Two phase Darcy flows in fractured porous media

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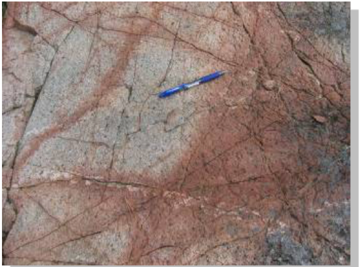
Outline

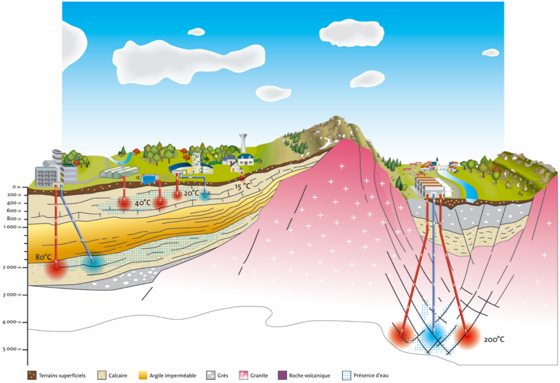
- Modelling Two-Phase Darcy flows in Discrete Fracture Networks
- Finite Volume Discretizations
- Numerical examples

Fractured/faulted porous media: multiple scales (figures from J. R. de Dreuzy, Geosciences Rennes and Inria)



Fractured/faulted porous media: applications

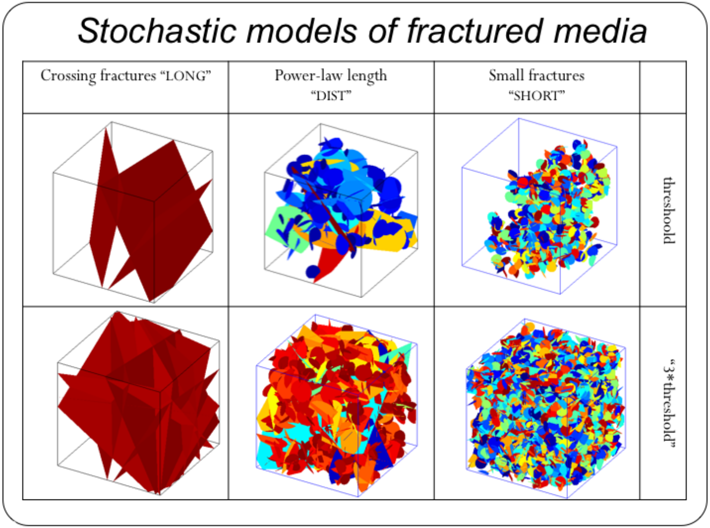
- Oil and gas
- Hydrogeology
- Geothermal energy
- Geological storages
- Soil remediation
- ...



Flow in Fractured porous media: two main approaches

- Single or double Continuum Media: homogeneization for dense fracture networks
- Discrete Fracture Matrix (DFM) models: 2D fracture model coupled to 3D matrix medium
- Possibility to couple both approaches
  - Double Continuum media for small fractures coupled with DFM for large fractures
  - Numerical Homogeneization: parameters of the Double Continuum media computed by a DFM model

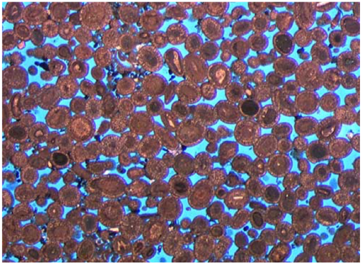
Discrete fracture networks (DFN) (figures from J. R. de Dreuzy, Geosciences Rennes and Inria)



PART 1

Modelling Two-Phase Darcy flows in Discrete Fracture Networks

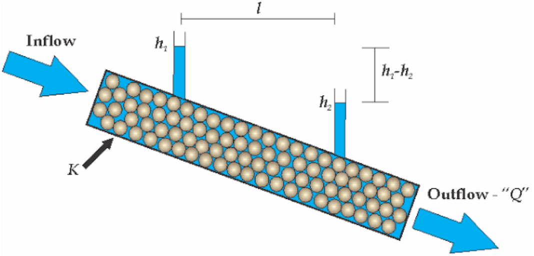
Porous medium: Darcy scale and porosity

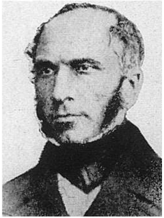


Sandtone: porous and permeable rock

$\phi(\mathbf{x})$: porosity = pore volume / total volume, $0.01 \leq \phi \leq 0.4$
Pore scale = micron meters
Darcy scale = mm

Darcy flow





Henry Darcy (1803-1858)

$$\mathbf{q} = -\frac{\Lambda(\mathbf{x})}{\mu}(\nabla u - \rho \mathbf{g}) \quad (\mathrm{m.s}^{-1})$$

u: fluid pressure (in Pa)
$\Lambda(\mathbf{x})$: rock permeability tensor in m^2 (1 Darcy $= 10^{-12}$ m^2).
μ: fluid dynamic viscosity (Pa.s)
ρ: fluid mass density (Kg.m^{-3})

Two-phase Darcy flow

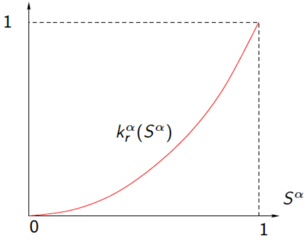
$\alpha = 1$: wetting phase
$\alpha = 2$: non wetting phase

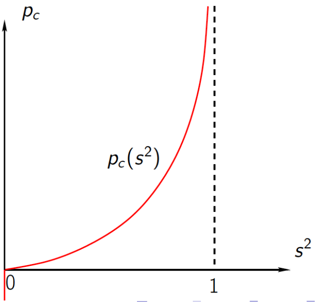
u^α : phase pressure
s^α : phase saturation

$p_c(s^2) = u^2 - u^1$: capillary pressure
$k_r^\alpha(s^\alpha)$: phase relative permeability

$$\mathbf{q}^\alpha = -\underbrace{\frac{k_r^\alpha(s^\alpha)}{\mu^\alpha}}_{k^\alpha(s^\alpha)} \Lambda(\mathbf{x})(\nabla u^\alpha - \rho^\alpha \mathbf{g})$$

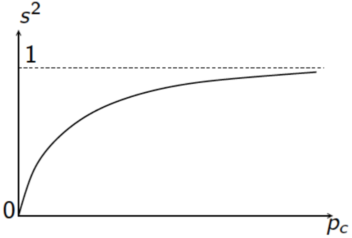
$k^\alpha(s^\alpha)$: phase mobility





Two-phase Darcy flow

$$s^2 = S^2(p_c),$$
$$s^1 = S^1(p_c) = 1 - S^2(p_c)$$



Fluids are assumed incompressible

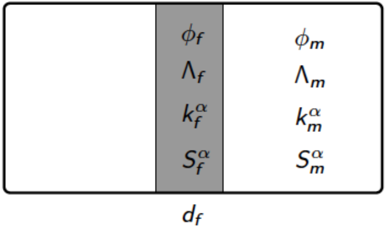
Phase pressure formulation of two-phase Darcy flows:

$$\begin{cases} \phi(\mathbf{x})\partial_t S^1(p_c) + \mathrm{div}(\mathbf{q}^1) = 0, \\ \phi(\mathbf{x})\partial_t S^2(p_c) + \mathrm{div}(\mathbf{q}^2) = 0, \\ p_c = u^2 - u^1 \end{cases}$$

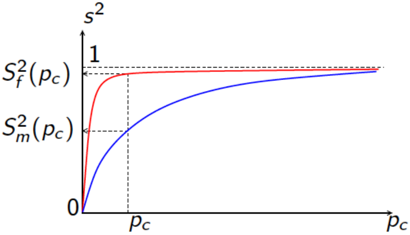
with

$$\mathbf{q}^\alpha = -k^\alpha(S^\alpha(p_c))\,\Lambda(\mathbf{x})(\nabla u^\alpha - \rho^\alpha \mathbf{g}), \quad \alpha = 1, 2,$$

Matrix and fracture domains



- Fracture width: $d_f << $ matrix size L
- Fracture rocktype (f): $\Lambda_f, \phi_f, k_f^\alpha, S_f^\alpha$
- Matrix rocktype (m): $\Lambda_m, \phi_m, k_m^\alpha, S_m^\alpha$
- The fracture can act as a drain or a barrier for the flow

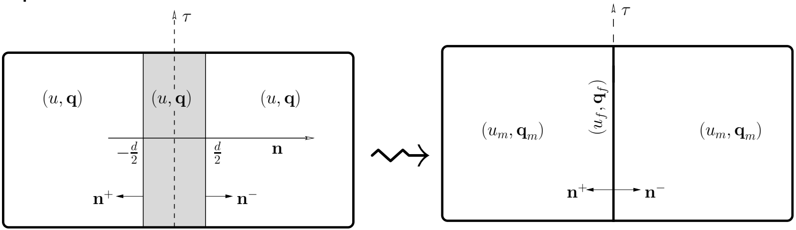


Dimensional reduction (codimension 1 in the fracture)

[Granet et al 2001], [Jaffré et al. 2002], [Bogdanov et al 2003], [Faille et al 2003], [Karimi Fard 2004], [Jaffré et al. 2005], [Angot et al. 2009]

- **Dimensional reduction**: averaging the model equations over the fracture width
- **Objectives**: facilitate the mesh generation and lower the number of degrees of freedom

equi-dimensional model: DFM model:



Dimensional reduction

$$\Lambda_f = \begin{pmatrix} \Lambda_{f,\tau} & 0 \\ 0 & \Lambda_{f,n} \end{pmatrix} \text{ in } (\tau, n) \text{ coordinates}$$

$$\begin{aligned} \mathbf{q}^\alpha &= -k_f^\alpha(S_f^\alpha(p_c))\, \Lambda_f(\nabla u^\alpha - \rho^\alpha \mathbf{g}) \\ &= \underbrace{-k_f^\alpha(S_f^\alpha(p_c))\, \Lambda_{f,\tau}(\nabla_\tau u^\alpha - \rho^\alpha \mathbf{g}_\tau)}_{\text{tangential flux } \mathbf{q}_\tau^\alpha} \quad \underbrace{-k_f^\alpha(S_f^\alpha(p_c))\, \Lambda_{f,n}(\partial_n u^\alpha - \rho^\alpha \mathbf{g}\cdot\mathbf{n})}_{\text{normal flux } (\mathbf{q}^\alpha\cdot\mathbf{n})\mathbf{n}} \end{aligned}$$

$$\mathrm{div}(\mathbf{q}^\alpha) = \mathrm{div}_\tau(\mathbf{q}_\tau^\alpha) + \partial_n(\mathbf{q}^\alpha \cdot \mathbf{n}).$$

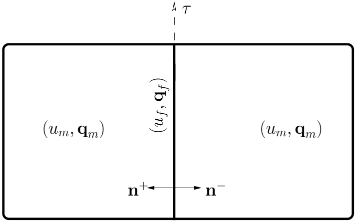
Dimensional reduction: averaging over the fracture width

- $$u_f^\alpha = \frac{1}{d_f}\int_{-\frac{d_f}{2}}^{\frac{d_f}{2}} u^\alpha \; dn, \qquad S_f^\alpha(p_{c,f}) \approx \frac{1}{d_f}\int_{-\frac{d_f}{2}}^{\frac{d_f}{2}} S_f^\alpha(p_c) \; dn$$
  $$p_{c,f} = u_f^2 - u_f^1.$$

- $$\mathbf{q}_f^\alpha = \int_{-\frac{d_f}{2}}^{\frac{d_f}{2}} \mathbf{q}_\tau^\alpha \; dn$$
  $$\approx -d_f k_f^\alpha(S_f^\alpha(p_{c,f}))\, \Lambda_{f,\tau}(\nabla_\tau u_f^\alpha - \rho^\alpha \mathbf{g}_\tau) \quad \text{(Fracture Darcy Law)}$$

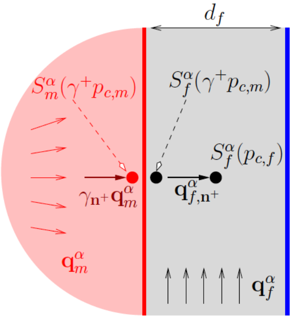
- $$\int_{-\frac{d_f}{2}}^{\frac{d_f}{2}} \Big(\phi_f \partial_t S_f(p_c) + \mathrm{div}(\mathbf{q}^\alpha)\Big) \; dn = 0$$
  $$\Rightarrow \quad d_f \phi_f \partial_t S_f^\alpha(p_{c,f}) + \mathrm{div}_\tau(\mathbf{q}_f^\alpha) + \gamma_{n^+}\mathbf{q}_m^\alpha + \gamma_{n^-}\mathbf{q}_m^\alpha = 0$$
  (Fracture conservation equation)

DFM models



$$
\begin{cases}
\text{Matrix Darcy Law:} & \mathbf{q}_m^\alpha = -k_m^\alpha(S_m^\alpha(p_{c,m}))\, \Lambda_m(\nabla u_m^\alpha - \rho^\alpha \mathbf{g}) \\
\text{Matrix Vol. Cons.:} & \phi_m \partial_t S_m^\alpha(p_{c,m}) + \mathrm{div}(\mathbf{q}_m^\alpha) = 0 \\
\text{Fracture Darcy Law:} & \mathbf{q}_f^\alpha = -d_f k_f^\alpha(S_f^\alpha(p_{c,f}))\, \Lambda_{f,\tau}(\nabla_\tau u_f^\alpha - \rho^\alpha \mathbf{g}_\tau) \\
\text{Fracture Vol. Cons.:} & \phi_f d_f \partial_t S_f^\alpha(p_{c,f}) + \mathrm{div}_\tau(\mathbf{q}_f^\alpha) + \gamma_{n^+}\mathbf{q}_m^\alpha + \gamma_{n^-}\mathbf{q}_m^\alpha = 0
\end{cases}
$$

Transmission conditions at the matrix fracture interface



- **Discontinuous pressure DFM model**:

$$\gamma_{\mathbf{n}^\pm}\mathbf{q}_m^\alpha = \mathbf{q}_{f,\mathbf{n}^\pm}^\alpha \approx$$

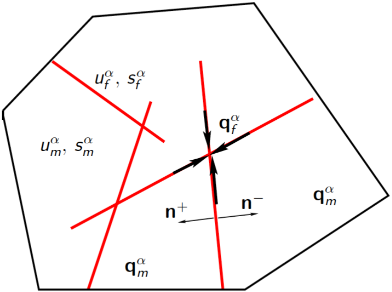
$$k_f^\alpha(S_f^\alpha(\gamma_\pm p_{c,m}))\Lambda_{f,\mathbf{n}}\left(\frac{u_f^\alpha - \gamma_\pm u_m^\alpha}{\frac{d_f}{2}} - \rho^\alpha \mathbf{g}\cdot\mathbf{n}^\pm\right)^-$$

$$+ k_f^\alpha(S_f^\alpha(p_{c,f}))\Lambda_{f,\mathbf{n}}\left(\frac{u_f^\alpha - \gamma_\pm u_m^\alpha}{\frac{d_f}{2}} - \rho^\alpha \mathbf{g}\cdot\mathbf{n}^\pm\right)^+$$

- **Continuous pressure DFM model** $\left(\frac{\Lambda_{f,\mathbf{n}}}{d_f} >> \frac{\Lambda_{m,\mathbf{n}}}{L}\right)$:

$$\gamma_+ u_m^\alpha = \gamma_- u_m^\alpha = u_f^\alpha.$$

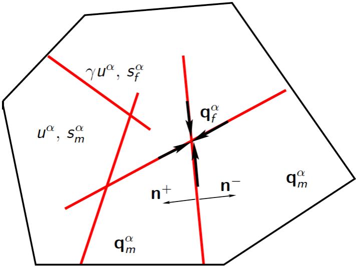
Generalization to complex Discrete Fracture Network



- Pressure continuity and flux conservation is assumed at fracture intersections
- Zero flux is assumed at immersed fracture tips

Continuous pressure two-phase Discrete Fracture Matrix model

- Continuous pressures: $u_m^\alpha = u^\alpha$, $u_f^\alpha = \gamma u^\alpha$, $\alpha = 1, 2$
- Capillary pressure: $p_c = u^2 - u^1$
- Saturations:
  - $s_m^\alpha = S_m^\alpha(p_c)$
  - $s_f^\alpha = S_f^\alpha(\gamma p_c)$



$$
\left\{
\begin{array}{ll}
\text{Matrix Darcy Law:} & \mathbf{q}_m^\alpha = -k_m^\alpha(S_m^\alpha(p_c))\,\Lambda_m(\nabla u^\alpha - \rho^\alpha \mathbf{g}) \\
\text{Matrix Vol. Cons.:} & \phi_m \partial_t S_m^\alpha(p_c) + \mathrm{div}(\mathbf{q}_m^\alpha) = 0 \\
\text{Fracture Darcy Law:} & \mathbf{q}_f^\alpha = -d_f k_f^\alpha(S_f^\alpha(\gamma p_c))\,\Lambda_{f,\tau}(\nabla_\tau \gamma u^\alpha - \rho^\alpha \mathbf{g}_\tau) \\
\text{Fracture Vol. Cons.:} & \phi_f d_f \partial_t S_f^\alpha(\gamma p_c) + \mathrm{div}_\tau(\mathbf{q}_f^\alpha) + \gamma_{n^+}\mathbf{q}_m^\alpha + \gamma_{n^-}\mathbf{q}_m^\alpha = 0
\end{array}
\right.
$$

Finite Volume Discretizations

Discretization of DFM models: State of the art for two-phase Darcy flows

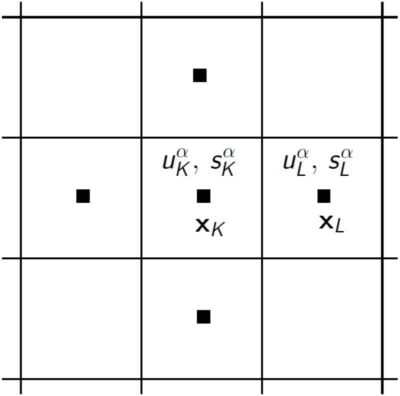
- **Continuous pressure models**:
  - Bogdanov et al. 2003 (CVFE)
  - Reichenberger et al 2006 (CVFE)
  - Firoozabadi et al 2007 (CVFE)
  - Matthai et al 2007 (CVFE)
  - Firoozabadi 2008 (MHFE + DG)
  - Groza et al 2013 (VAG)
  - Xing et al 2016 (VAG)
- **Discontinuous pressure models with harmonic average**:
  - Karimi-Fard et al 2004 (TPFA)
  - Faille et al, Nordbotten et al, 2012, Edwards et al 2014 (MPFA)
  - Gläser et al 2017 (MPFA)
- **Discontinuous pressure models with nonlinear transmission conditions**:
  - Elyes et al 2017 (MFE, splitting)
  - Hennicker et al 2017 (VAG, HFV)
  - Aghili et al 2018 (Two Point Flux Approximation (TPFA))

Cell centred finite volume discretization of two phase Darcy flows [Peaceman 77, Aziz and Settari 79]

- Set of cells: $K \in \mathcal{M}$
- Cell center: $\mathbf{x}_K$
- Subset of cells sharing a face with K: $\mathcal{M}_K$

- Discrete unknowns: for all $K \in \mathcal{M}$:

$$u_K^\alpha,\, s_K^\alpha,\, \alpha = 1, 2.$$

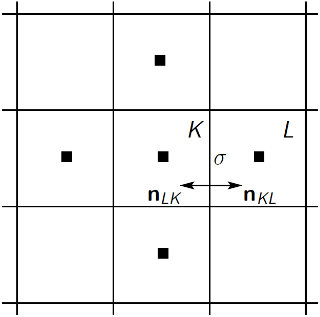


Cell centred finite volume discretization of two phase Darcy flows

Conservation equation: $\phi \partial_t s^\alpha + \mathrm{div} \mathbf{q}^\alpha = 0$

- Discrete conservation equations on each cell K:

$$\frac{1}{t^n - t^{n-1}} \int_{t^{n-1}}^{t^n} \Big(\int_K \phi \, \partial_t s^\alpha d\mathbf{x} + \sum_{L \in \mathcal{M}_K} \int_{\sigma = KL} \mathbf{q}^\alpha \cdot \mathbf{n}_{KL} d\sigma \Big) dt = 0$$



- Conservative approximation of the fluxes

$$F_{K,L}^\alpha = -F_{L,K}^\alpha \approx \int_{\sigma = KL} \mathbf{q}^\alpha \cdot \mathbf{n}_{KL} d\sigma$$

Two-Point Flux Approximation (orthogonal mesh)

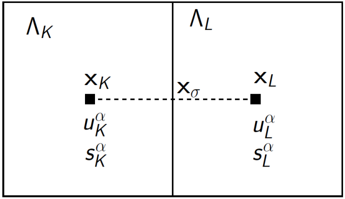
Conservative approximation of the fluxes:

$$F^{\alpha}_{K,L} = -F^{\alpha}_{L,K} \approx \int_{\sigma=KL} -k^{\alpha}(s^{\alpha})\Lambda(\mathbf{x})\nabla u^{\alpha}\cdot \mathbf{n}_{KL} d\sigma$$

$$V^{\alpha}_{K,L} = T_{KL}(u^{\alpha}_K - u^{\alpha}_L)$$

$$\approx \int_{\sigma=KL} -\Lambda(\mathbf{x})\nabla u^{\alpha}\cdot \mathbf{n}_{KL} d\sigma$$

$$\text{with} \quad T_{KL} = \frac{|\sigma|}{\frac{|\mathbf{x}_K\mathbf{x}_\sigma|}{\Lambda_K} + \frac{|\mathbf{x}_L\mathbf{x}_\sigma|}{\Lambda_L}}$$



$$F^{\alpha}_{K,L} = k^{\alpha}(s^{\alpha,n}_K)\,(V^{\alpha,n}_{KL})^{+} + k^{\alpha}(s^{\alpha,n}_L)\,(V^{\alpha,n}_{KL})^{-}$$

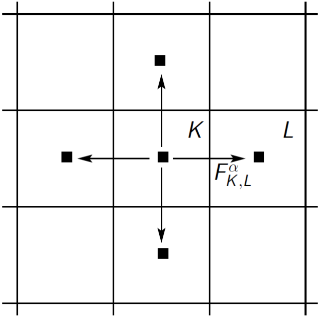
(two point monotone flux for the saturation equation)

Discrete conservation equations in each cell K

- $\phi_K = \int_K \phi(\mathbf{x}) d\mathbf{x}$
- Euler implicit time integration

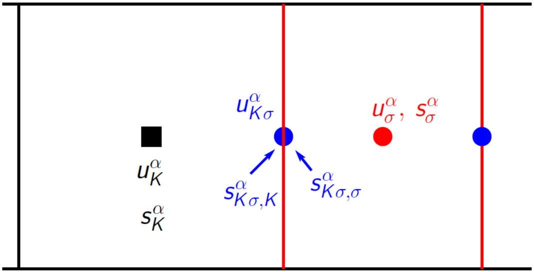
$$\phi_K \frac{s_K^{\alpha,n} - s_K^{\alpha,n-1}}{t^n - t^{n-1}} + \sum_{L \in \mathcal{M}_K} F_{K,L}^{\alpha,n} = 0$$

- $p_{c,K} = u_K^2 - u_K^1$
- $s_K^\alpha = S^\alpha(p_{c,K})$

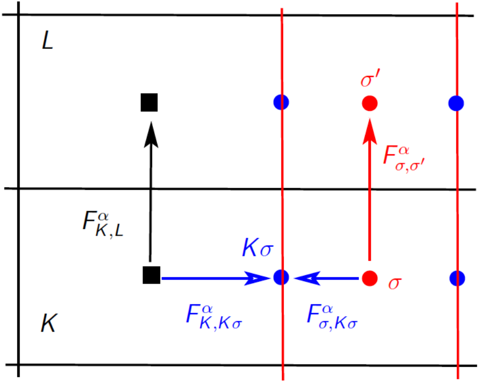


Discontinuous pressure DFM model: discrete unknowns

$$
\begin{cases}
s_K^\alpha = S_m^\alpha(u_K^2 - u_K^1), \\
s_\sigma^\alpha = S_f^\alpha(u_\sigma^2 - u_\sigma^1), \\
s_{K\sigma,K}^\alpha = S_m^\alpha(u_{K\sigma}^2 - u_{K\sigma}^1), \\
s_{K\sigma,\sigma}^\alpha = S_f^\alpha(u_{K\sigma}^2 - u_{K\sigma}^1)
\end{cases}
$$



Discontinuous pressure DFM model: fluxes



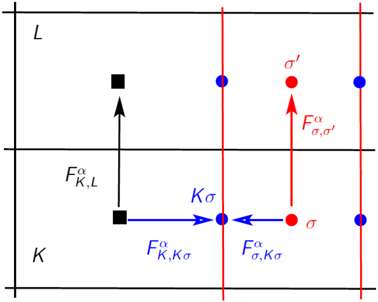
$$F^{\alpha}_{K,K\sigma} = k^{\alpha}_{m}(s^{\alpha}_{K})T_{K,K\sigma}(u^{\alpha}_{K} - u^{\alpha}_{K\sigma})^{+} + k^{\alpha}_{m}(s^{\alpha}_{K\sigma,K})T_{K,K\sigma}(u^{\alpha}_{K} - u^{\alpha}_{K\sigma})^{-},$$

$$F^{\alpha}_{\sigma,K\sigma} = k^{\alpha}_{f}(s^{\alpha}_{\sigma})T_{\sigma,K\sigma}(u^{\alpha}_{\sigma} - u^{\alpha}_{K\sigma})^{+} + k^{\alpha}_{f}(s^{\alpha}_{K\sigma,\sigma})T_{\sigma,K\sigma}(u^{\alpha}_{\sigma} - u^{\alpha}_{K\sigma})^{-}.$$

Discontinuous pressure DFM model: discrete conservation equations

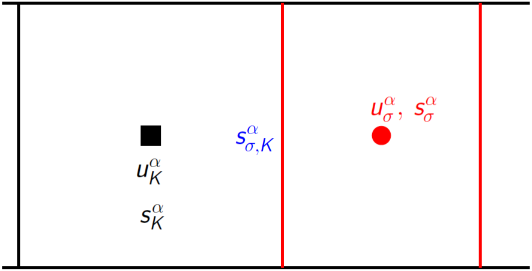
$$\begin{cases} \phi_K \dfrac{s_K^\alpha - s_K^{\alpha,n-1}}{t^n - t^{n-1}} + \displaystyle\sum_L F_{K,L}^\alpha + \sum_\sigma F_{K,K\sigma}^\alpha = 0 \\ \phi_\sigma \dfrac{s_\sigma^\alpha - s_\sigma^{\alpha,n-1}}{t^n - t^{n-1}} + \displaystyle\sum_{\sigma'} F_{\sigma,\sigma'}^\alpha + \sum_K F_{\sigma,K\sigma}^\alpha = 0, \end{cases}$$

$$F_{K,K\sigma}^\alpha + F_{\sigma,K\sigma}^\alpha = 0.$$

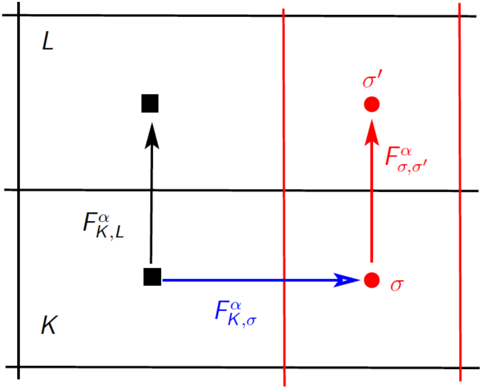


Continuous pressure DFM model: discrete unknowns

$$
\begin{cases}
s_K^\alpha = S_m^\alpha(u_K^2 - u_K^1), \\
s_\sigma^\alpha = S_f^\alpha(u_\sigma^2 - u_\sigma^1), \\
s_{\sigma,K}^\alpha = S_m^\alpha(u_\sigma^2 - u_\sigma^1),
\end{cases}
$$



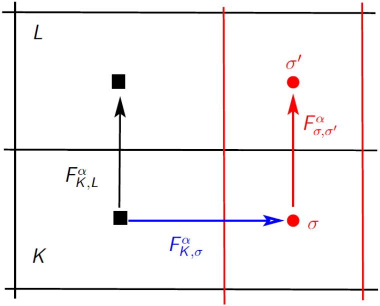
Continuous pressure DFM model: fluxes



$$F^{\alpha}_{K,\sigma} = k^{\alpha}_{m}(s^{\alpha}_{K})T_{K,\sigma}(u^{\alpha}_{K} - u^{\alpha}_{\sigma})^{+} + k^{\alpha}_{m}(s^{\alpha}_{\sigma,K})T_{K,\sigma}(u^{\alpha}_{K} - u^{\alpha}_{\sigma})^{-},$$

Continuous pressure DFM model: discrete conservation equations

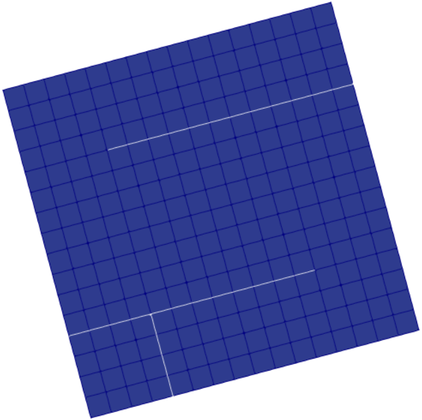
$$
\begin{cases}
\phi_K \dfrac{s_K^\alpha - s_K^{\alpha,n-1}}{t^n - t^{n-1}} + \displaystyle\sum_L F_{K,L}^\alpha + \sum_\sigma F_\sigma^\alpha = 0, \\[2ex]
\phi_\sigma \dfrac{s_\sigma^\alpha - s_\sigma^{\alpha,n-1}}{t^n - t^{n-1}} + \displaystyle\sum_{\sigma'} F_{\sigma,\sigma'}^\alpha - \sum_K F_{K,\sigma}^\alpha = 0,
\end{cases}
$$



Numerical examples

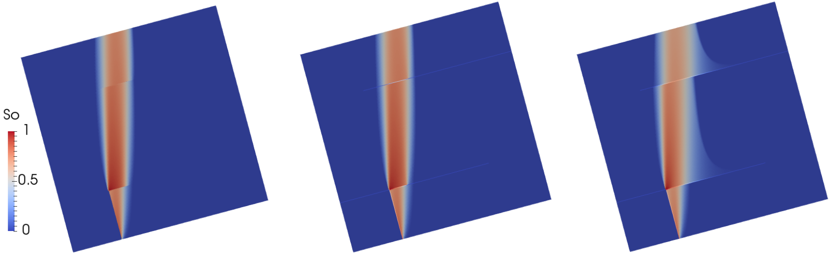
Comparisons between DFM and equi-dimensional models

- $\Omega = (0, 100 \text{ m})^2$ rotated
- $d_f = 1$ cm, $\Lambda_f = \lambda_{f,n} = 10^3 \Lambda_m$, $\phi_f = 0.35$.
- $\Lambda_m = 0.1$ Darcy, $\phi_m = 0.2$.
- $\rho^w = 1000$ and $\rho^o = 800$ Kg.m^{-3}.
- Initially water saturated
- Oil injection in the bottom fracture

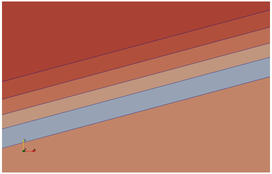


Comparisons between DFM and equi-dimensional models: gravity dominant flow, homogeneous $P_c(s^2)$

$P_{c,m}(s^2) = P_{c,f}(s^2) = -b \log(1 - s^2)$ with $b = 10$ Pa.

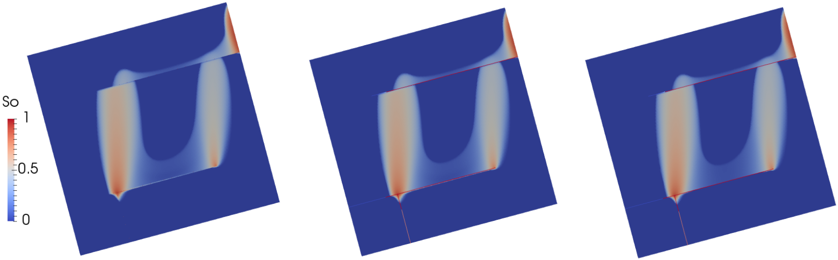


equi dim | disc. pressure | cont. pressure



Comparisons between DFM and equi-dimensional models: gravity dominant flow, matrix acting as a capillary barrier

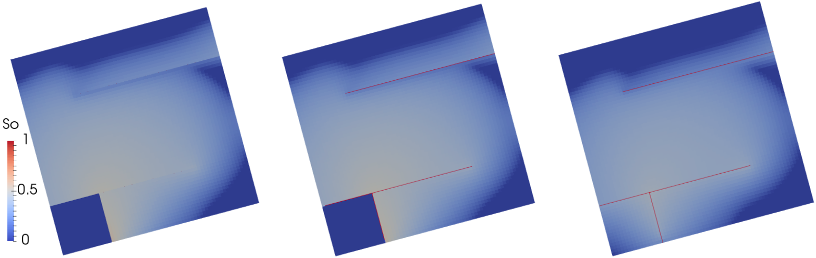
$$P_{c,m}(s^2) = 10^3(1 - \log(1 - s^2))\ \mathrm{Pa}, \quad P_{c,f}(s^2) = -10\log(1 - s^2)\ \mathrm{Pa}.$$



equi dim   disc. pressure   cont. pressure

Comparisons between DFM and equi-dimensional models: viscous dominant flow, matrix acting as a capillary barrier

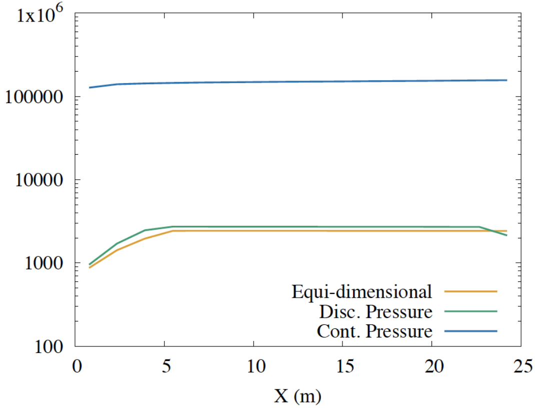
$$P_{c,m}(s^2) = 10^5(1 - \log(1 - s^2))\ \mathrm{Pa}, \quad P_{c,f}(s^2) = -100\log(1 - s^2)\ \mathrm{Pa}.$$



equi dim　　disc. pressure　　cont. pressure

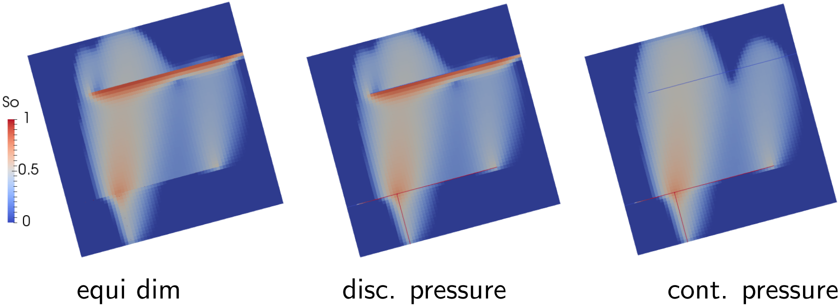
Comparisons between DFM and equi-dimensional models: viscous dominant flow, matrix acting as a capillary barrier

$$P_{c,m}(s^2) = 10^5(1 - \log(1 - s^2))\ \mathrm{Pa}, \quad P_{c,f}(s^2) = -100\log(1 - s^2)\ \mathrm{Pa}.$$



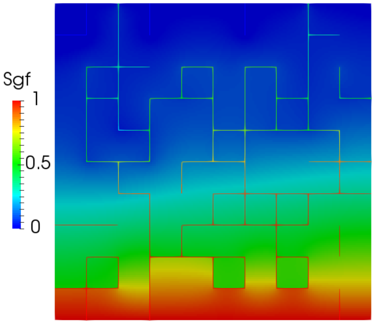
Capillary pressure along the vertical fracture.

Comparisons between DFM and equi-dimensional models: drains and barrier

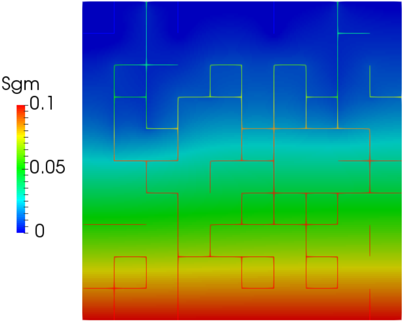


Drains acting as a barrier for water

Desaturation by suction of a water saturated low permeability rock



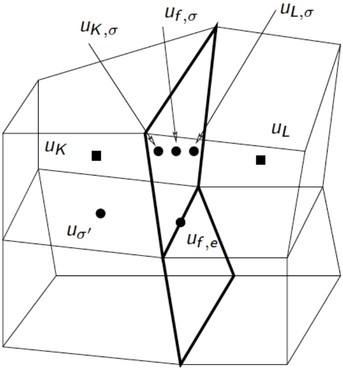
disc. pressure



cont. pressure

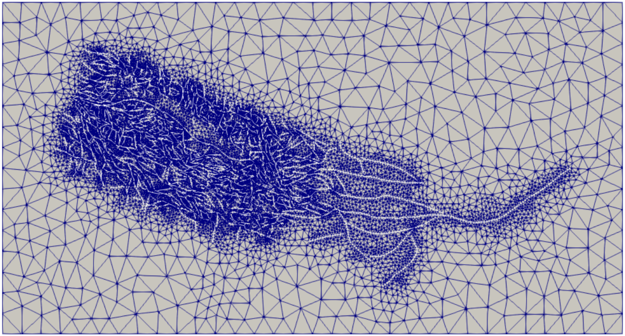
Discretization: extension to more complex meshes and geometries

- **Face based approaches**: Hybrid Finite Volume (HFV) discretization
  - adapted to discontinuous pressure models
  - expensive on 3D meshes



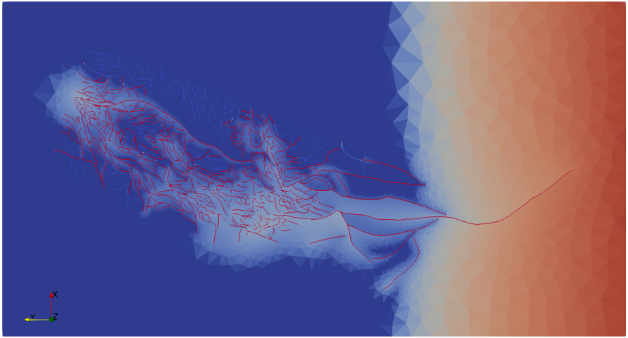
2D simulation of the discontinuous pressure DFM model with the HFV scheme

Data set: $P_{c,m}(s^w) = 10^5(1 - \log(s^w))$, $P_{c,f}(s^w) = -100 \log(s^w)$ Pa. $\Lambda_m = 10^{-13}$ m^2, $\Lambda_f = \lambda_{f,\mathbf{n}} = 10^{-10}$ m^2, $d_f = 1$ cm, $t_f = 1600$ days.



Mesh: (Courtesy of M. Karimi-Fard, Stanford, and A. Lapène, Total): $\Omega = (0, 100\,\mathrm{m}) \times (0, 186.5\,\mathrm{m})$, 32340 cells, 48558 faces, 5344 fracture faces.

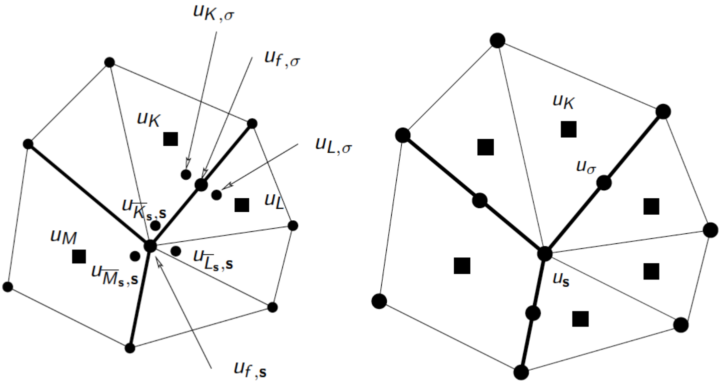
2D simulation of the discontinuous pressure DFM model with the HFV scheme



- 1442 time steps
- 19 Newton it. per time step
- 19 GMRes it. per Newton step (CPR-AMG preconditioner)
- total CPU time with 1 core Intel i7 2.6 GHz: 8h.

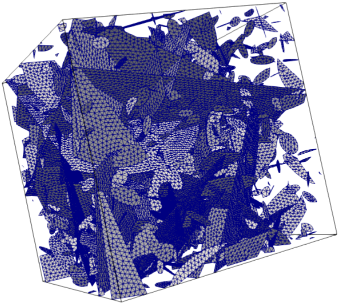
Discretization: extension to more complex meshes and geometries

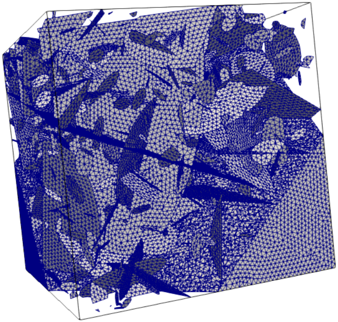
- **Vertex based approaches**: Vertex Approximate Gradient (VAG) discretization
  - adapted to continuous pressure models
  - efficient on tetrahedral meshes for large fracture networks
  - difficulties to solve the nonlinear systems for discontinuous pressure models



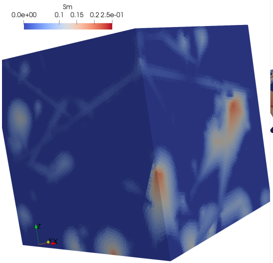
Example: Large 3D DFM simulation

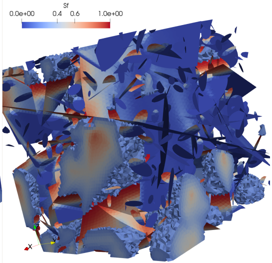
- $\Omega = (0, 300)^3$ m, 1000 fractures, $d_f = 1$ cm.
- tetrahedral mesh with 1.7 10^6 cells, 2.9 10^5 nodes, 10^5 fracture faces (P. Laug, G. Pichot, Inria)
- $\frac{\Lambda_f}{\Lambda_m} = 10^3$, $p_{c,m} = -10^5 \log(s_m^1)$, $p_{c,f} = -10^3 \log(s_f^1)$.
- oil injected during 15 years in the bottom fractures, initially water saturated.





Large 3D DFM simulation: continuous pressure model





- Vertex Approximate Gradient Scheme
- Total Velocity formulation (with El Houssaine Quenjel)
- 87 time steps for $t_f = 15$ years
- 10.8 Newton it. per time step
- 18 GMRes it. per Newton step (CPR-AMG preconditioner)
- total CPU time with 1 core Intel i7 2.6 GHz: 10.7 hours.

Conclusions and perspectives

- Complex geometries
- Highly nonlinear transmission conditions at matrix fracture interfaces
- Robustness challenges for large fracture networks in 3D
- The continuous pressure model is not always a good approximation for two-phase flows even for drains
- More physics: thermodynamics, thermics, chemistry, poromechanics

Acknowledgements

Thanks for your attention and to Total, Storengy, BRGM and Andra for their support.