^* = f(\varphi_{\varpi})$$

Ramified regime

need ε^*_β

$$K^* = f(\varepsilon^*_\beta)$$



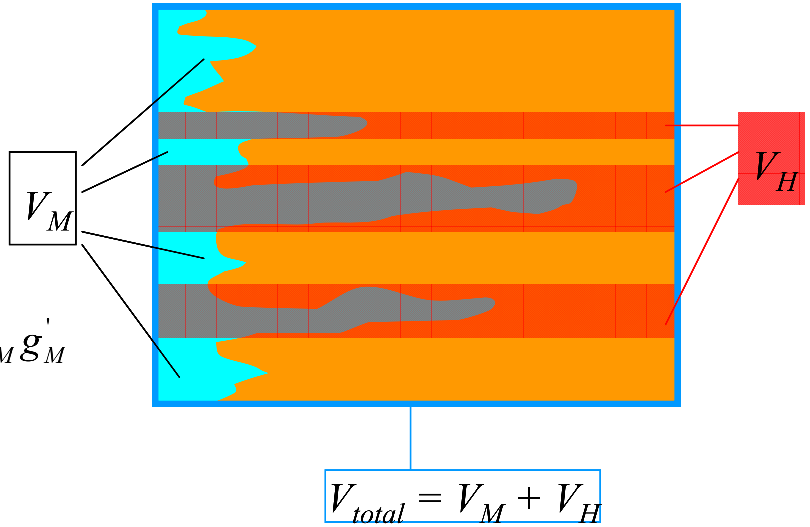
New Model (Cohen et al., 2006)

Media H

$$\begin{cases} \phi_H \varepsilon^H \dfrac{\partial C'^H}{\partial t} + \nabla.\left(\phi_H V'^H f'^H\right) - \psi' C_{H-M}\left(P'^M - P'^H\right) = -\phi_H g'_H \\ V'^H = -\mathbf{K}'^H \nabla P'^H \\ \dfrac{\partial \varepsilon^H}{\partial t} = N_{ac} g'_H \\ \nabla.\left(\phi_H V'^H\right) - \psi'\left(P'^M - P'^H\right) = 0 \end{cases}$$

Media M

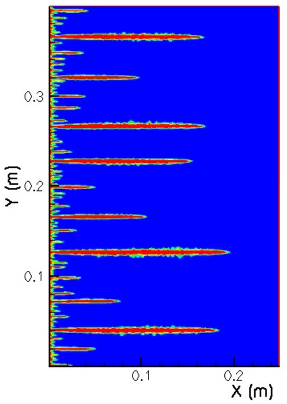
$$\begin{cases} \phi_M \varepsilon^M \dfrac{\partial C'^M}{\partial t} + \nabla.\left(\phi_M V'^M f'^M\right) + \psi' C_{H-M}\left(P'^M - P'^H\right) = -\phi_M g'_M \\ V'^M = -\mathbf{K}'^M \nabla P'^M \\ \dfrac{\partial \varepsilon^M}{\partial t} = N_{ac} g'_M \\ \nabla.\left(\phi_M V'^M\right) + \psi'\left(P'^M - P'^H\right) = 0 \end{cases}$$

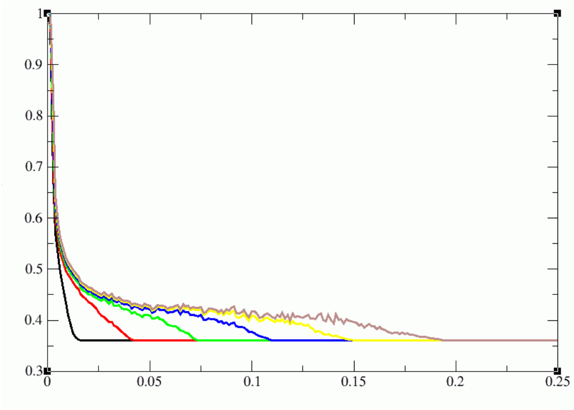


V_H contains dominant wormholes

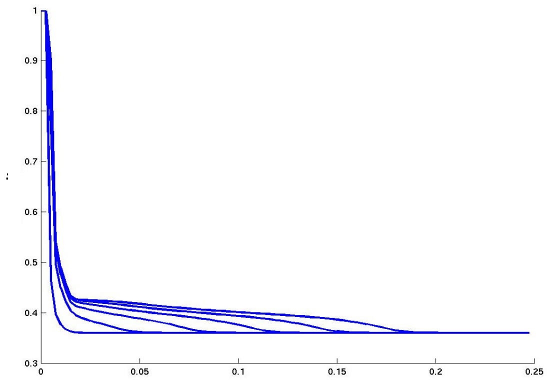
V_M contains face dissolution and short wormholes

Validation: example from dominant wormhole regime

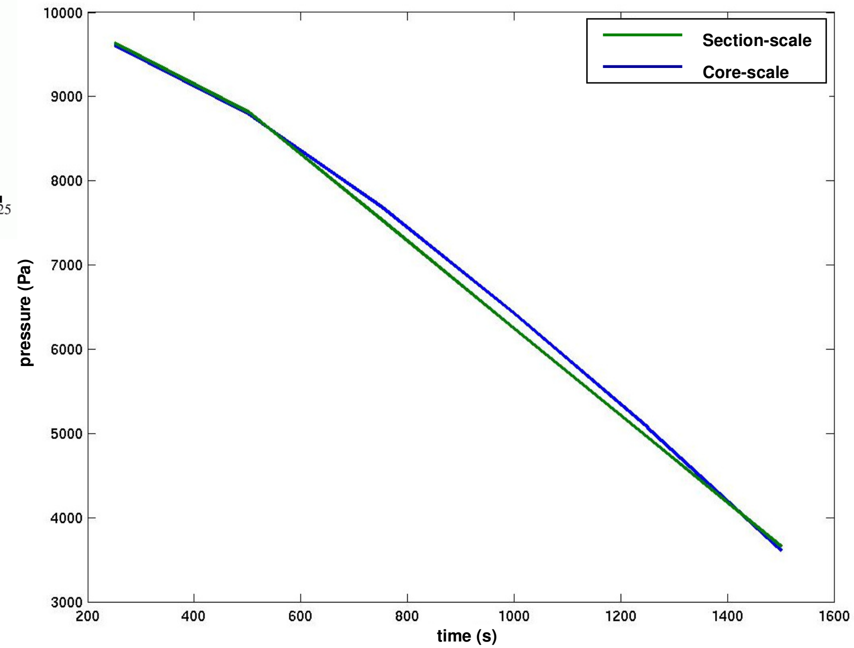




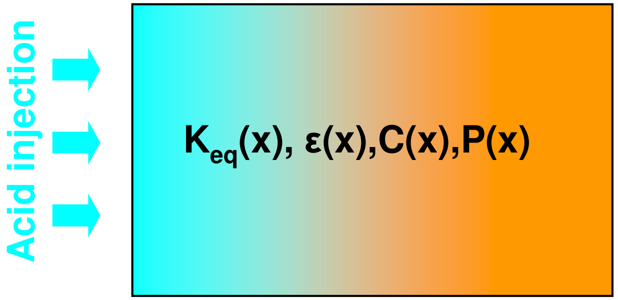
Core-scale simulation



Section-scale simulation

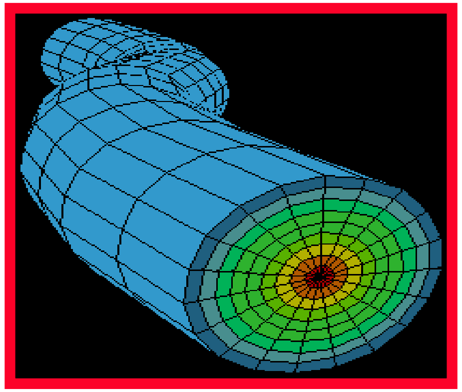


Reservoir Scale: goals

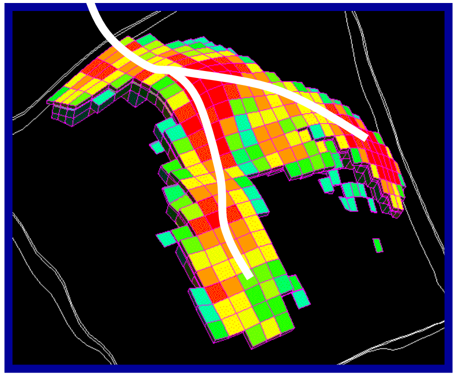


1st step : Section-scale – dissolution modelling

2nd step : treatment simulation – skin calculation



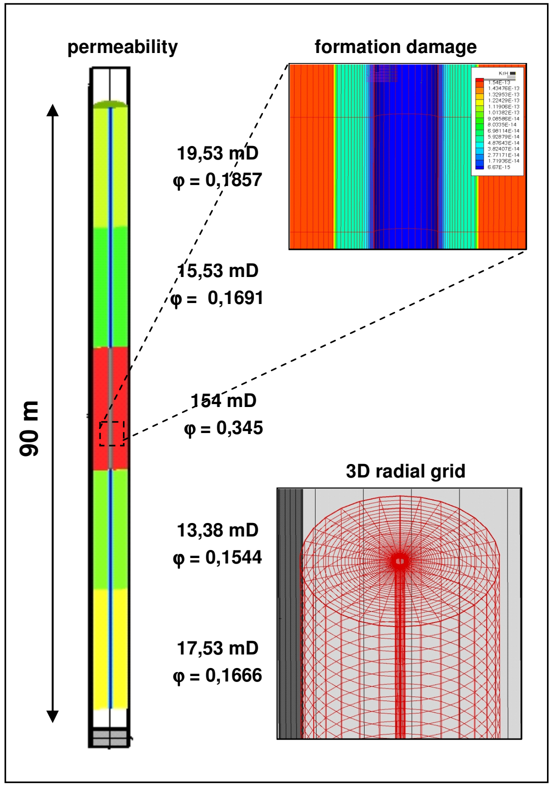
3rd step : introduction of skin in simulator reservoir – treatment optimisation



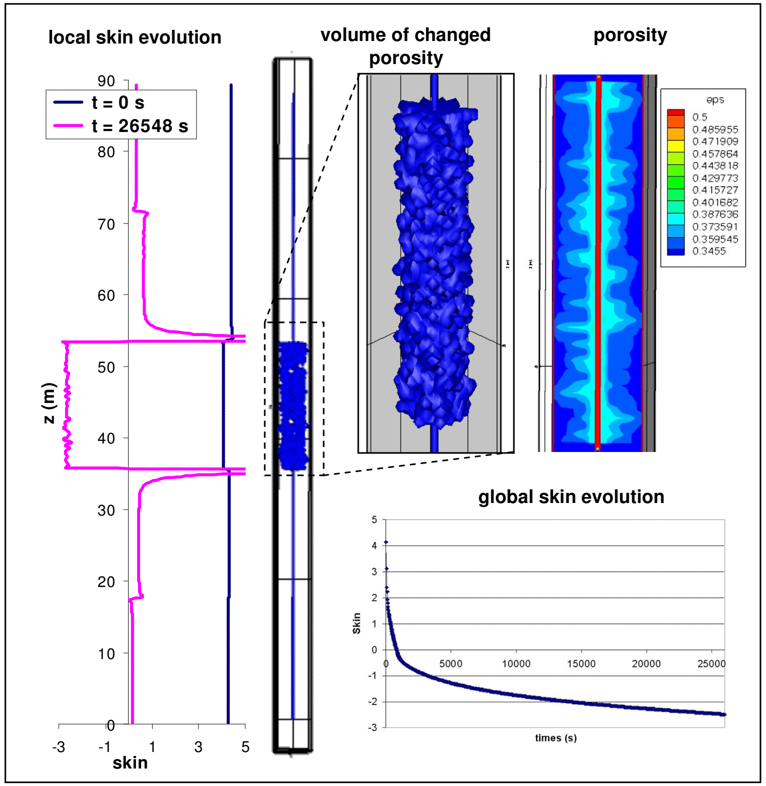
$$Q = \frac{2\pi kh}{B\mu} \frac{\Delta P}{\ln \frac{r_e}{r_w} + S}$$

Example (Cohen, 2006)

- 3D radial simulation



Acidizing Simulation



Conclusions

- **Effective Surface:**
  - If not limit cases, or if no steady-state: → DNS?
  - Coupling with instabilities?
- **Darcy-scale models:**
  - LNE model has potential for representing instabilities with a minimum of parameters
  - Coupling with strong heterogeneities?
- **Reservoir-scale models?**