DIGITAL ROCK PHYSICS:
OBJECTIVES AND CHALLENGES

29ÈME JOURNÉE CASCIMODOT

ORLEANS, DEC 12, 2018

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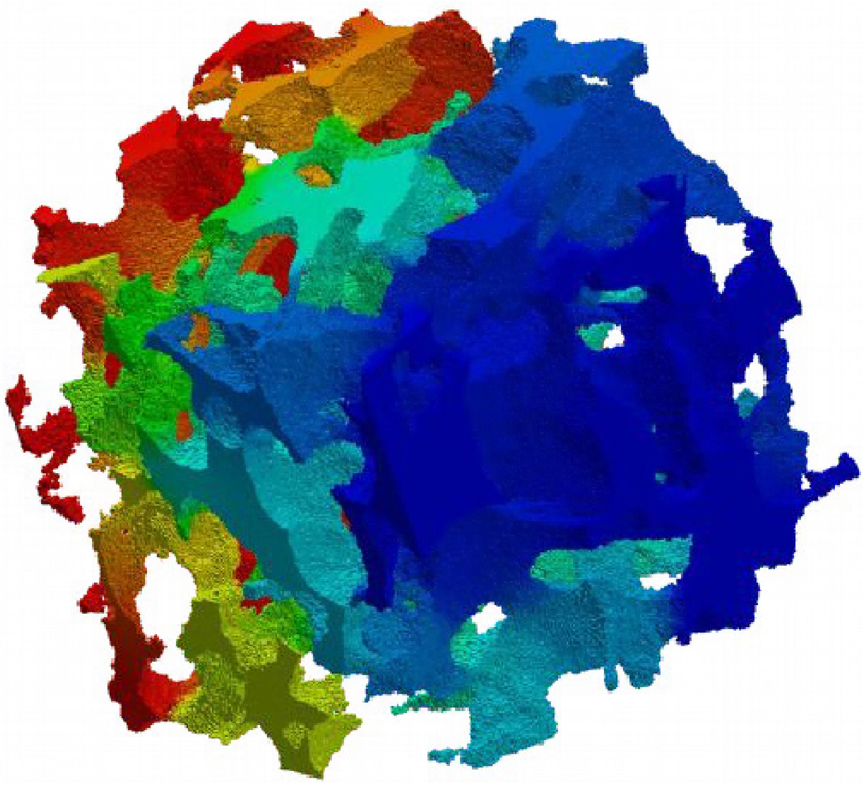
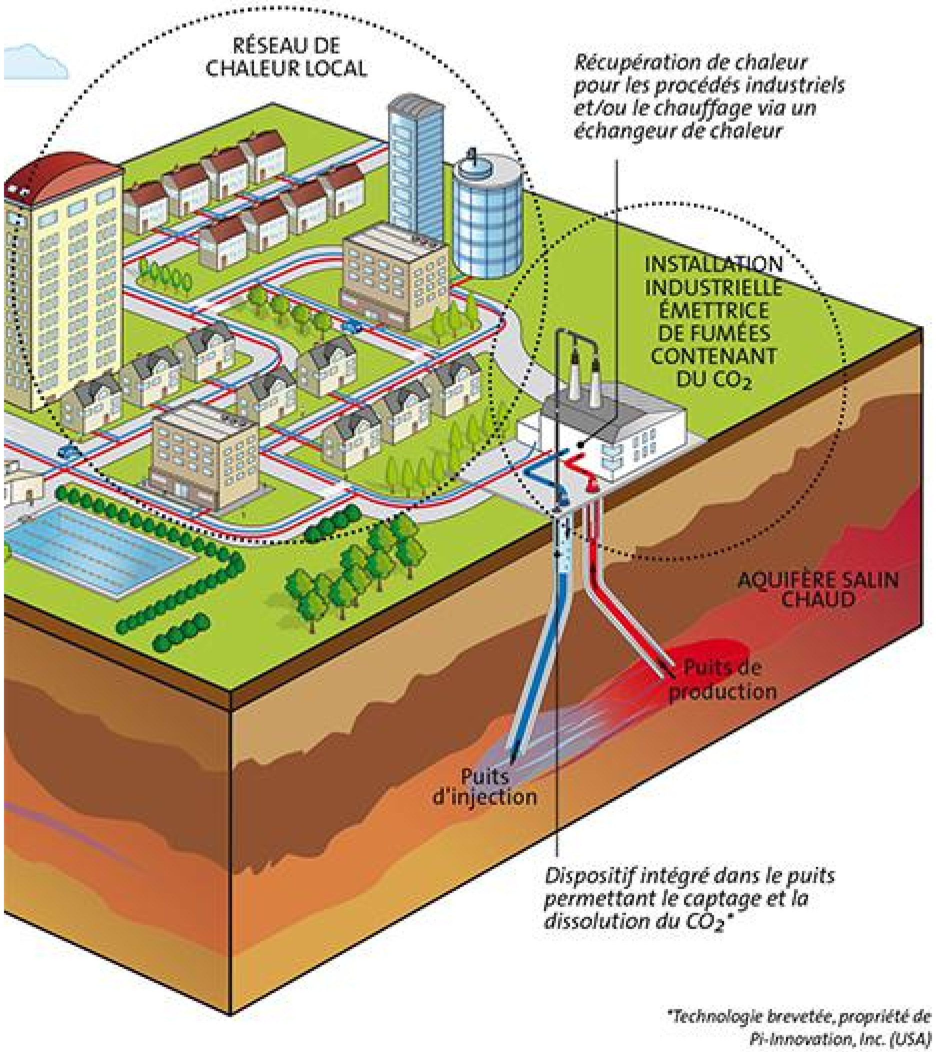


Background: porous media modeling

Target:

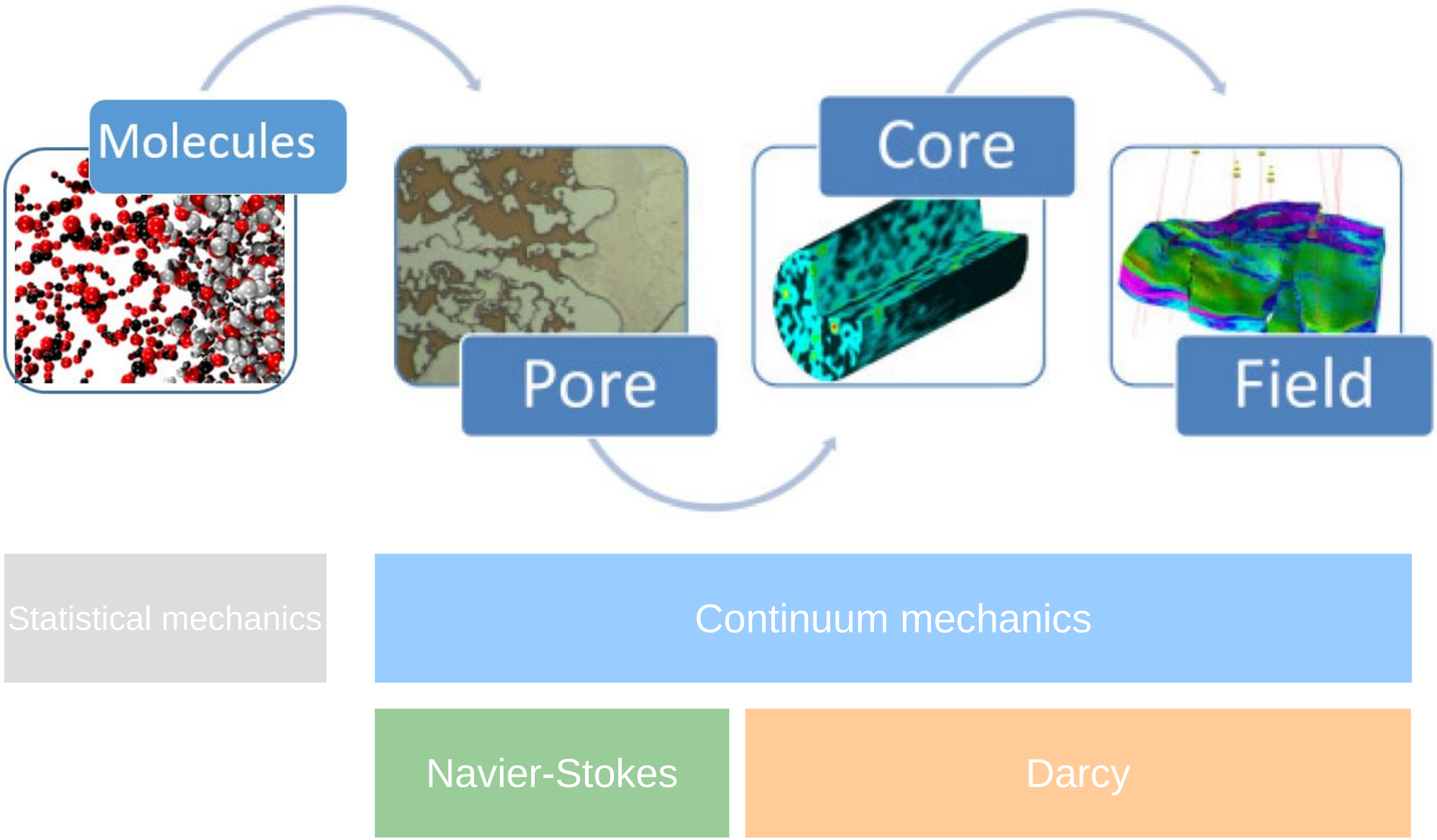
- Understand and model complex physics of flow and transport in reservoirs (geothermal energy, nuclear wast storage, water resources, oil and gas recovery, CO_2 sequestration, …),
- Replace/complement lab-scale experiments (permeability...)



Challenges:

- Multi-scale problem,
- Multiphase flow,
- Fractured/damaged media,
- Thermal processes,
- Phase change
- Bio-geochemistry,
- Evolution of the pore structure,
- Mechanics,
- ...

Multi-scale modeling



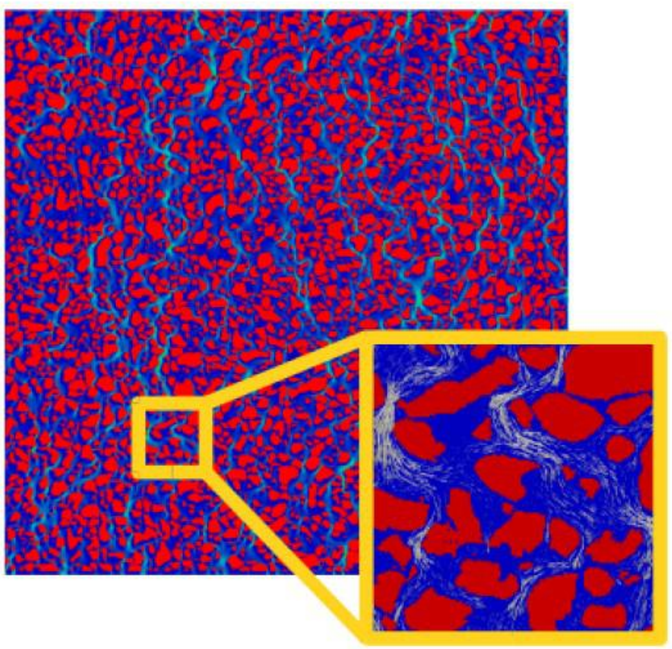
(Adapted from Buchgraber 2012)

Discret vs continuum

direct modeling

p_β

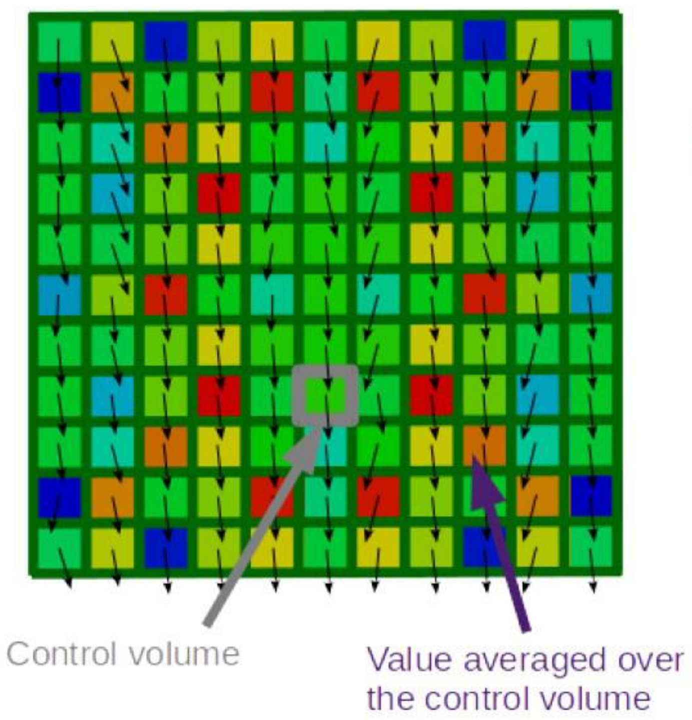
$\mathbf{v}_\beta$



continuum modeling

$\langle p_\beta \rangle^\beta$

$\langle \mathbf{v}_\beta \rangle$



for every point of the domain

fluid OR solid

$$\rho \frac{\partial \boldsymbol{v}}{\partial t} + \rho \boldsymbol{v}.\nabla \boldsymbol{v} = -\nabla p + \rho \boldsymbol{g} + \mu \nabla^2 \boldsymbol{v}$$

fluid AND solid

$$\boldsymbol{V} = -\frac{\mathrm{K}}{\mu}.\left(\nabla P - \rho_f \boldsymbol{g}\right)$$

Why working at the pore-scale?

Understand

Characterize

Upscale

Digital Rock Physics

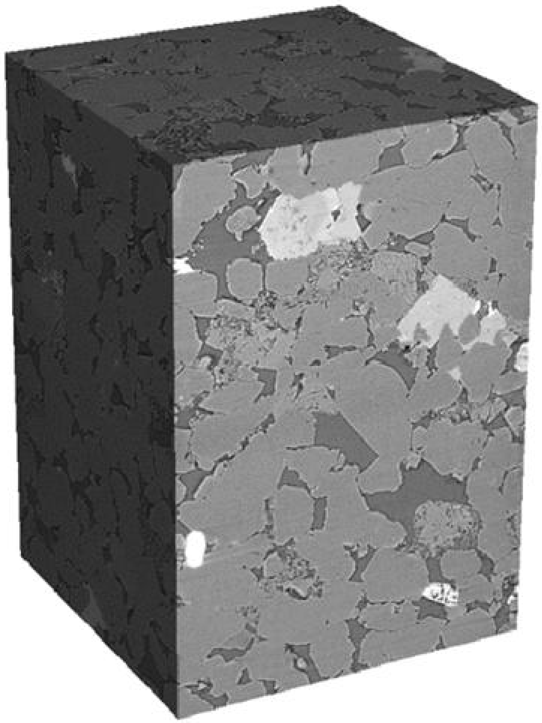
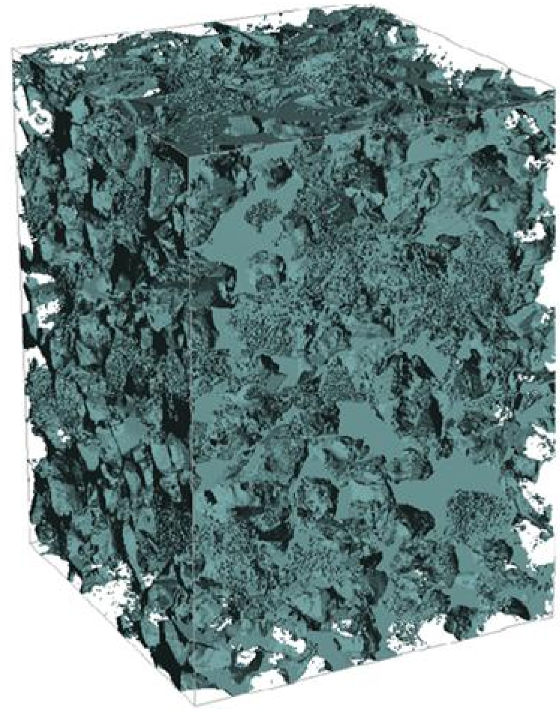
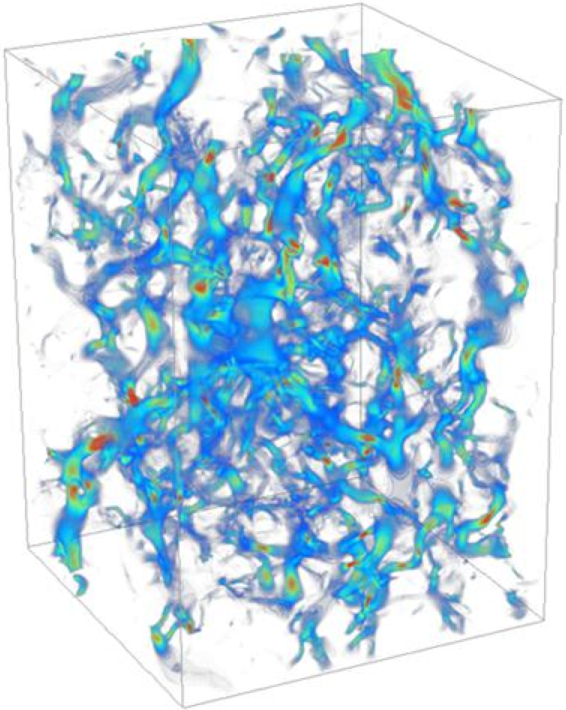


Image of core, plug or cutting



Segmented pores/minerals in image



Computation of rock properties

(source: GeoDict)

Geometrical parameters
- Porosity
- Percolation
- Surface area
- Tortuosity

Flow Parameters
- Permeability
- Multi-scale/phase flow
- Capillary pressure curve

Electrical parameters
- Formation factor
- Resistivity index
- Saturation exponent
- Cementation exponent

Mechanical parameters
- Elastic moduli
- Stiffness
- In-Situ conditions

Advantages of using digital experiments

- Non-destructive,
- Sensitivity analysis,
- Laboratory hazards such as leaks or temperature variations are simply removed,
- Can reach pressure and temperature conditions that are difficult to consider in the lab without the use of dedicated equipment,
- Moreover, the information resulting from these simulations is spatialized (distribution of phases, velocities or stresses) which gives a greater flexibility of post-treatment whereas the classical petrophysical experiments only give access to macroscopic data.

Challenges

Solve the physics:

- Define correct models
- Develop solution algorithm
- Model validation

Interpret the results:

- Link with mascroscale properties

Pre-processing

- Image segmentation
- Gridding

Reach a REV

- High Performance Computing
- Efficient time-stepping

Direct Numerical Simulation techniques

Direct modeling

Navier-Stokes on Eulerian grids (CFD)

- Solve Navier-Stokes equations on a Eulerian grid,
- Differential operators discretized with FVM, FDM or FEM,
- Nowadays, all the CFD softwares are efficient, robust and parallelized.

Lattice Boltzmann Method (LBM)

- Solve the discrete Boltzmann equation instead of Navier-Stokes,
- The nature of the lattice determines the degree of freedom for the particle movement,
- Easy to program, massively parallel,
- No limitation due to Knudsen number.

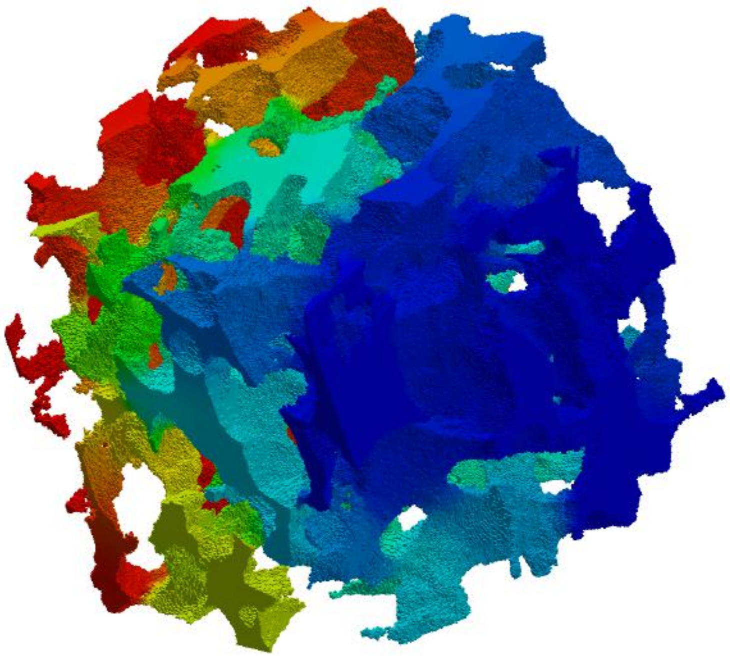
Smoothed-Particle Hydrodynamics (SPH)

- Mesh-free technique,
- Fluid is divided into a set of discrete particles,
- To represent continuous variables, a kernel defined the sphere of influence of a particle,
- Particles are tracked in time as they move in the pore-space using a Lagrangian framework.

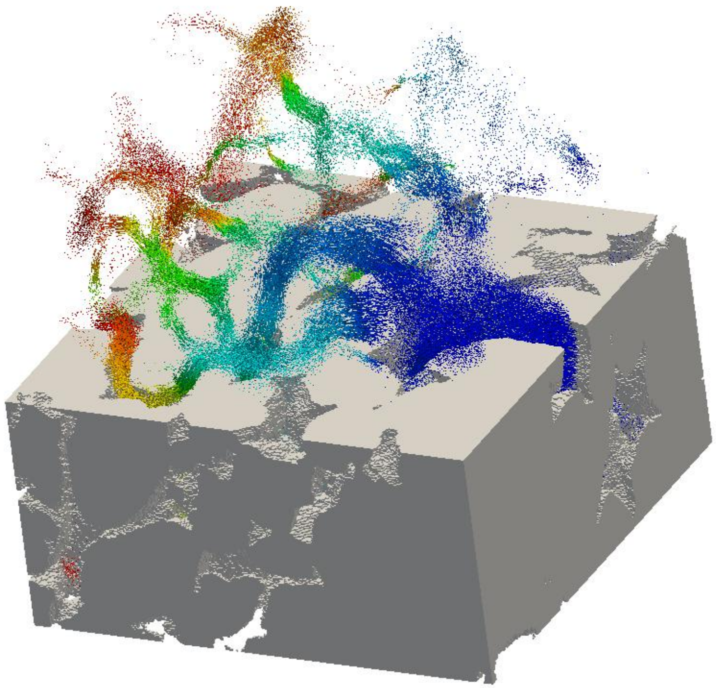
- Directly deal with the real pore structure geometry,
- Can be used to investigate the physics

- More computationally expensive than PNM,
- Efficient multiphase solver are still in development.

Application: compute the permeability of a sandstone



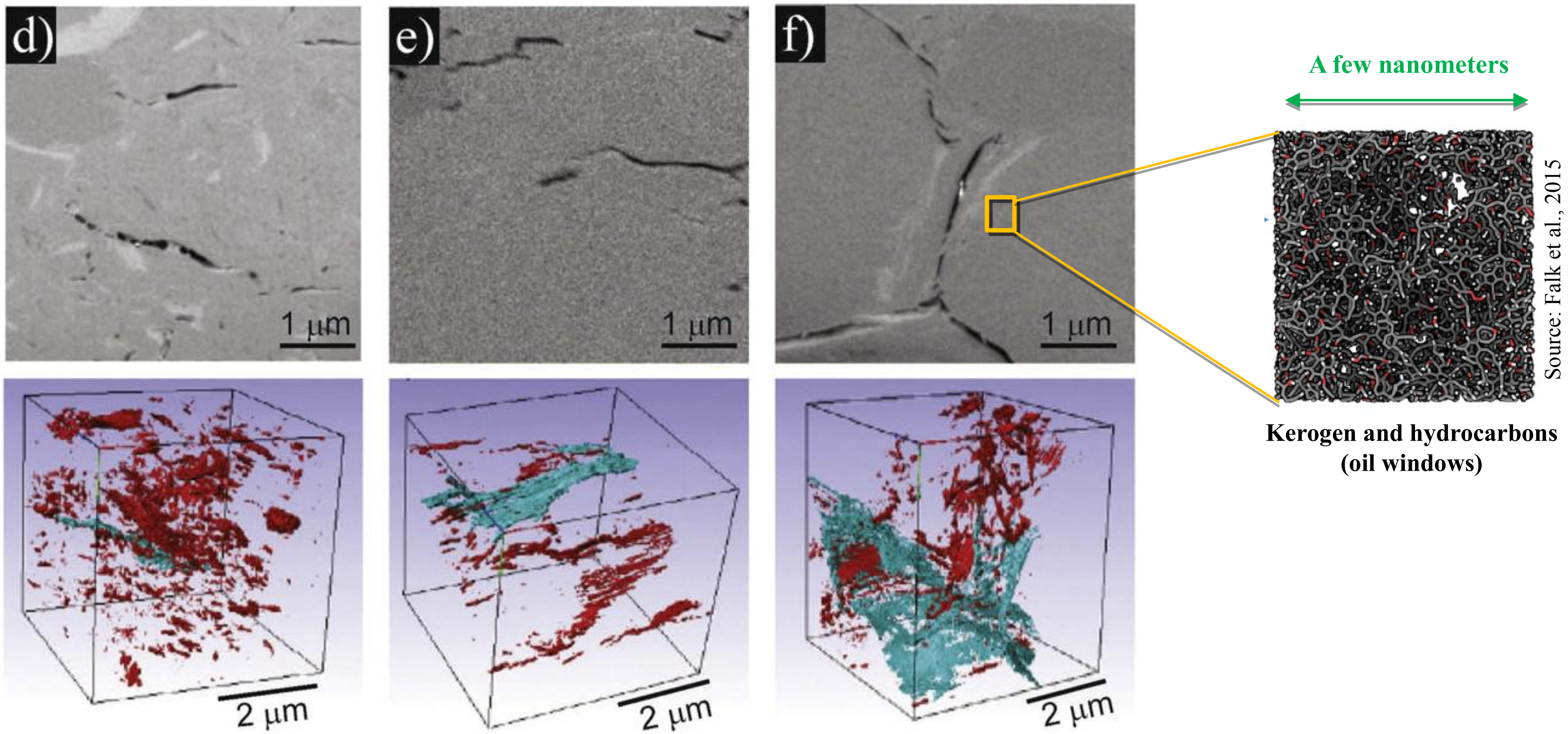
$$K_{ij} = \mu \langle v_i \rangle \left(\frac{\triangle P}{L} \right)^{-1} \quad i = x, y, z$$



- Digital rock obtained from microtomography imaging,
- Grid the pore-space,
- In CFD simulations, the results may be very sensitive to the grid quality. At least 10 cells are required in each pore-throat,
- The grid quality is even more important when dealing with multiphase flow (refinement near the walls),
- Solve steady-state Stokes equations (SIMPLE algorithm with OpenFOAM).

Challenge 1: How to account for sub-voxel porosity?

… for example when imaging a source rock including micro-cracks and nanoporosity



Heath et al. (2011)

(red = non-connected porosity, blue = connected)

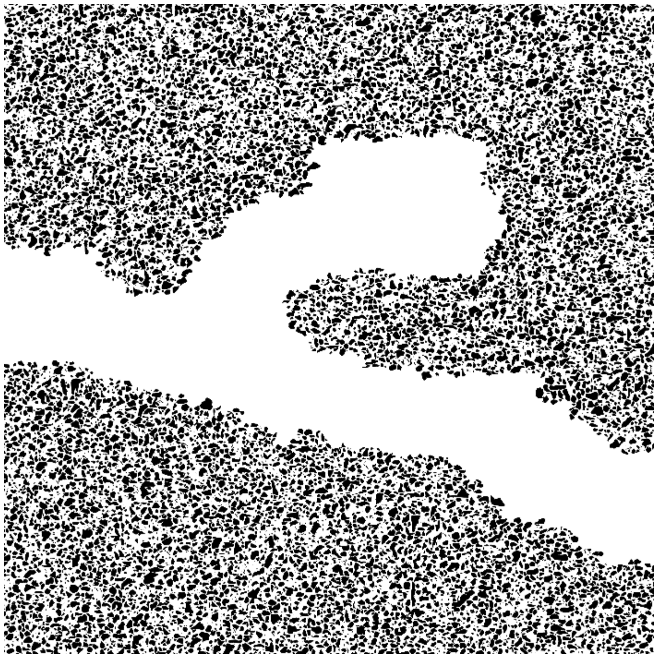
- At the SEM scale, only the larger pores are captured
- The nanoporosity is not resolved in the image,
- But hydrocarbon molecules are transported through the nanoporosity...

[1]Heath et al., *Pore Networks in continental and marine mudstones: Characteristics and controls on sealing behavior* Geosphere, 2011, 7, 429 – 454

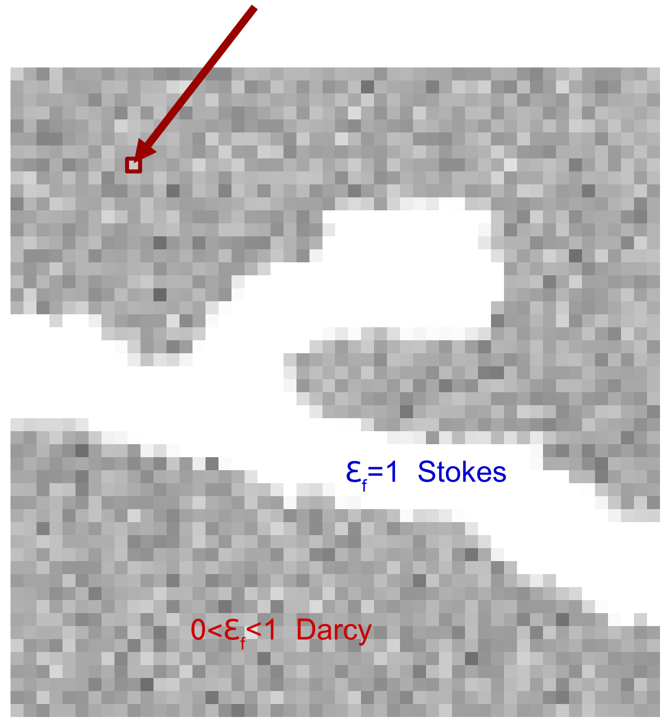
[2]Falk et al., *Effect of Chain Length and Pore Accessibility on Alkane Adsorption in Kerogen*, Energy & Fuels, 2015, 29, 7889-7896

Darcy-Brinkman-Stokes equation

control volume, *V*



Full Navier-Stokes approach



Filtering approach

Solid and fluid differentiated by the void fraction per control volume:

$$\varepsilon_f$$

$$\bar{\mathbf{v}}_f = \frac{1}{V}\int_{V_f}\mathbf{v}_f dV$$

$$\bar{p}_f = \frac{1}{V_f}\int_{V_f} p_f dV$$

The <u>Darcy-Brinkman-Stokes</u>[1,2,3] equation allows a single domain formulation

$$0 = -\nabla\bar{p}_f + \frac{\mu_f}{\varepsilon_f}\nabla^2\bar{\mathbf{v}}_f - \mu_f k^{-1}\bar{\mathbf{v}}_f$$

Vanishes in the void space

Dominant in the porous region

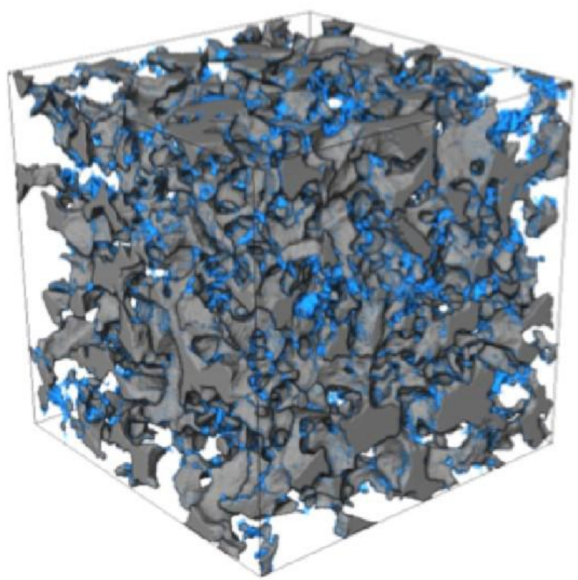
[1]Brinkman *A Calculation of The Viscous Force Exerted by a Flowing Fluid on a Dense Swarm of Particles* Appl. Sci. Res. (1947)

[2]Neale and Nader *Practical significance of Brinkman's extension of Darcy's law: coupled parallel flows within a channel and a bounding porous medium*. (1974)

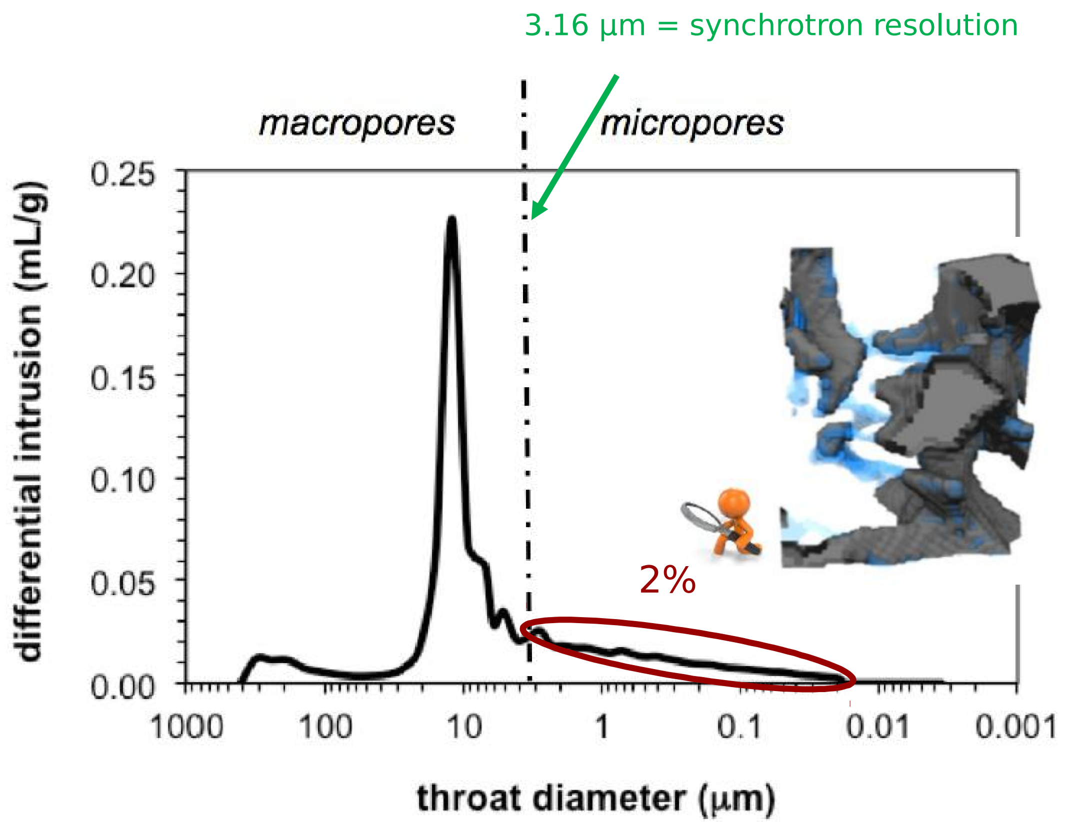
[3]Soulaine and Tchelepi *Micro-continuum approach for pore-scale simulation of subsurface processes* Transport in Porous Media (2016)

Impact of sub-voxel porosity in microtomography images[1]

Cube 300 x 300 x 300



dark grey : macropores
blue : microporous phase



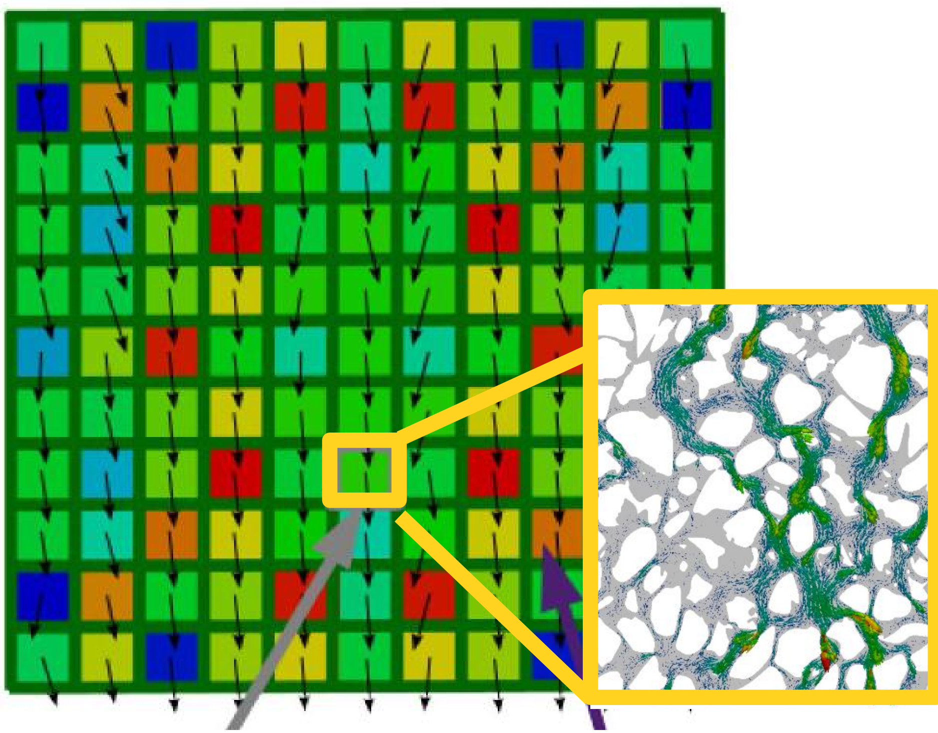
Sub-grid model:

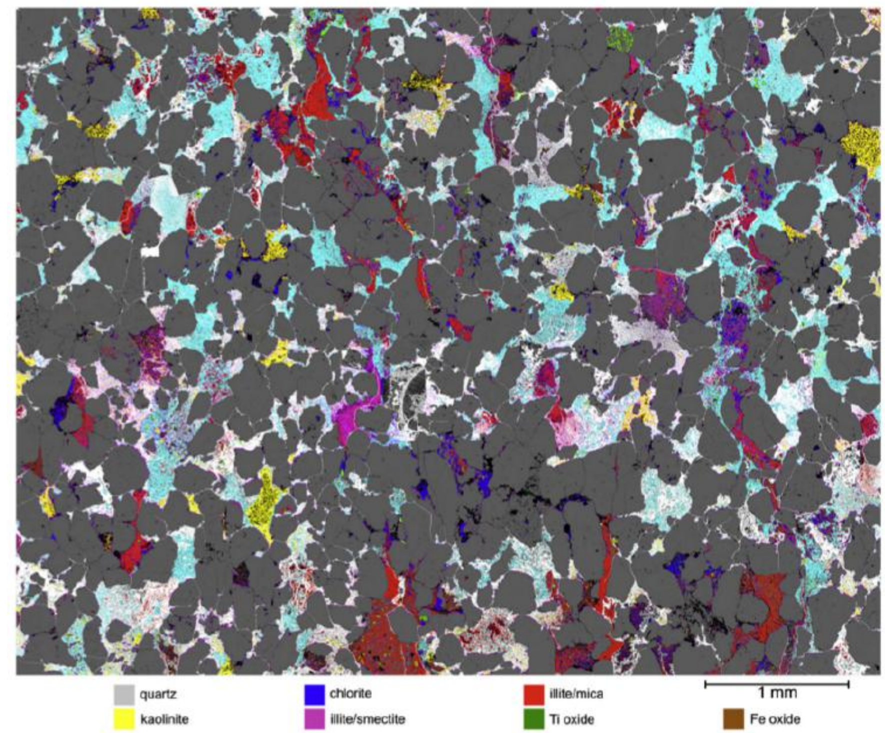
- Sub-voxel porosity from the grayscale,
- Local permeability from Kozeny-Carman combined with the image resolution,

sample	1	2	3
K (mD)	**518**	**534**	**341**
K- (mD)	211 (-59%)	475	305
K+ (mD)	913	804	673 (+97%)

[1]Soulaine et al. *The impact of sub-resolution porosity of X-ray microtomography images on the permeability* Transport in Porous Media (2016)

Challenge 2: hydro-geochemical coupling





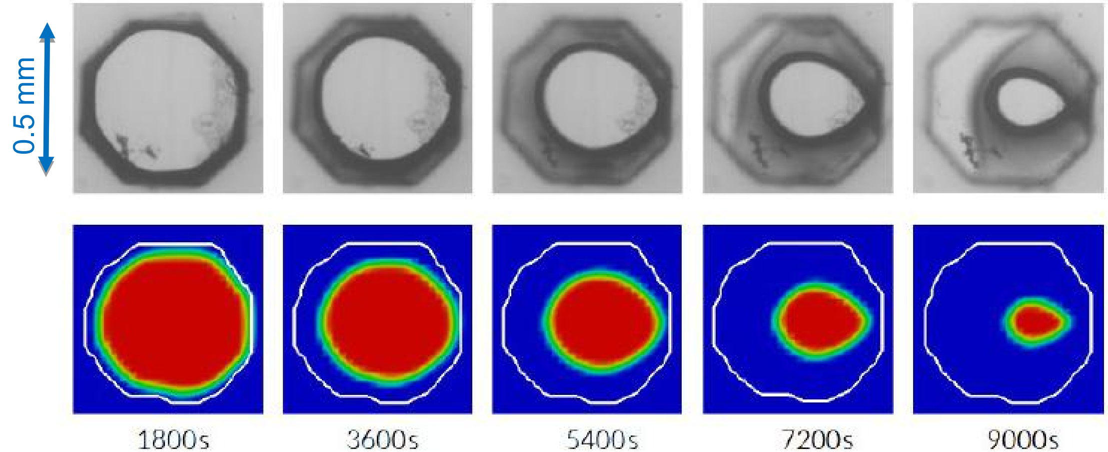
Landrot et al. (2012)

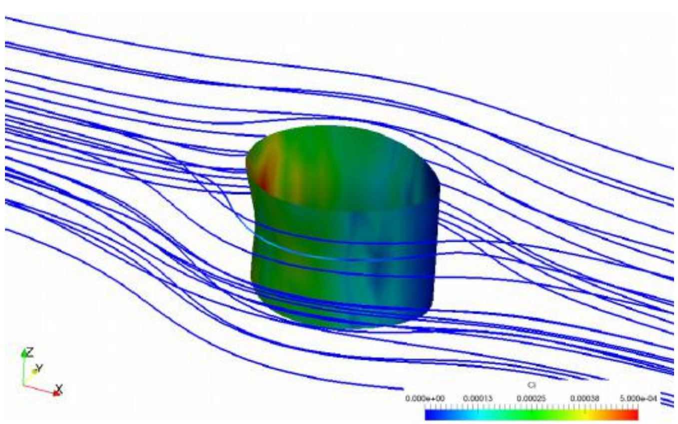
- Darcy scale = averaged equations with averaged properties (permeability, surface area...)
- How does the permeability evolves when the pore-structure changes due to the dissolution/precipitation?
- What is the surface area accessible to the acid component? Complex interplay of diffusion, convection, reaction

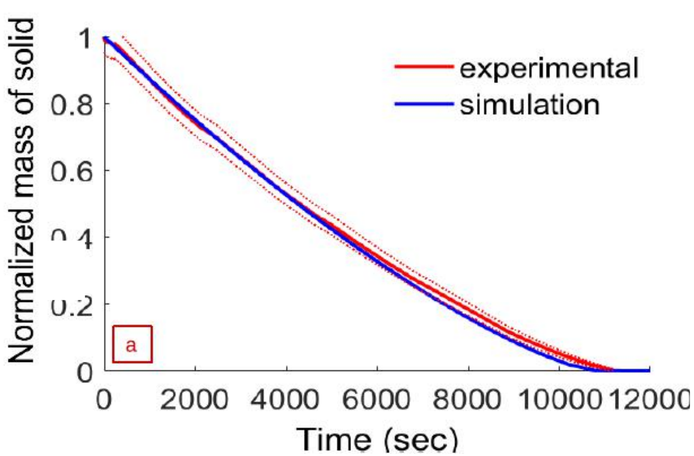
Landrot, G., J. B. Ajo-Franklin, L. Yang, S. Cabrini, and C. I. Steefel (2012). Measurement of accessible reactive surface area in a sandstone, with application to CO_2 mineralization. Chemical Geology 318, 113–125.

Calcite dissolution: Simulation vs Experiment

- Dissolution of a calcite crystal in a micro-channel (Sophie Roman, Wen Song and Tony Kovscek, Stanford University),
- Acquisition of a high resolution dataset to compare with numerical simulations.

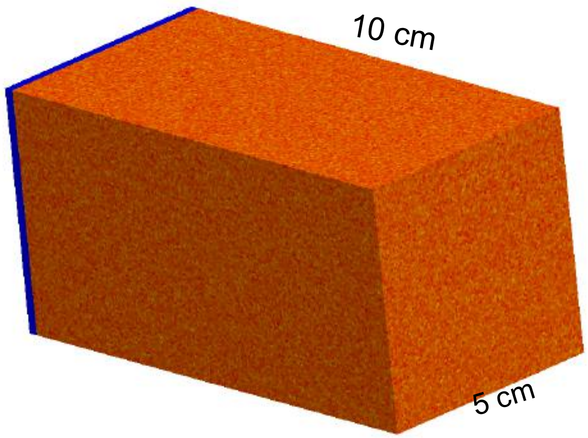




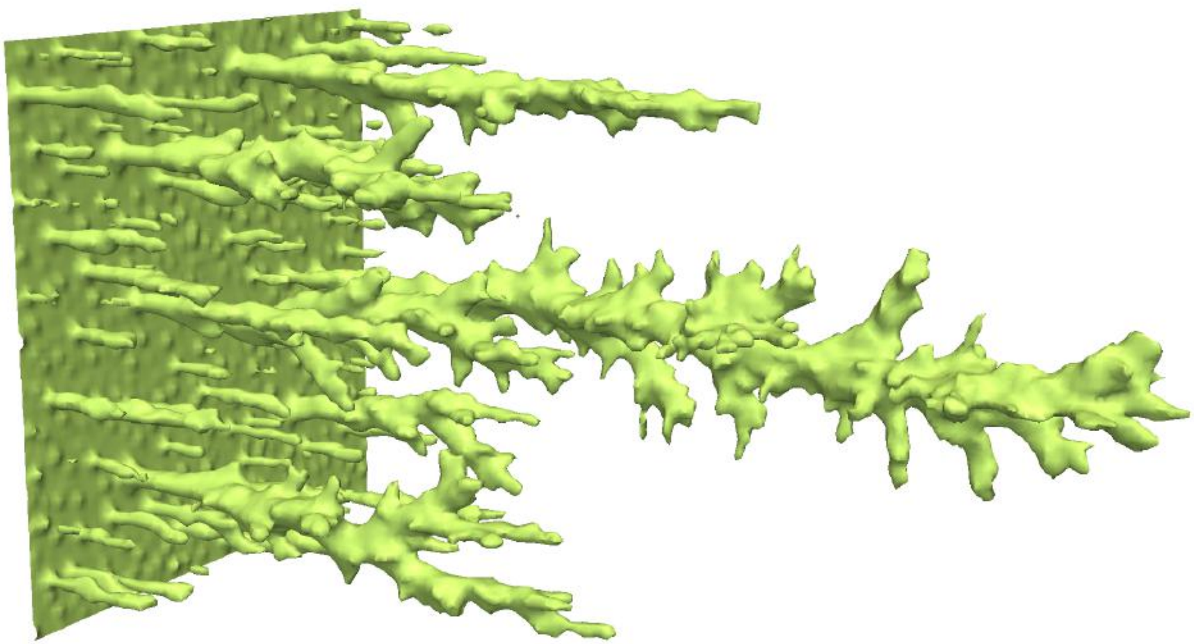


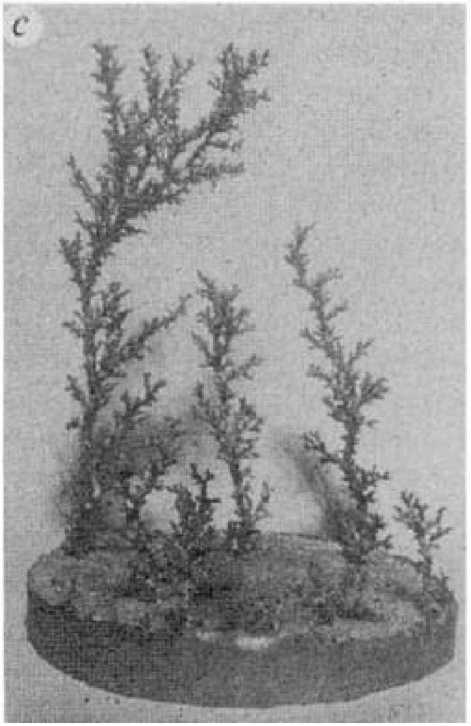
[1]Soulaine et al., *Mineral dissolution and wormholing from a pore-scale perspective,* Journal of Fluid Mechanics 827 (2017)

Dissolution at the core-scale



- Core-scale model (Darcy formulation)
- Diffuse Interface Model (DIM)
- Now the porous region has porosity and permeability (ε_0= 0.1 ± 3% and k_0 = 10^{-11} m² ± 10 %)



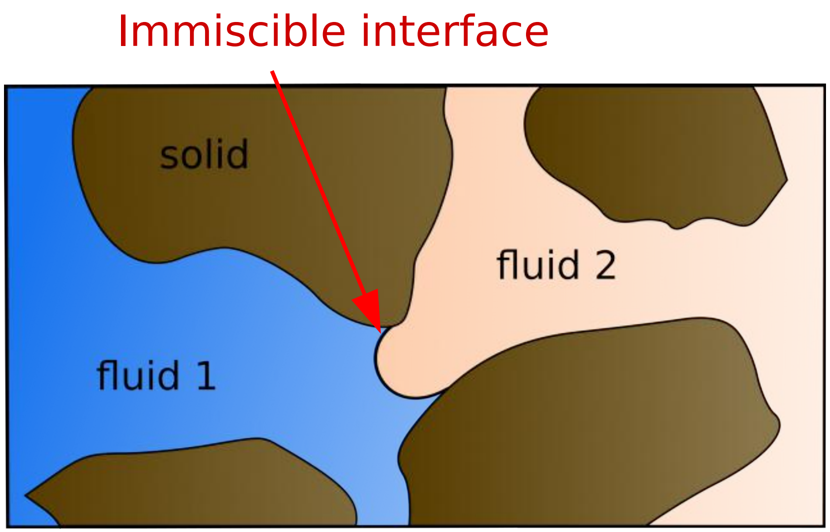


Daccord and Lenormand (1987)

[1]Soulaine and Tchelepi *Micro-continuum approach for pore-scale simulation of subsurface processes* Transport in Porous Media (2016)

[2]Daccord, G. and Lenormand, R. *Fractal patterns from chemical dissolution*. Nature, 1987, 325

Challenge 3: two-phase flow in porous media



Particularity of multi-phase flow

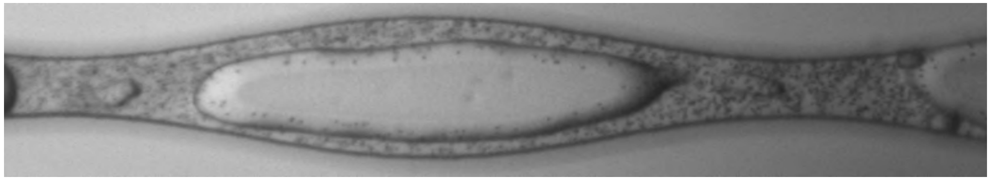
- Navier-Stokes equation in each phases
- Continuity of the tangential component of the velocity at the fluid/fluid interface
- Laplace law for a surface at the equilibrium

$$\Delta p = \sigma \left(\frac{1}{R_1} + \frac{1}{R_2} \right)$$

Surface tension (N/m)

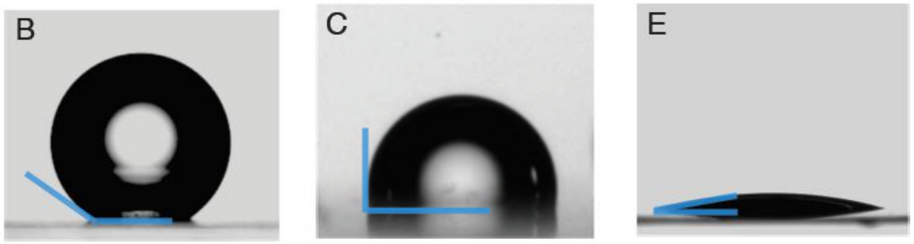
- Contact line dynamics at the solid surface

Surface tension is the elastic tendency of a fluid surface which makes it acquire the least surface area possible



Sophie Roman (Univ of Orléans, FR)

The contact angle quantifies the wettability affinity of a solid surface by a liquid



Zhao et al. (2016), PNAS

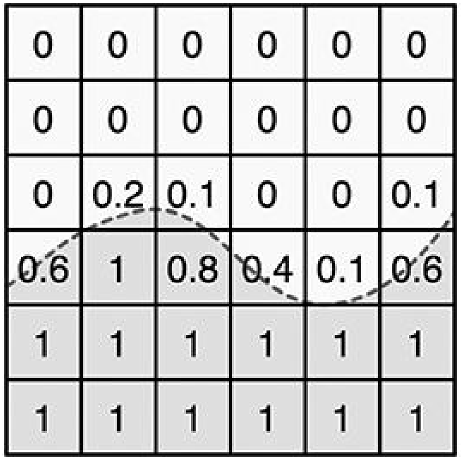
θ=150° non-wetting

θ=90°

θ=7° wetting

The displacement of a wetting fluid by a non-wetting fluid (drainage) is different than the displacement of a non-wetting fluid by a wetting fluid (imbibition)

The Volume of Fluid (VOF) technique



Color function

$$\alpha = \begin{cases} 0 & \text{in phase 2} \\ 0 < \alpha < 1 & \text{on the interface} \\ 1 & \text{in phase 1} \end{cases}$$

Single-field variables

$$\boldsymbol{v} = \alpha \boldsymbol{v}_1 + (1-\alpha)\,\boldsymbol{v}_2$$
$$p = \alpha p_1 + (1-\alpha)\,p_2$$
$$\rho = \alpha \rho_1 + (1-\alpha)\,\rho_2$$
$$\mu = \alpha \mu_1 + (1-\alpha)\,\mu_2$$

Single-field equations[1]

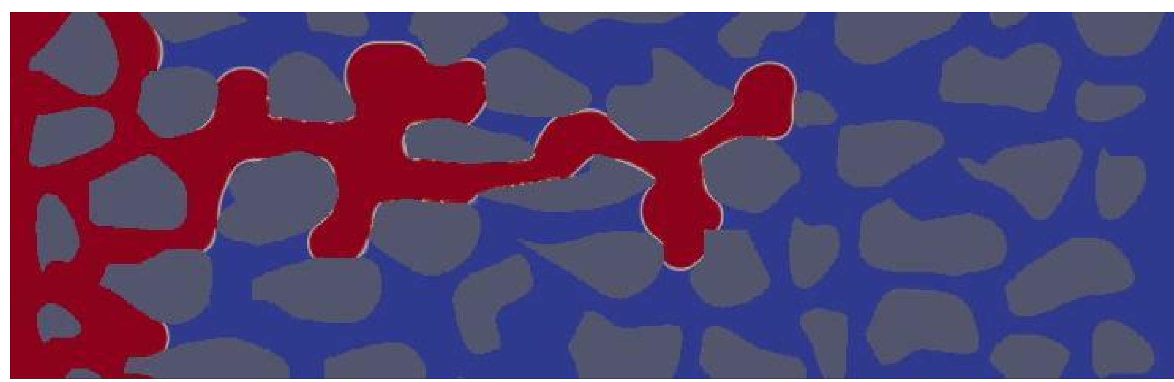
$$\rho \frac{\partial \boldsymbol{v}}{\partial t} + \rho \boldsymbol{v}.\nabla \boldsymbol{v} = -\nabla p + \rho \boldsymbol{g} + \nabla.\mu\left(\nabla \boldsymbol{v} + {}^t\nabla \boldsymbol{v}\right) + \boldsymbol{F}_c$$

$$\nabla.\boldsymbol{v} = 0$$

$$\frac{\partial \alpha}{\partial t} + \boldsymbol{v}.\nabla\alpha = 0$$

Continuum Surface Force (CSF)[2]

$$\boldsymbol{F}_c = \sigma \nabla.\left(\frac{\nabla\alpha}{\|\nabla\alpha\|}\right)\nabla\alpha$$



Graveleau et al. 2017

[1]Hirt, C. & Nichols, B. *Volume of fluid (VOF) method for the dynamics of free boundaries* Journal of Computational Physics, 1981, 39, 201 - 225

[2]Brackbill et al. *A continuum method for modeling surface tension* Journal of Computational Physics, 1992, 100, 335 - 354

Summary

- An on-going revolution in the porous media community!
- Digital Rock Physics technologies aim at replacing or at least complement standard petrophysical experiments
- Still a lot of interesting challenges to solve (coupled physics, solution algorithm efficiency, HPC….)

Thank you for your attention!

www.cypriensoulaine.com