Sequentially Coupled Multiphase Flow and Geomechanics Modeling of Hydraulically Fractured Unconventional Reservoirs

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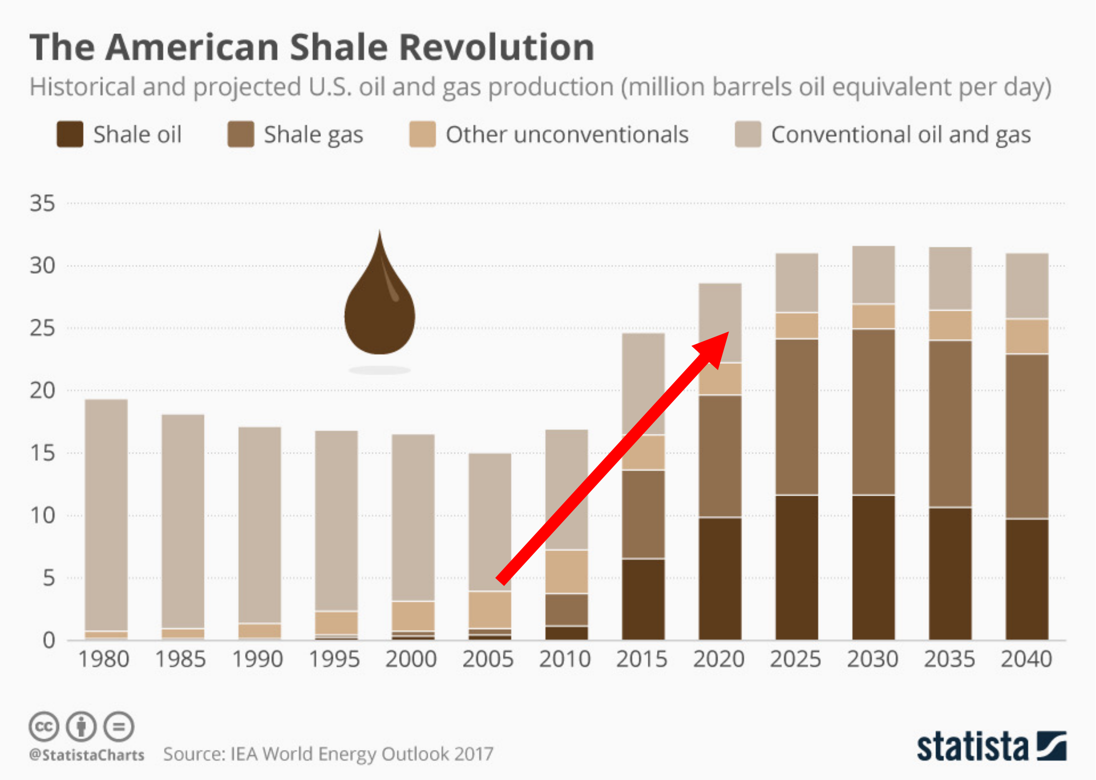
Earth & Environmental Sciences

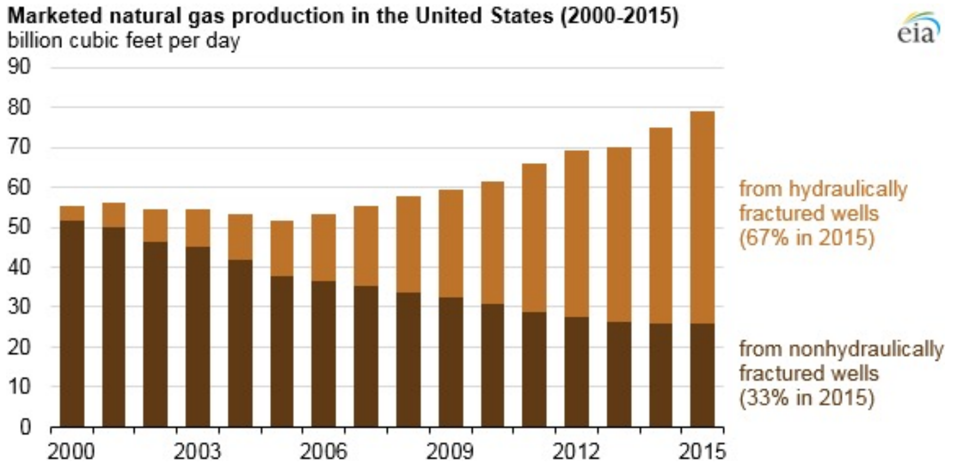
Outline

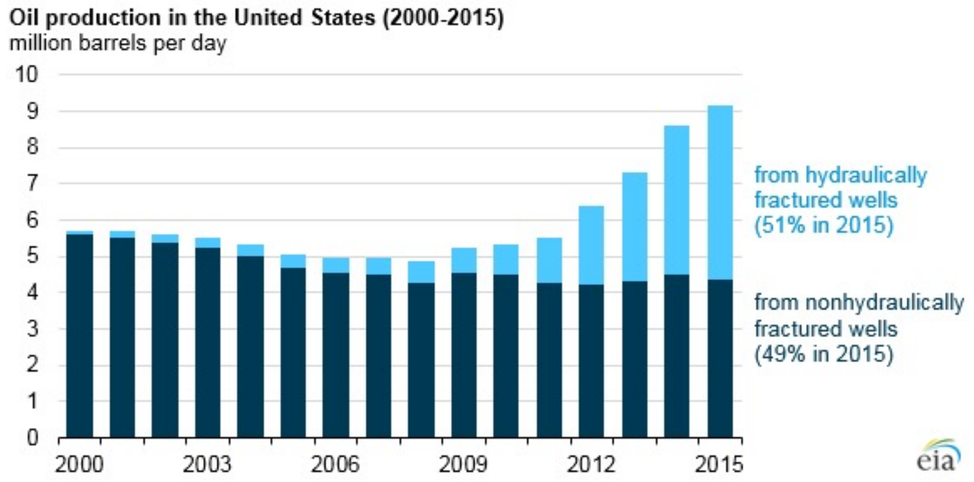
- **Introduction**
  - Challenges and opportunities in unconventional reservoir development
  - Role of geomechanics and coupling to flow
- **Sequential Coupling Numerical Framework**
  - Fixed-stress splitting algorithm
  - Two grid structures to explicitly model fractures
- **Applications**
  - Depletion-induced stress evolution, water injection, flow in dilated fracture networks
- **Conclusive Remarks**

Introduction

- **Hydraulically Fractured Reservoirs**



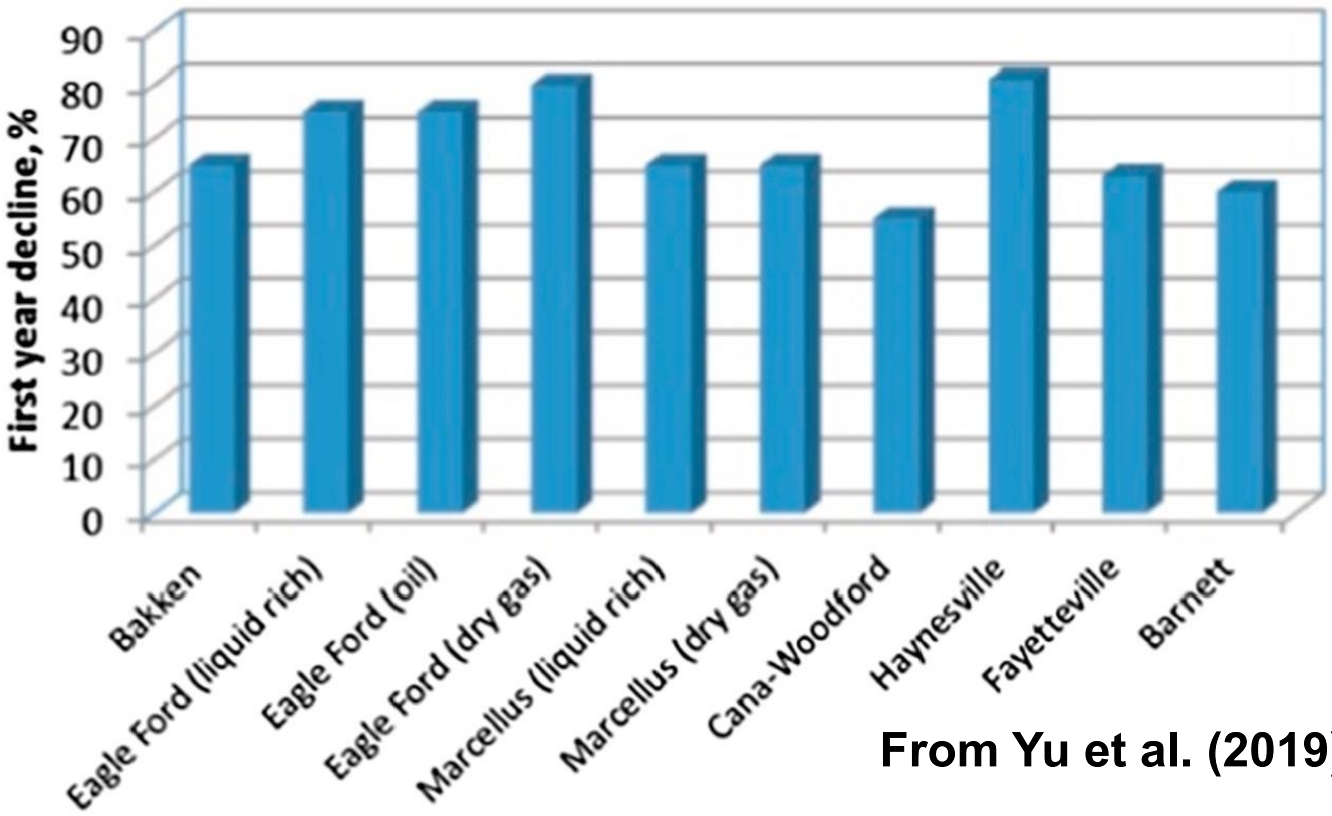




Introduction

- **Challenges – production decline; low primary recovery**

First year production decline rate of major US shale wells

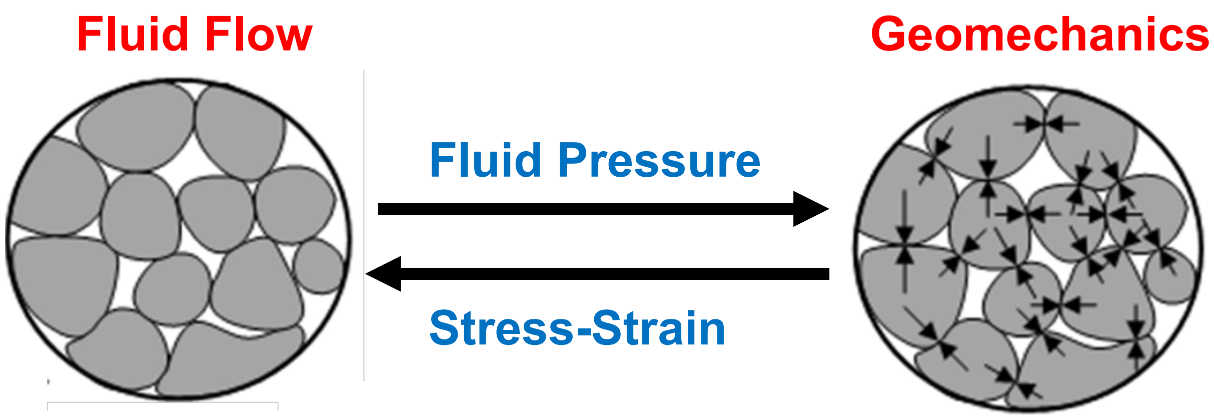


From Yu et al. (2019)

Introduction

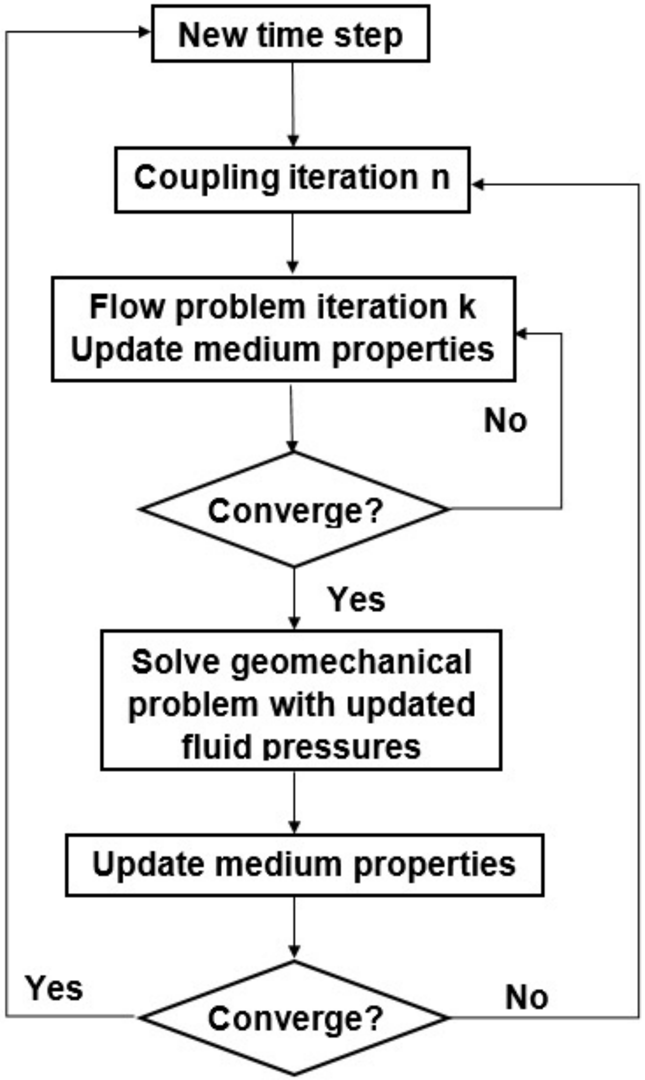
- Strategies: infill-well drilling, refracturing, EOR methods, etc.
  - Characterization of depletion-induced stress-state changes
  - Fractures, as weak surfaces, are highly stress sensitive
- Geomechanics is essential in fractured reservoirs
- Requirements: tightly coupled flow and geomechanics model
  - Efficiency in fracture modeling
  - Flexibility in Multiphysics coupling

Multiphase
Multicomponent
Phase behaviors
Non-linear system



Elastic/Elastoplastic
(Non)-linear fracture closure
Fracture shear dilation
Linear or non-linear

Fixed-Stress Splitting Algorithm



Advantages

- Separate modules for flow and mechanics
- Domain and mesh can be different
- Unconditionally stable/fast convergence

Flow Problem – Finite Volume Method

$$R = \frac{\partial}{\partial t}\int_V M^{\kappa}\mathrm{d}V - \int_{\Gamma} \boldsymbol{F}^{\kappa}\cdot\boldsymbol{n}\,\mathrm{d}\Gamma - \int_V q^{\kappa}\mathrm{d}V$$

$$\sum \frac{\partial R^{t+1}\left(\boldsymbol{x}_p^{t+1}\right)}{\partial x}\delta x_{p+1} = -R^{t+1}\left(\boldsymbol{x}_p^{t+1}\right)$$

Geomechanical Problem – Finite Element Method

$$\int_{\Omega}\delta\boldsymbol{\varepsilon}:\boldsymbol{\sigma}'\mathrm{d}\Omega - \int_{\Omega}\delta\boldsymbol{\varepsilon}:\alpha p_t\mathbf{I}\mathrm{d}\Omega - \int_{\Omega}\delta\boldsymbol{u}\cdot\rho_{\mathrm{b}}\mathbf{g}\mathrm{d}\Omega +$$
$$\int_{\Gamma_{\mathrm{f}}}\delta\boldsymbol{\Delta}\cdot\boldsymbol{t}_{\mathrm{f}}\mathrm{d}\Gamma + \int_{\Gamma_{\mathrm{f}}}\delta\boldsymbol{\Delta}\cdot p_{\mathrm{t}}\mathbf{I}\cdot\boldsymbol{n}_{\mathrm{f}}\mathrm{d}\Gamma - \int_{\Gamma_{\mathrm{t}}}\delta\boldsymbol{u}\cdot\hat{\boldsymbol{t}}\mathrm{d}\Gamma = 0$$

Porosity Coupling

- **True porosity variation(Geertsma 1957)** $\delta\phi = \phi\left[\frac{1}{\phi}\frac{b}{K_b} - \frac{1}{K_b}\right](\delta\sigma_v + \delta p)$

- **During flow simulation**

$$\delta\sigma_v = 0$$

$$\delta\phi = \left(\frac{b-\phi}{K_b}\right)\delta p \rightarrow \phi^k = \phi^{k-1} + \frac{\left(b-\phi^{k-1}\right)}{K_b}\delta p^{k-1}$$

$$\phi^* = \phi\left(1+\varepsilon_v\right)$$

$$\phi^{*k} = \phi^{*k-1} + \left[\frac{b\left(1+\varepsilon_v\right) - \phi^{*k-1}}{K_b}\right]\delta p^{k-1}$$

- **After geomechanical calculation**

$$\delta\sigma_v = K_b\delta\varepsilon_v - b\delta p$$

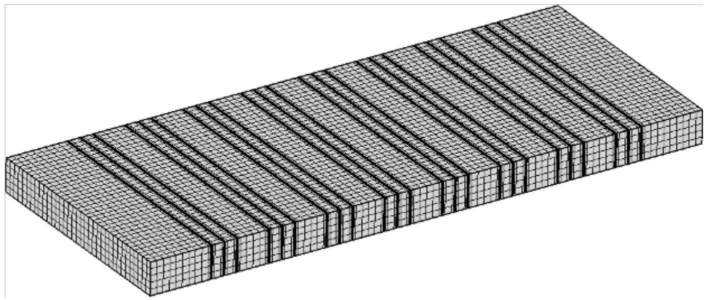
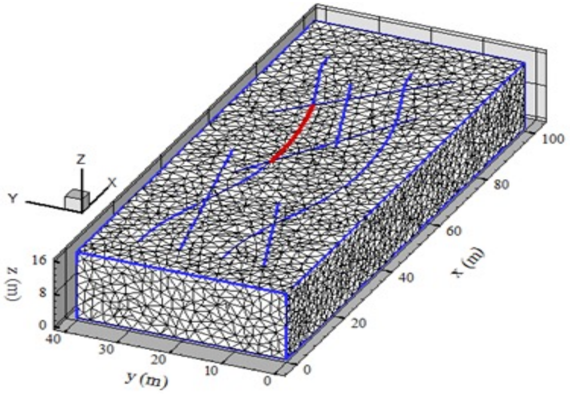
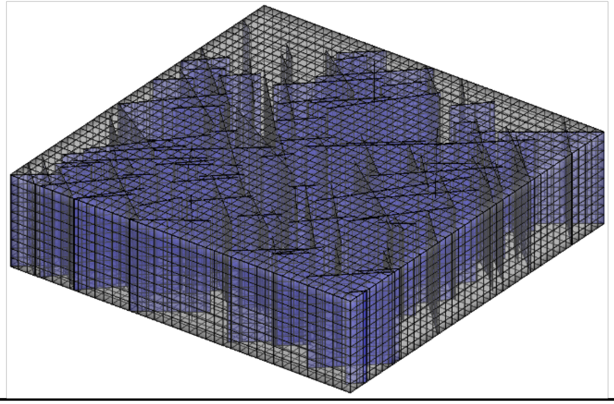
$$\delta\phi = \left(b-\phi\right)\delta\varepsilon_v + \frac{\left(b-\phi\right)\left(1-b\right)}{K_b}\delta p$$

$$\phi - \phi_0 = \left(b-\phi_0\right)\left(\varepsilon_v - \varepsilon_{v0}\right) + \frac{\left(b-\phi_0\right)\left(1-b\right)}{K_b}\left(p-p_0\right)$$

$$\phi^* = \phi_0 + b\left(\varepsilon_v - \varepsilon_{v0}\right) + \frac{\left(b-\phi_0\right)\left(1-b\right)}{K_b}\left(p-p_0\right) + O\left(\varepsilon_v^2\right)$$

$$\approx \phi_0 + b\left(\varepsilon_v - \varepsilon_{v0}\right) + \frac{\left(b-\phi_0\right)\left(1-b\right)}{K_b}\left(p-p_0\right)$$

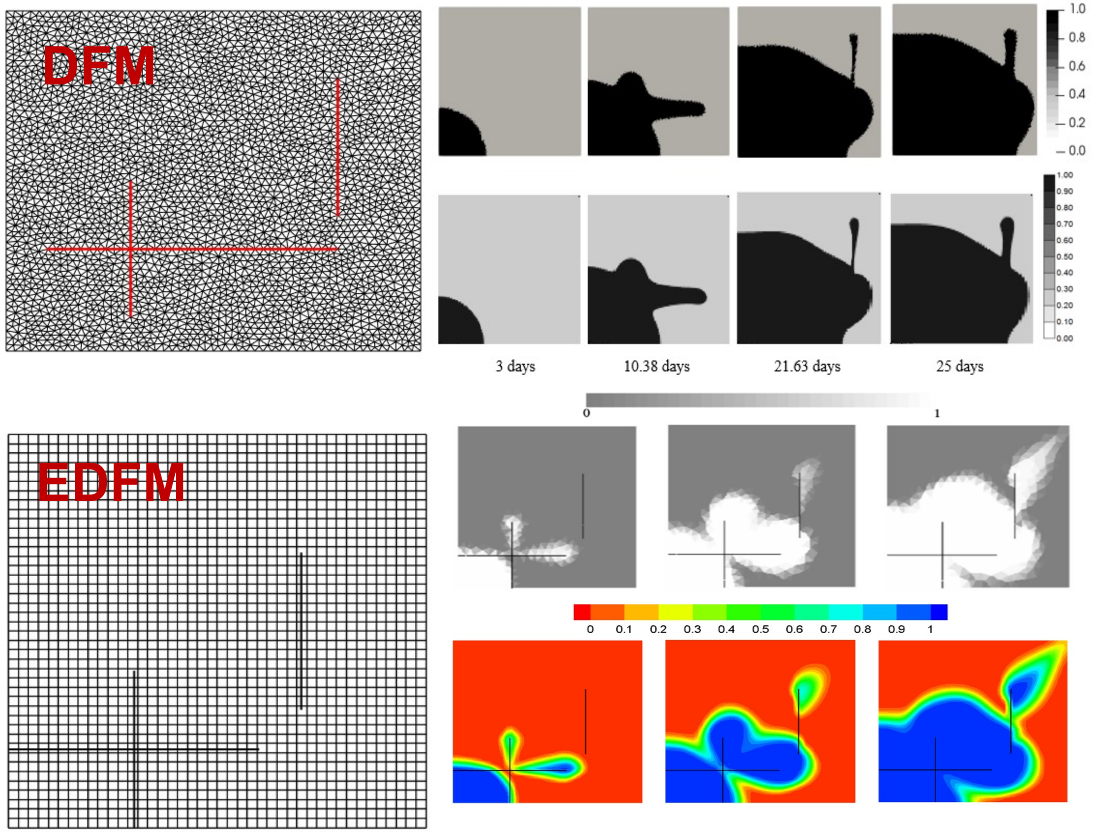
Grid Structures

Structured grid with local grid refinement (LGR)	Unstructured grid with discrete fracture model (DFM)	Structured grid with embedded discrete fracture model (EDFM)
• Realistic representation of physical model (flow) • Small-scale detailed mechanism analysis	• Handle complex fracture geometries • Discontinuous fracture interface • Small-medium scale applications	• Coarse background mesh • Large scale applications
• Model planar fracture • Fractures treated as continuum media	• Unstructured mesh generator • Small grids around fractures	• Accuracy in multiphase flow • Fractures in geomechanics
		

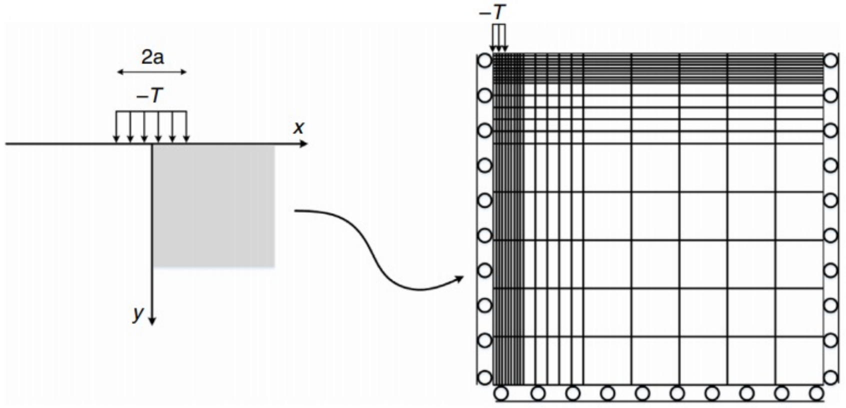
Validations

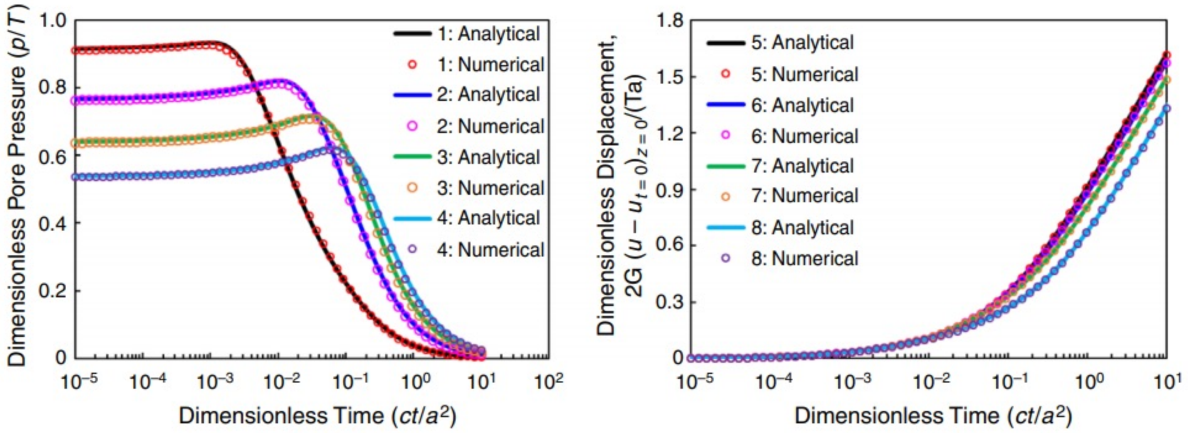
- **DFM and EDFM**

Model Schematic **Water Distribution**



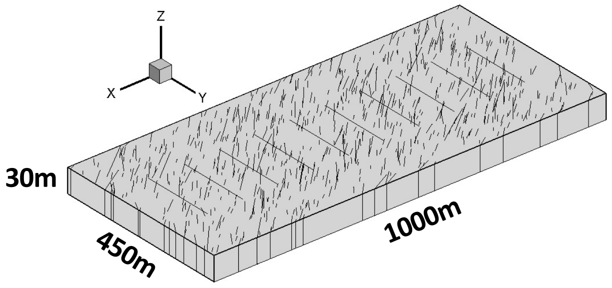
- **McNamee and Gibson (1960)**



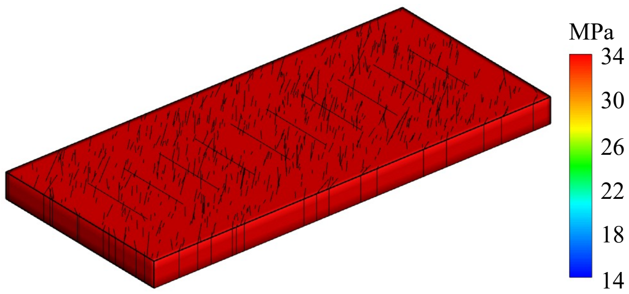


Stress Evolution in Shale-Gas Reservoir

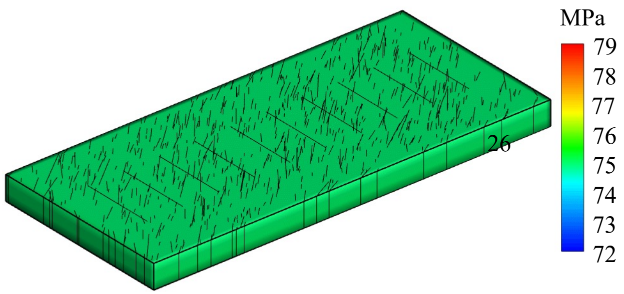
Model Schematic



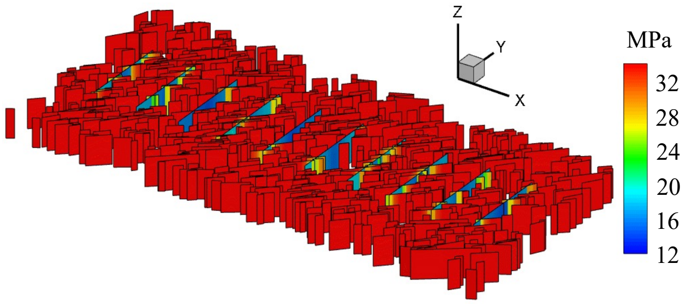
Matrix Pressure Distribution



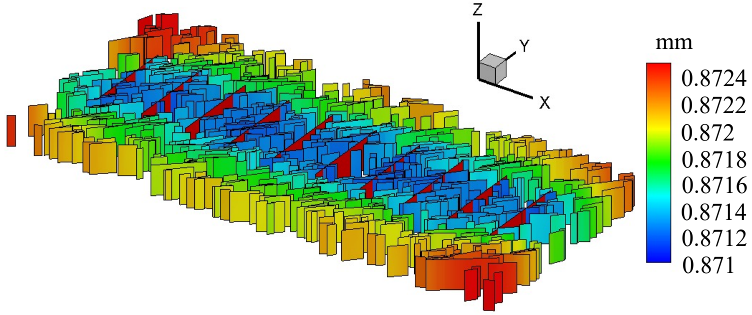
σ_{xx} Distribution



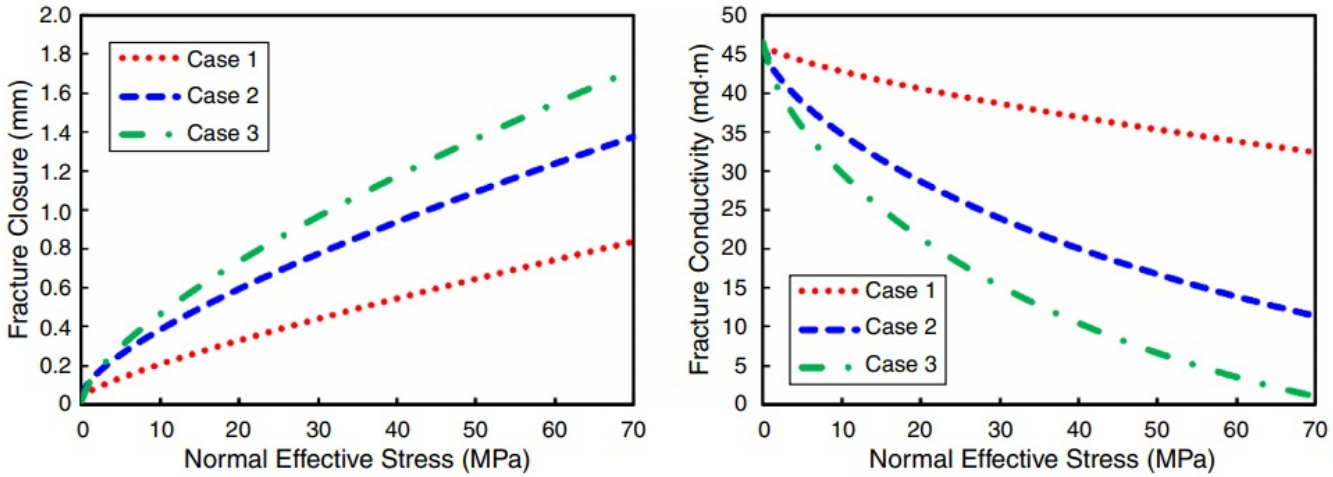
Fracture Pressure Distribution

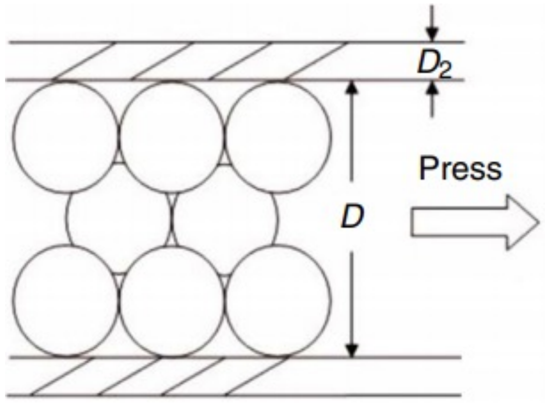


Fracture Aperture Distribution



Effects of Fracture Deformation





From Li et al. (2015)

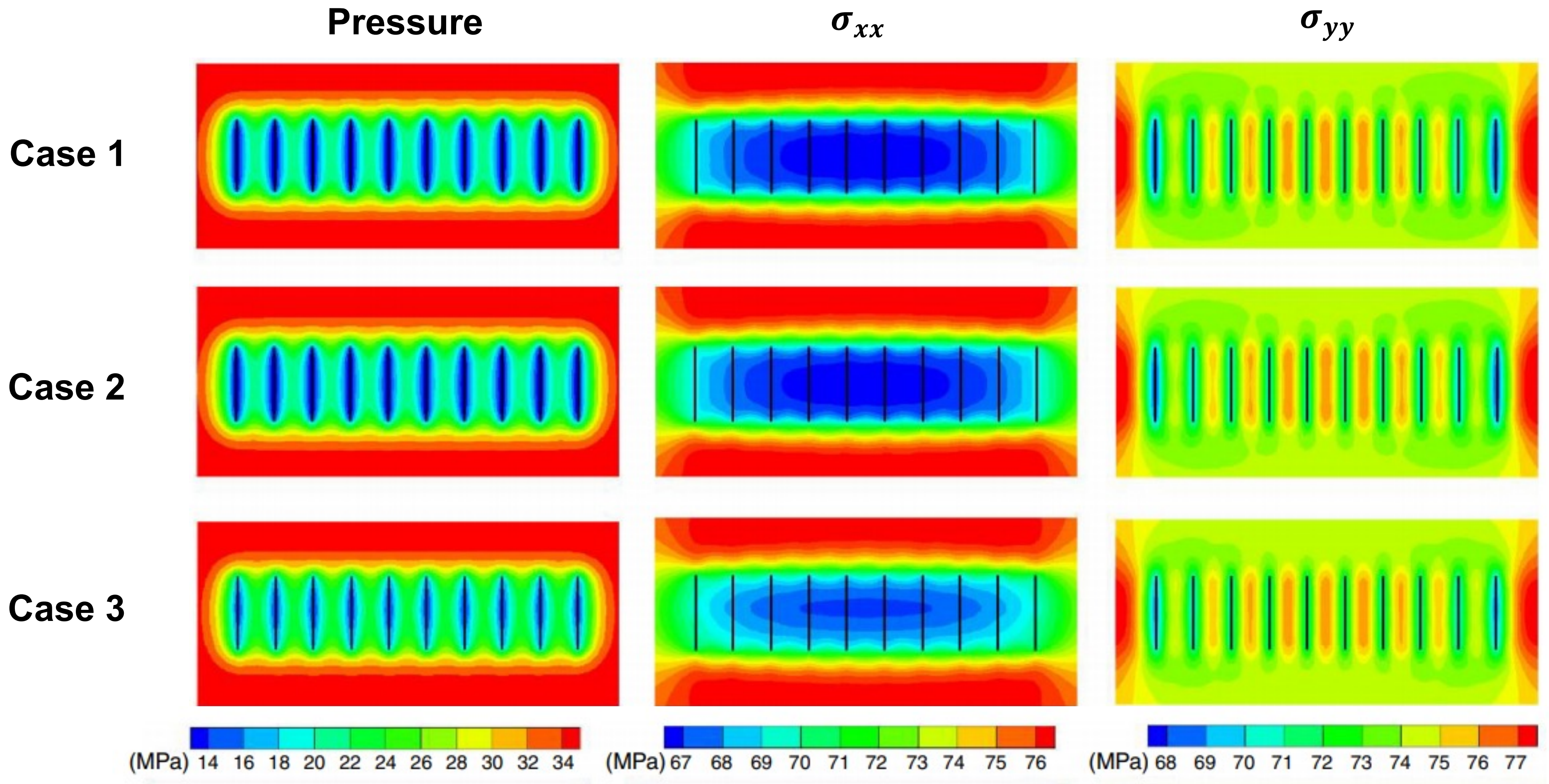
$$\Delta d_{\mathrm{hf}} = \Delta d_{\mathrm{hf,d}} + \Delta d_{\mathrm{hf,e}}$$ **(deformation + embedment)**

$$\Delta d_{\mathrm{hf,d}} = 2.08 d_{\mathrm{hf0}} \left(K^2 \sigma_{\mathrm{n}} \frac{1-\nu_1^2}{E_1} \right)^{\frac{2}{3}}$$

$$\Delta d_{\mathrm{hf,e}} = b_0 + b_1 \left\{ 2.08 D_1 \left(K^2 \sigma_{\mathrm{n}} \right)^{\frac{2}{3}} \left[\left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_1} \right)^{\frac{2}{3}} - \left(\frac{1-\nu_1^2}{E_1} \right)^{\frac{2}{3}} \right] + D_2 \frac{\sigma_{\mathrm{n}}}{E_2} \right\}$$

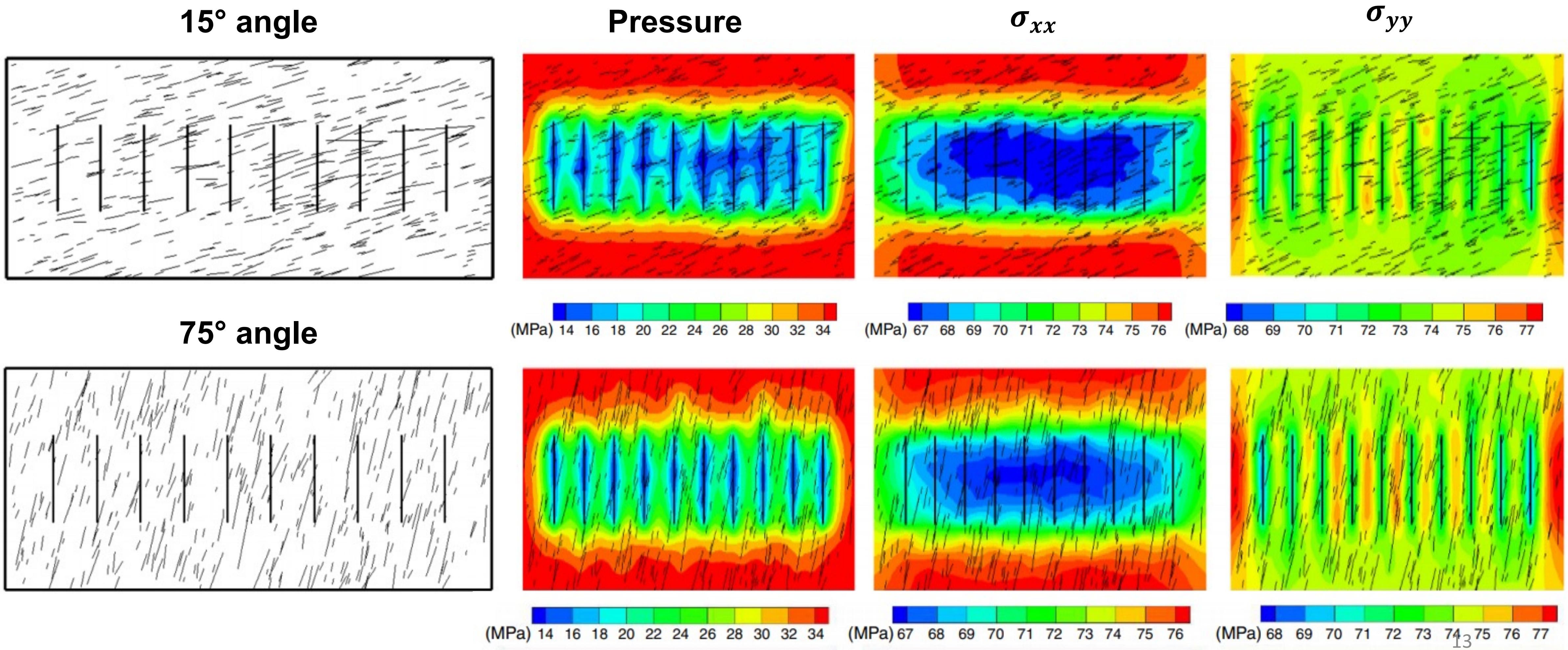
Effects of Fracture Deformation

Poorly-propped fractures hinder pressure depletion and stress evolution



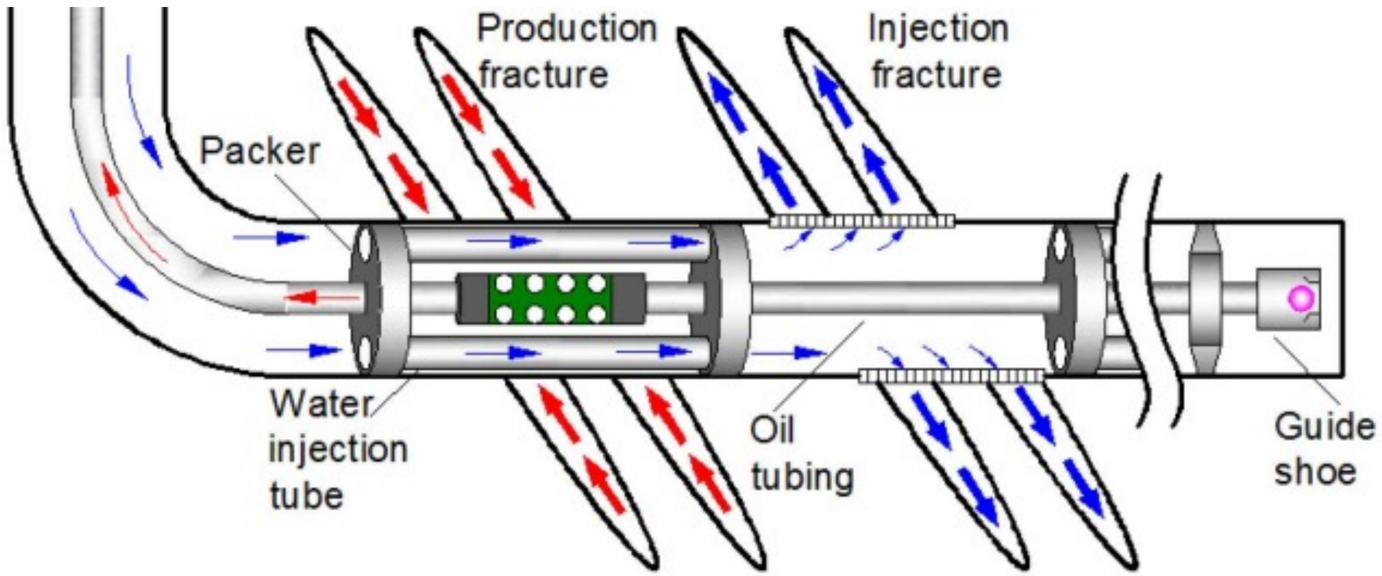
Effects of Natural Fractures

Patterns of depletion area depend on distribution of NF connected with HF



Inter-Fracture Water Injection

- Dombrowski et al. (2015): a novel fluid injection scheme
- Inject/produce simultaneously in the same wellbore



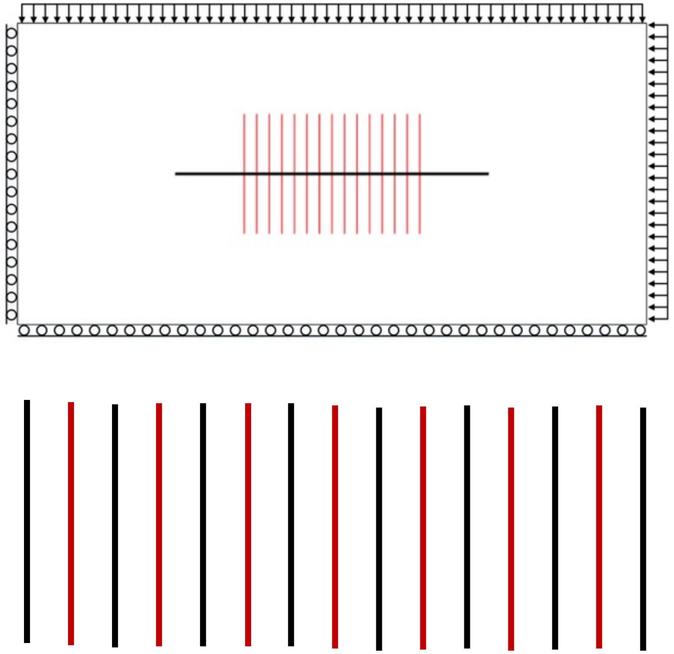
Adapted from He et al. (2019)

Dombrowski, R. J., Fonseca, E. R., Karanikas, J. M. et al. 2015. Fluid Injection in Light Tight Oil Reservoirs. US Patent.

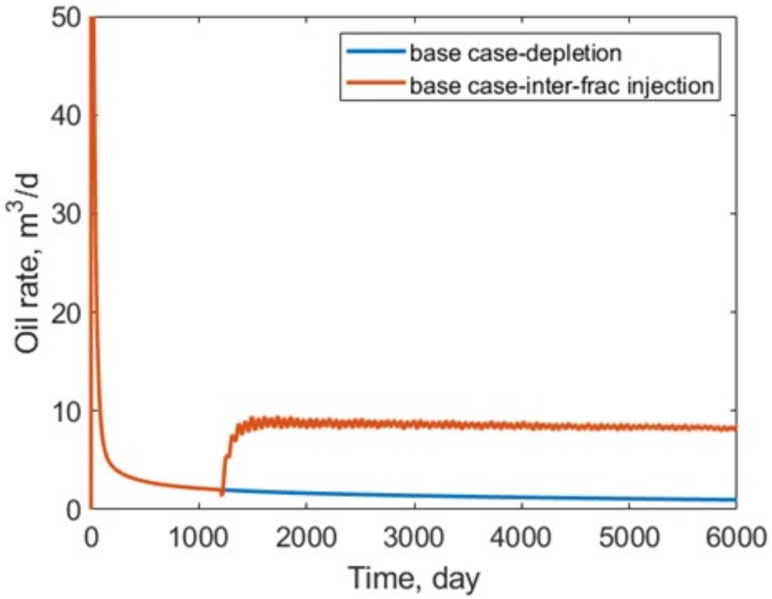
Inter-Fracture Water Injection

- **Tight oil reservoir, located in Ordos Basin, China (Li et al. 2015)**
- **Implement injection when oil rate below 2 m^3/d**
- **Cumulative oil production increased about 3.5 times**

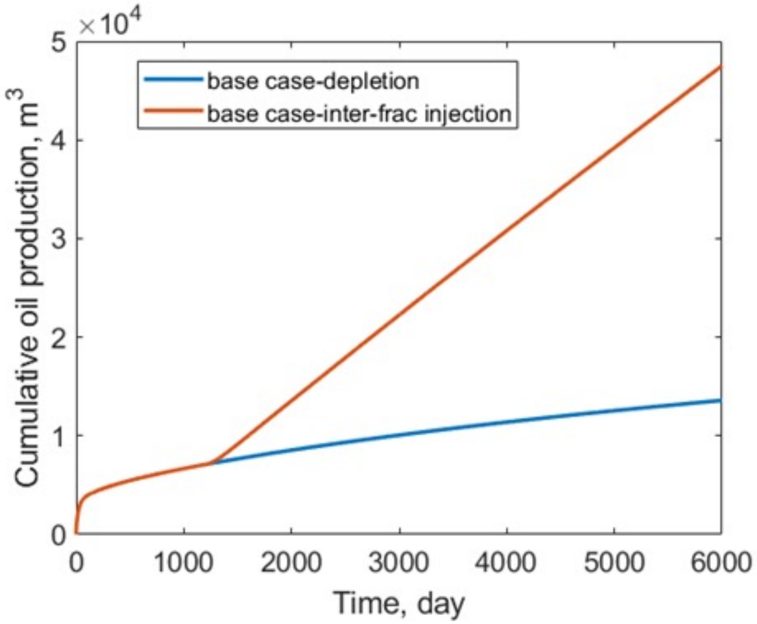
Model Schematic



Oil Rate



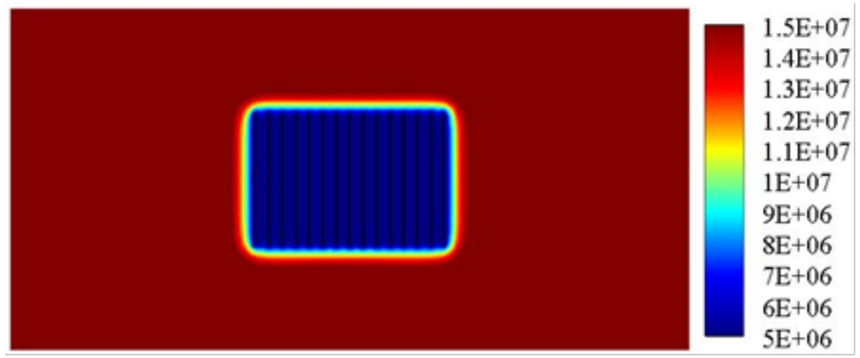
Water Rate



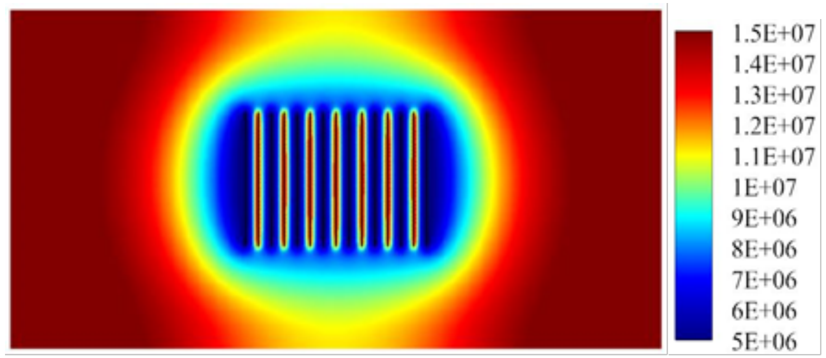
EOR Mechanisms

- **Water flooding/Pressure Enhancement**

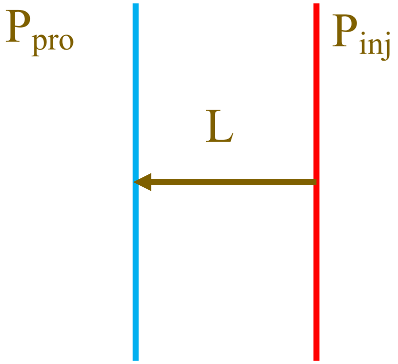
Pressure Sink

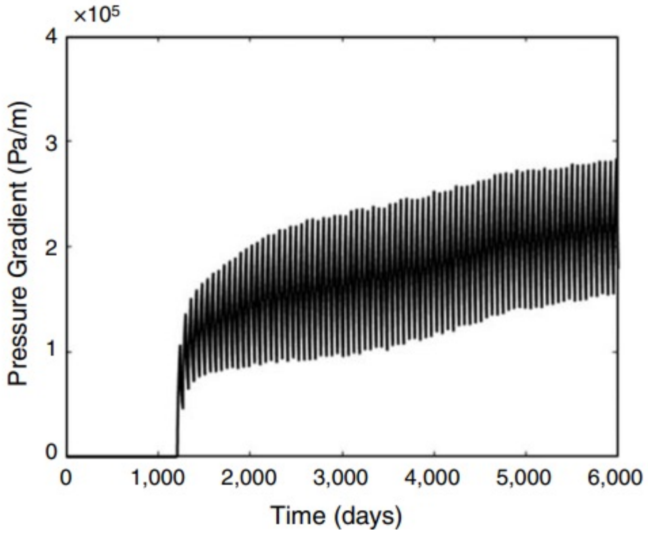


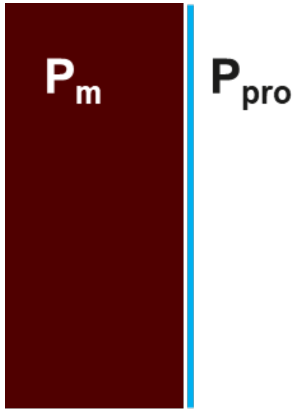
Pressure Increase

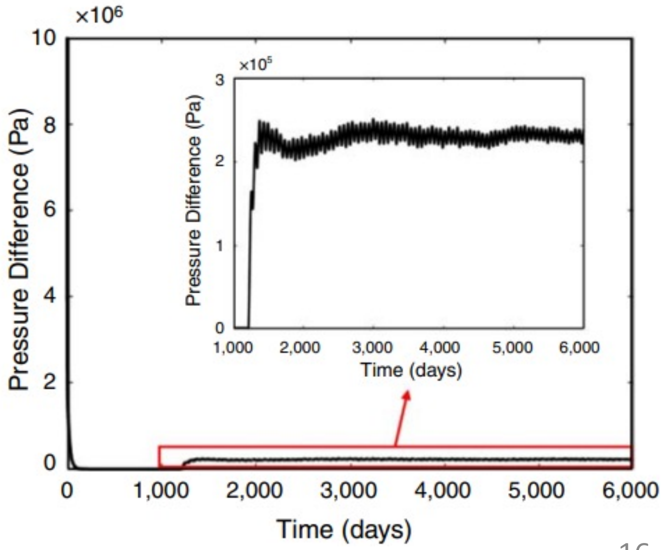


$$\mathrm{Grad}P = \frac{P_{inj} - P_{pro}}{L}$$





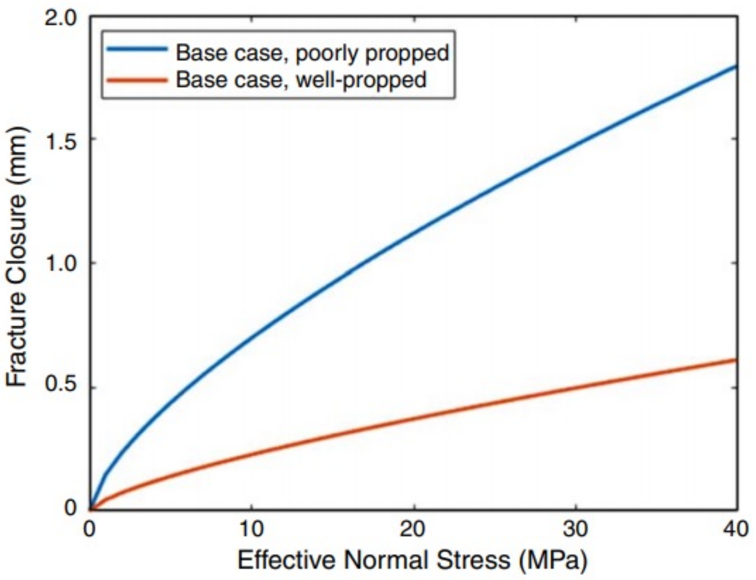




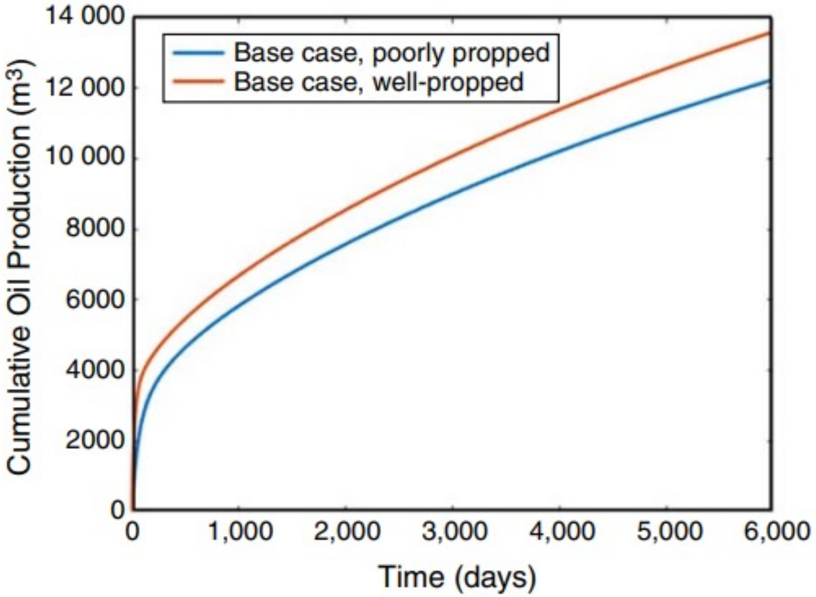
Role of Fracture Deformation

- During **depletion**, fracture **closure** reduces oil production
- During **injection**, fracture **opening** increases oil production
- Incorporate geomechanics is important for well performance prediction

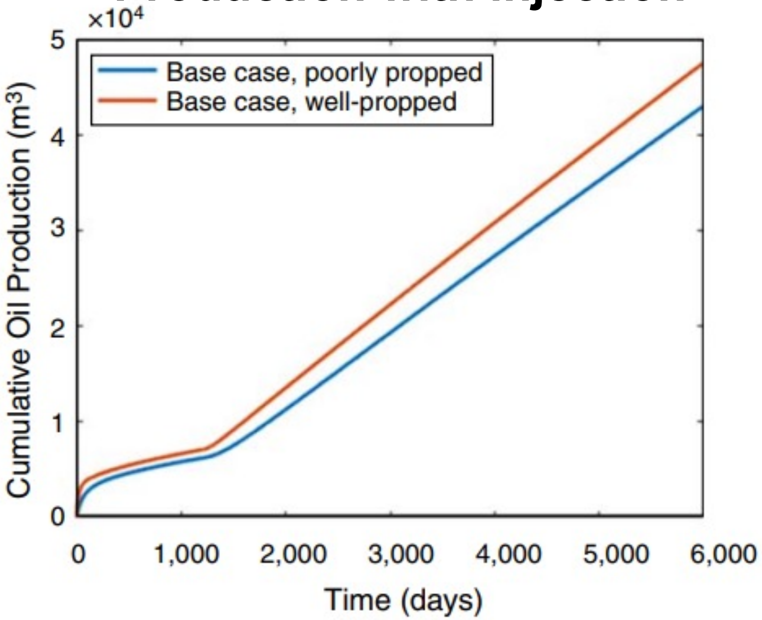
Fracture deformation curve



Production without injection

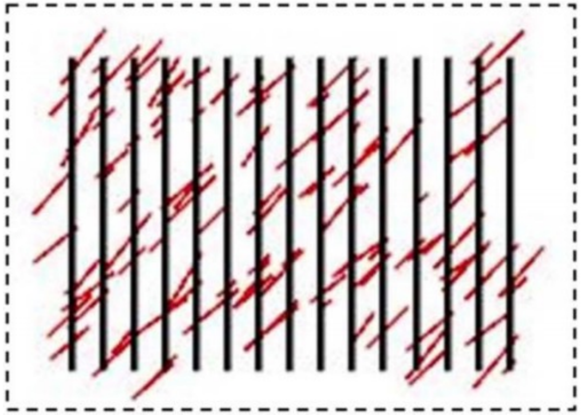


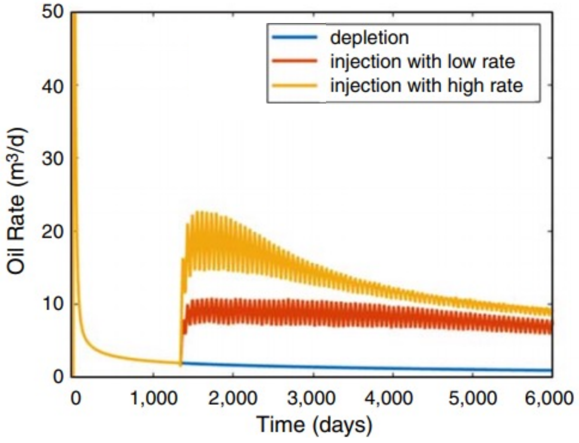
Production with injection

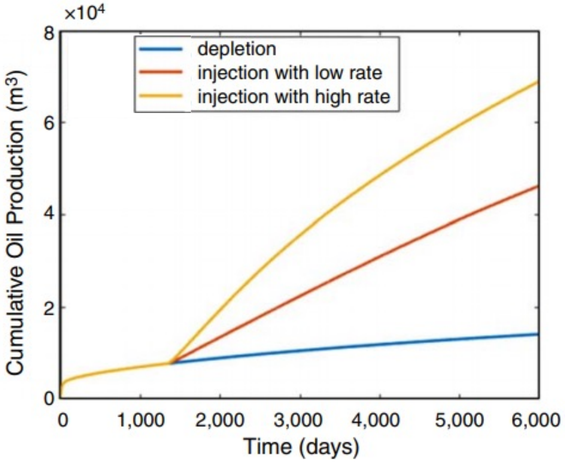


Impacts of Natural Fracture

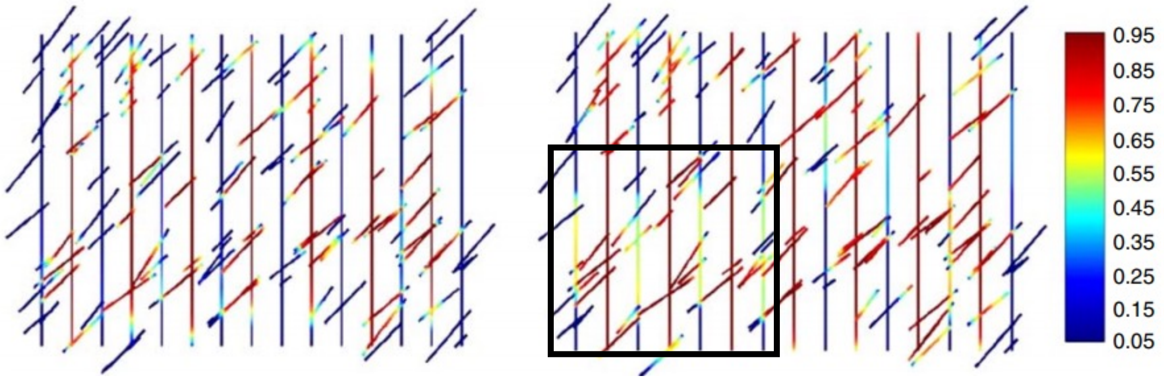
- **HF Connectivity through NFs reduce EOR performance**
- **Water breakthrough earlier under higher injection rate**





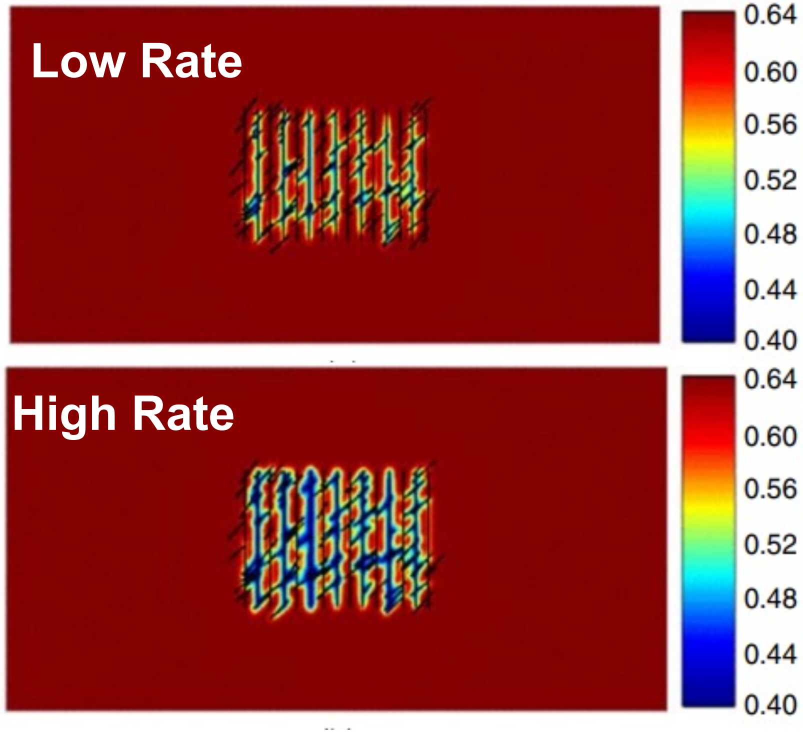


NF water saturation distribution



Low Rate **High Rate**

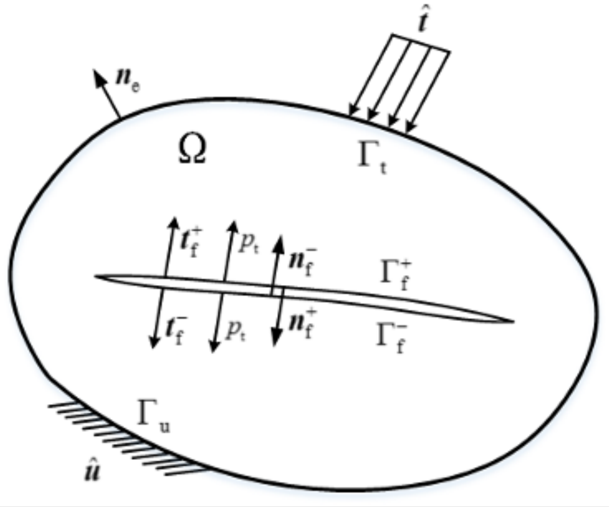
matrix water saturation distribution



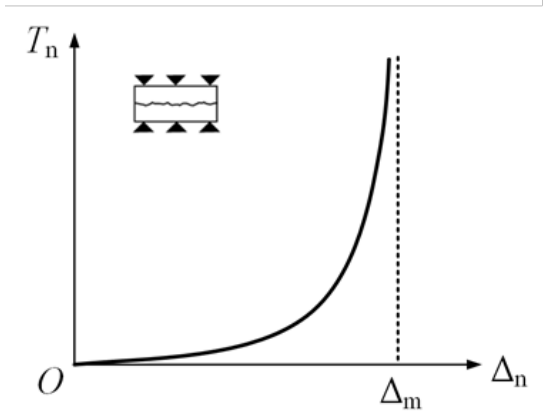
Fluid Flow in Dilated Fracture Networks

- **Discrete Fracture Model + Interface Element (node splitting)**
- **Barton-Bandis Model**

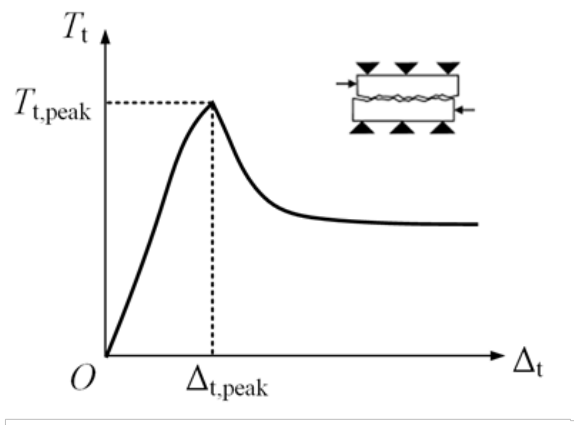
Conceptual Model



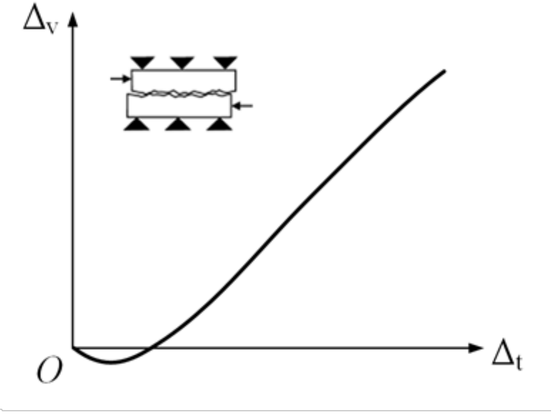
Normal deformation



Shear Deformation



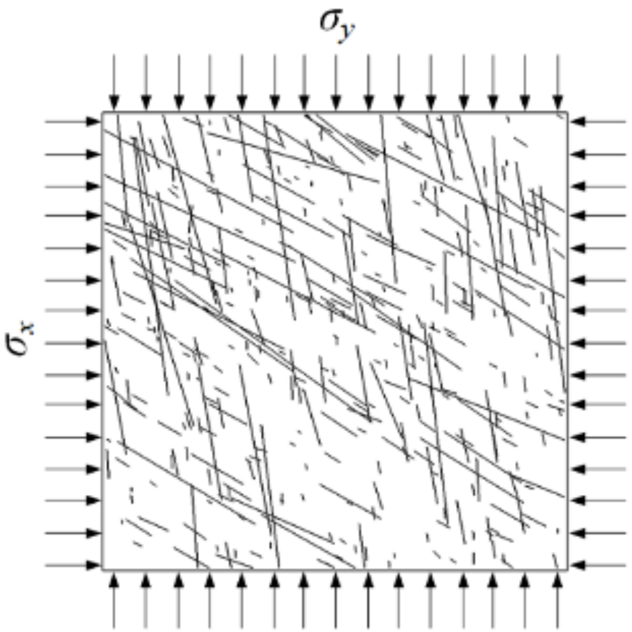
Shear Dilation



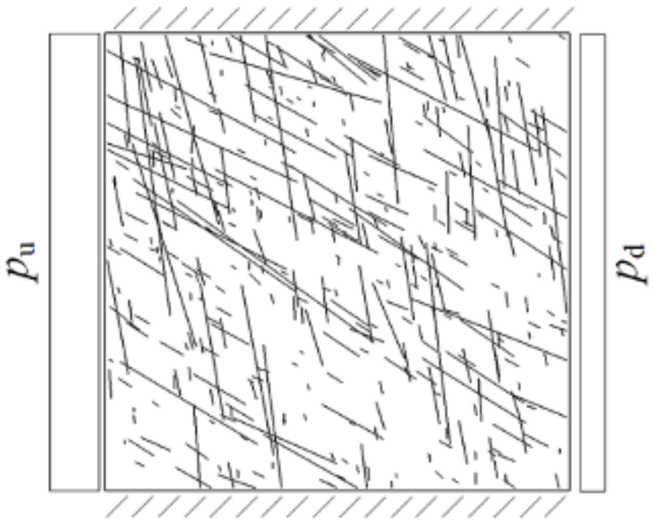
Fluid Flow in Dilated Fracture Networks

- **Steady-state pressure and saturation distributions**

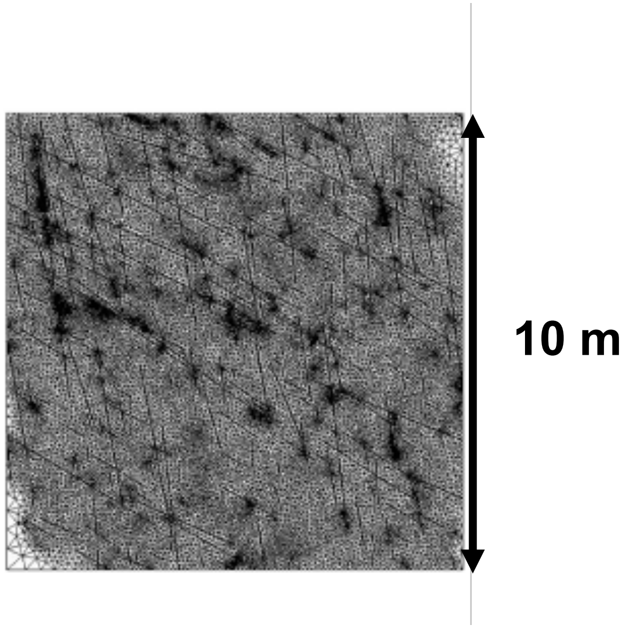
Stress boundary condition



Flow boundary condition

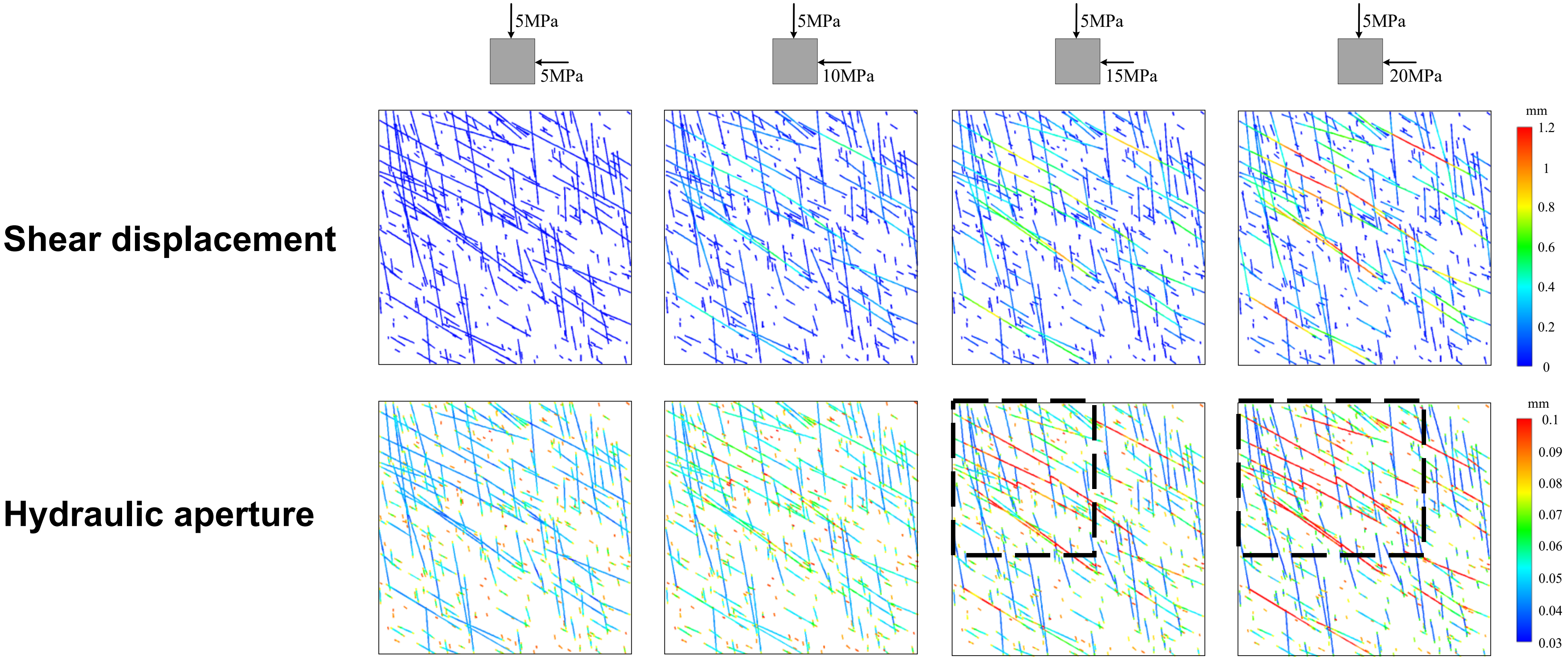


Computational mesh



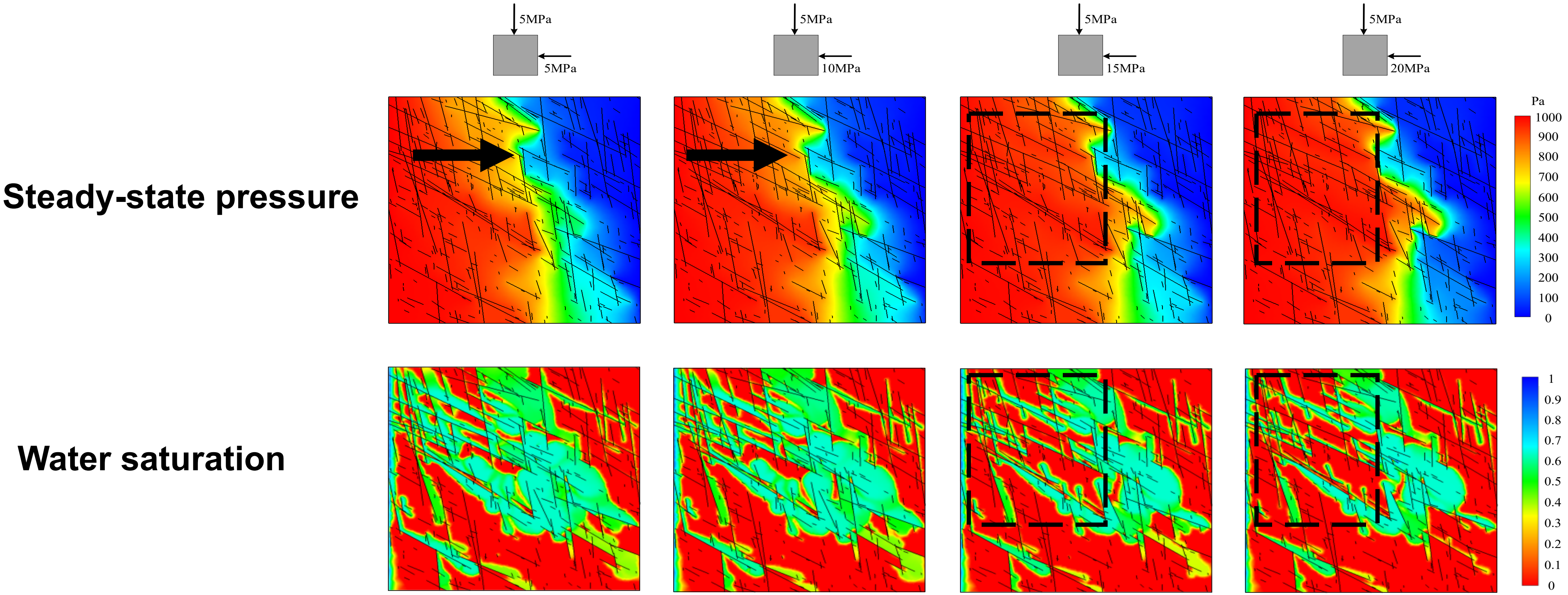
Effect of In-Situ Stress Condition

- **Preferential angle; long fractures show large shear disp.**

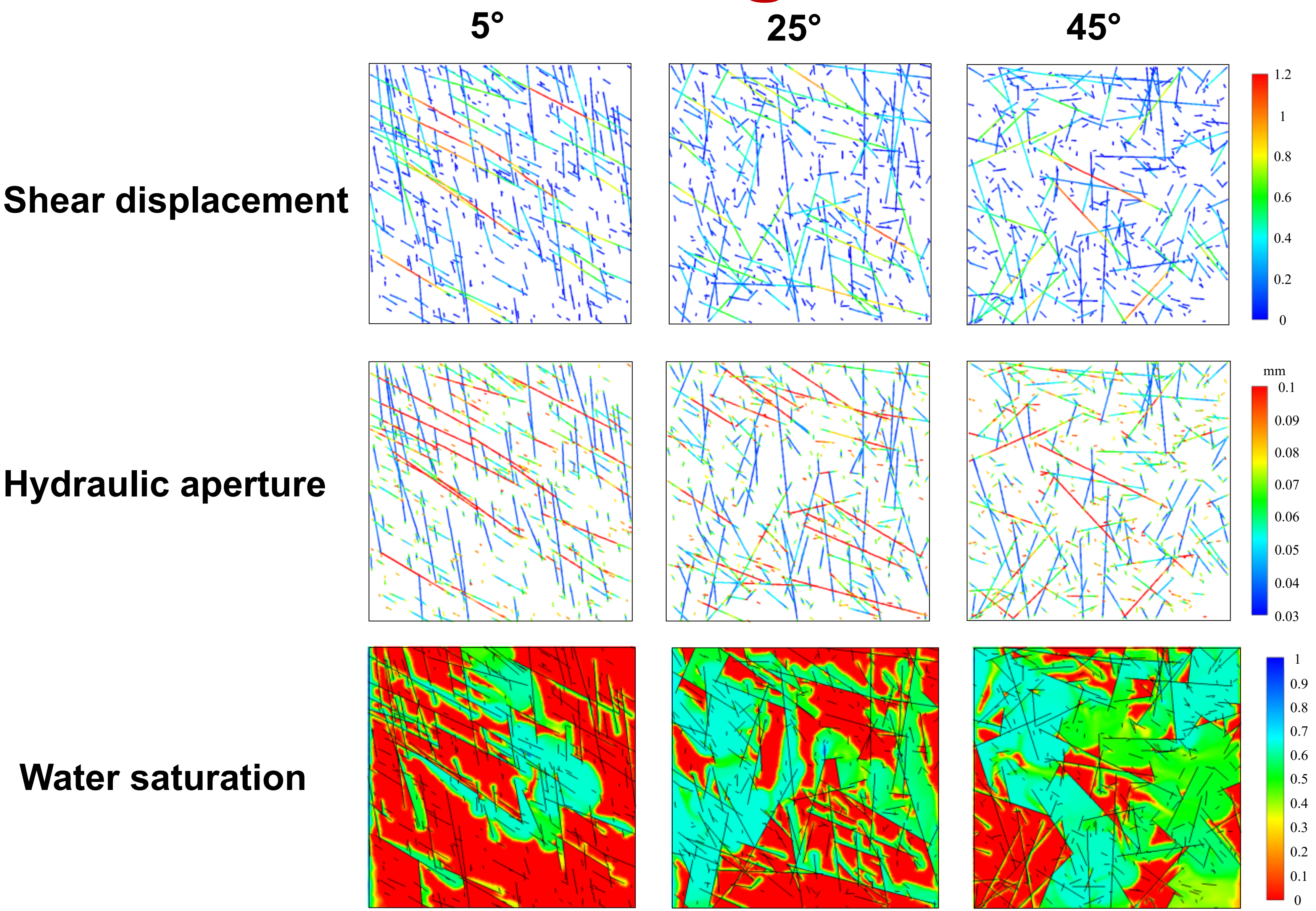


Effect of In-Situ Stress Condition

- **Pressure gradients concentrate in the area without shear dilation**
- **Reduced matrix water saturation considering shear dilation**



Effect of Fracture Angle



Conclusive Remarks

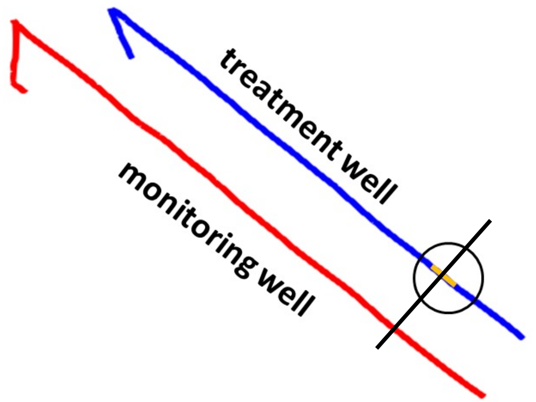
- **Developed a sequentially coupled flow and geomechanics simulator based on fixed-stress splitting algorithm**
- **Efficient in modeling complex fracture networks: DFM/EDFM**
- **Investigated the importance of geomechanics and the coupling to flow in unconventional reservoir development**
- **Depletion-induced stress changes, injection-type EOR, shear dilation**
- **Future work**
    - **thermal coupling: EGS**
    - **rock damage/failure model: local secondary fractures during depletion or injection**
    - **fracture propagation: field scale (hydraulic fracturing), all-way coupled manner**

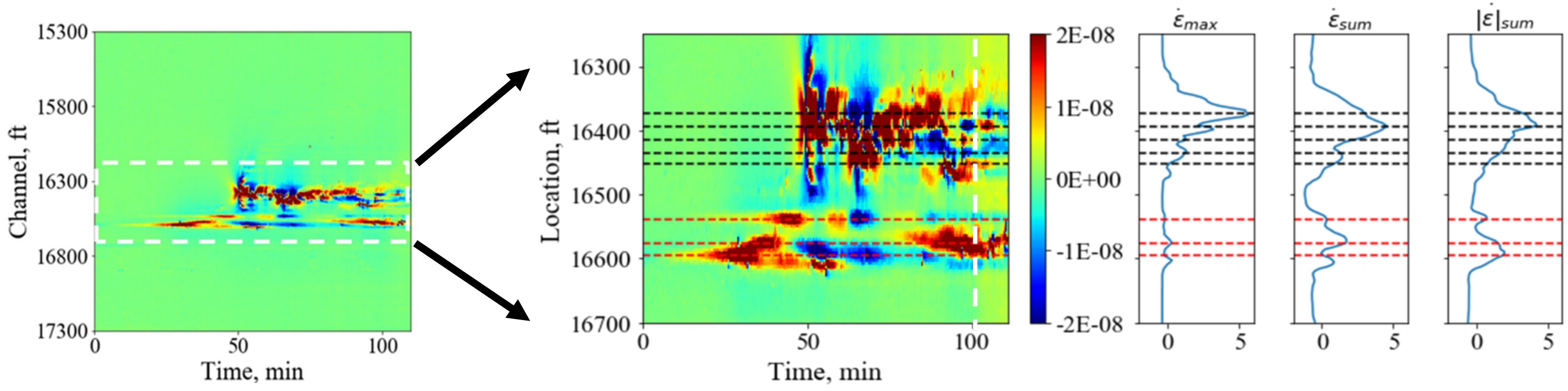
Related Publications

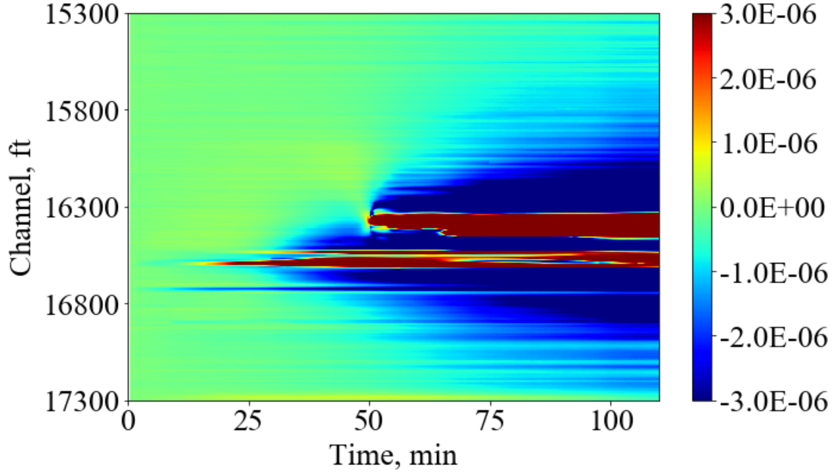
- Liu, Y., Liu, L., Leung, J. Y., Wu, K., Moridis, G. J. 2021. Coupled Flow/Geomechanics Modeling of Interfracture Water Injection To Enhance Oil Recovery in Tight Reservoirs. *SPE Journal* **26** (01): 1-21. SPE-199983-PA.
- Liu, Y., Liu, L., Leung, J. Y., Moridis, G. J. 2020. Sequentially Coupled Flow and Geomechanical Simulation with a Discrete Fracture Model for Analyzing Fracturing Fluid Recovery and Distribution in Fractured Ultra-Low Permeability Gas Reservoirs. *Journal of Petroleum Science and Engineering* **189**: 107042.
- Liu, L, Liu, Y., Yao, J., Huang, Z. 2020. Efficient Coupled Multiphase-Flow and Geomechanics Modeling of Well Performance and Stress Evolution in Shale-Gas Reservoirs Considering Dynamic Fracture Properties. *SPE Journal*. **25** (03): 1523-1542. SPE-200496-PA.
- Liu, L, Liu, Y., Yao, J., Huang, Z. (under review). Numerical investigation of shear dilation effects on fluid flow in fractured porous media using zero-thickness interface elements. *Journal of Hydrology*.

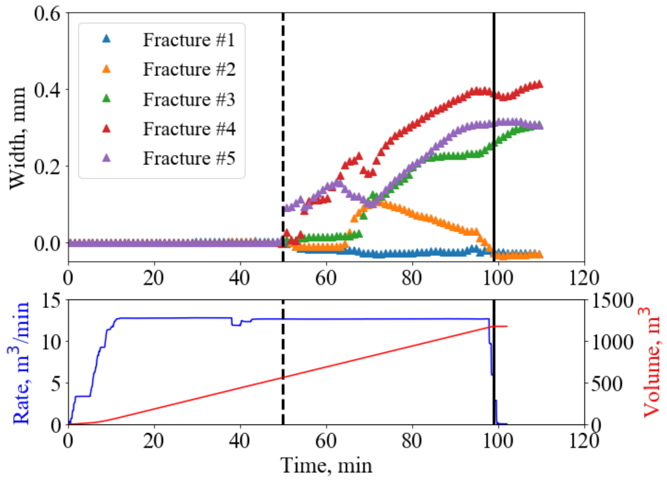
Monitoring of Subsurface Activities

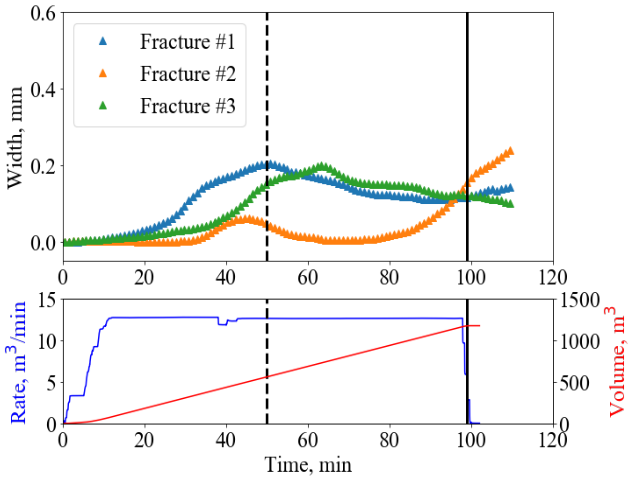
- **Distributed Acoustic Sensing**











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Thank you!

Questions?