

Enhanced Geothermal Systems (EGS): Permeability Stimulation Through Hydraulic Fracturing in a Thermo-Poroelastic Framework

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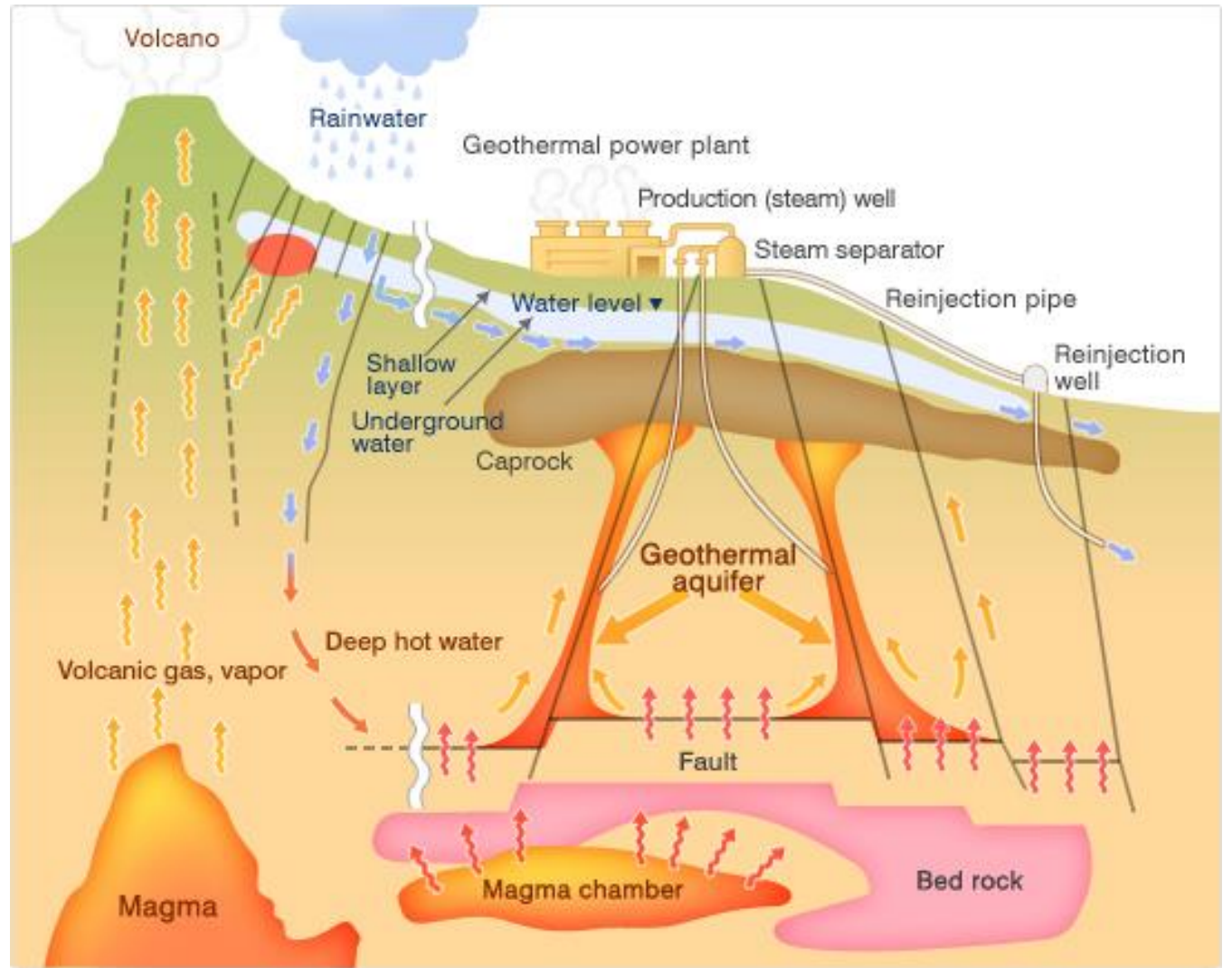
Deep geothermal energy:

Earth's stored energy

Gradient of temperature

Mankind's energy needs (electricity)

Exploitation of geothermal energy

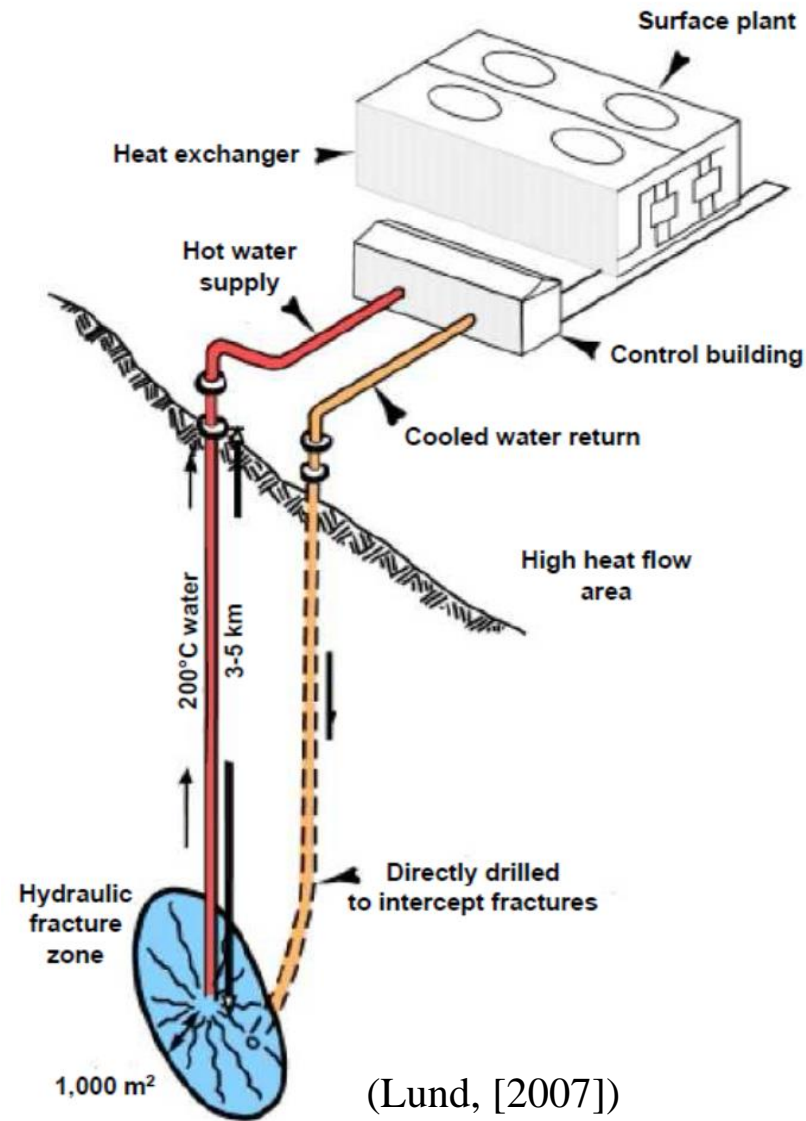


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Exploitation – Enhanced Geothermal Systems (EGS)

Impermeable Hot Dry Rock (HDR) reservoirs

Enhance/create geothermal resources by Hydraulic Fracturing



(Lund, [2007])

Overview of the research:

- **Thermo-poroelasticity**
 - Mathematics
 - Simulations by ABAQUS and FE domestic code
- **Fracture evolution and permeability enhancement**
 - Fracturing criterion:
 - ❖ Evolution of fracture radius
 - ❖ Fracture aperture change
 - Anisotropic permeability tensor
- **FE simulations of Hydraulic Fracturing (HF)**
 - Circulation tests without and with considering HF
 - Designing HDR reservoirs: Impedance, efficiency and life-time
- **Convection of heat - Stabilization**
- **Conclusion**

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Thermo-poroelasticity - Mathematics - Constitutive equations

Homogeneous single-porosity media

- Stress mixture equation:

$$\sigma_{ij} + \kappa p \delta_{ij} = 2G \varepsilon_{ij} + \frac{2G\nu}{1-2\nu} \varepsilon_{kk} \delta_{ij} - K \alpha_s \theta \delta_{ij}$$

- Change in mixture fluid content equation:

$$\zeta = \frac{1}{3} \left(\frac{1}{K} - \frac{1}{K_s} \right) (\sigma_{kk} + \frac{3}{B} p) - \phi_0 (\alpha_f - \alpha_s) \theta$$

- Darcy's equation:

$$\mathbf{q}_f = \phi_0 (\mathbf{v}_f - \mathbf{v}_s) = -\frac{\mathbf{k}}{\mu} \cdot (\nabla p - \rho_f \mathbf{g})$$

- Fourier's law of thermal conduction:

$$\mathbf{h} = -\chi \nabla \theta, \quad \chi = (1 - \phi_0) \chi_s + \phi_0 \chi_f$$

Thermo-poroelasticity - Mathematics – Balance equations

- Balance of momentum:

$$\frac{\partial \sigma_{ij}}{\partial x_j} + F_i = 0, \quad i = 1, 2$$

- Balance of fluid mass:

$$\frac{\partial \zeta}{\partial t} + \nabla \cdot \mathbf{q}_f = 0$$

- Balance of energy:

$$\underbrace{\frac{\partial \theta}{\partial t}}_{\text{Heat storage}} + \underbrace{\frac{\rho_f c_{vf}}{\rho c_v} q_{f,i}(\mathbf{x}, t) \frac{\partial \theta}{\partial x_i}}_{\text{Heat convection}} - \underbrace{\psi \frac{\partial^2 \theta}{\partial x_i \partial x_i}}_{\text{Heat conduction}} = 0, \quad \psi = \frac{\chi}{\rho c_v} \quad (\text{Thermal diffusivity})$$

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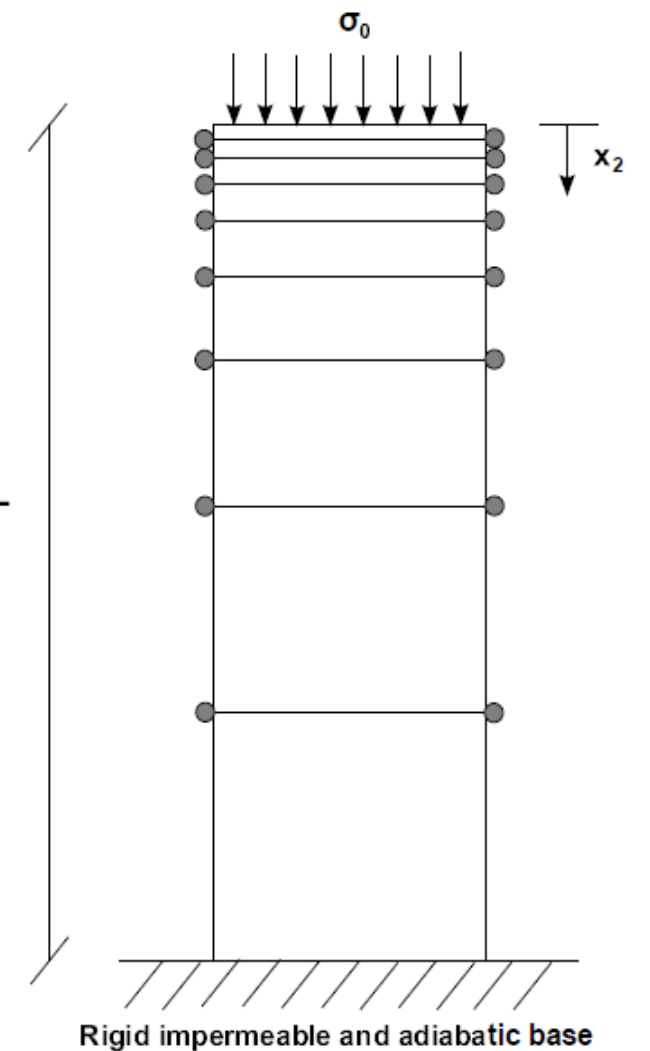
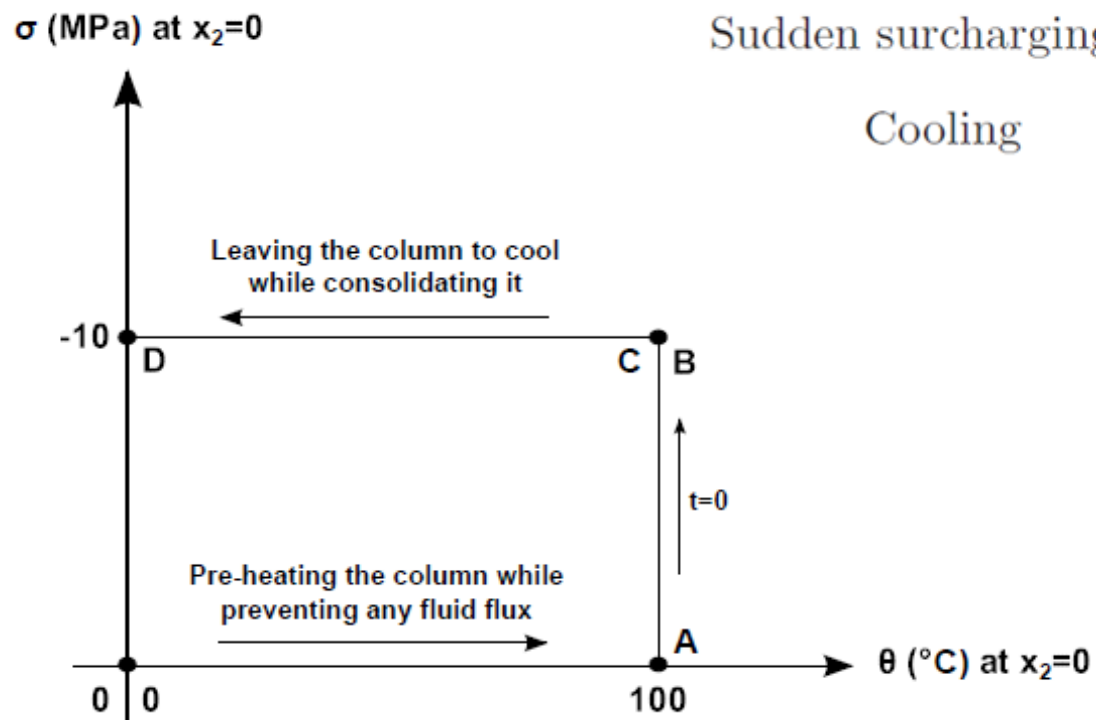
Thermo-poroelasticity – Simulations by ABAQUS

The transient BVP:

Heat transfer effect compared to the abrupt changes due to the surcharge (σ_0)

History of loading:

Pre-heating $\rightarrow p_0^-$
 Sudden surcharging $\sigma_0 \rightarrow \Delta p_\sigma$
 Cooling $\rightarrow \Delta p_\theta$



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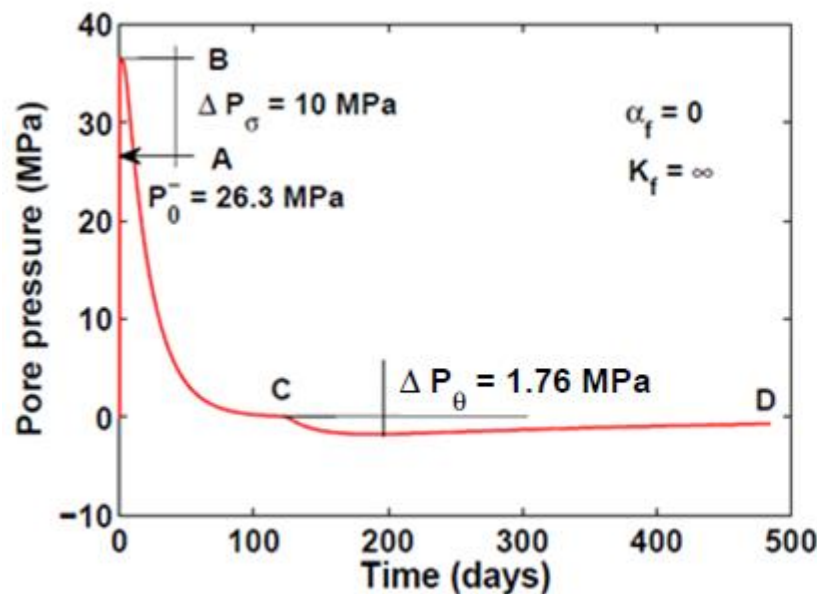


Thermo-poroelasticity – Thermal to mechanical loading

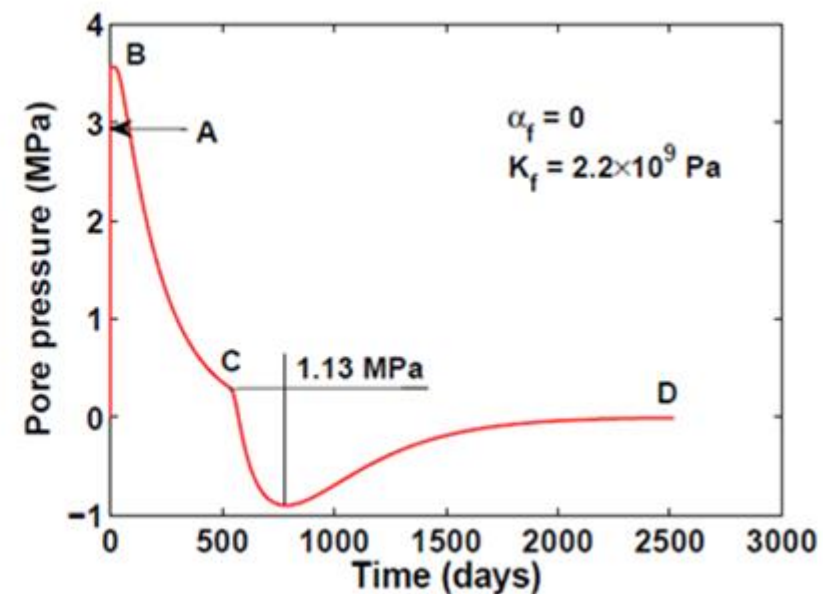
Parametric study:

Thermal expansivity	Bulk modulus	p_0^- (MPa)
(1) $\alpha_f=0,$	$K_f=\infty$	26.30
(2) $\alpha_f=0,$	$K_f=2.2 \times 10^9$ Pa	2.950
(3) $\alpha_f=4.2 \times 10^{-4}$ /°C,	$K_f=2.2 \times 10^9$ Pa	85.91
(4) $\alpha_f=4.2 \times 10^{-4}$ /°C,	$K_f=\infty$	830.0

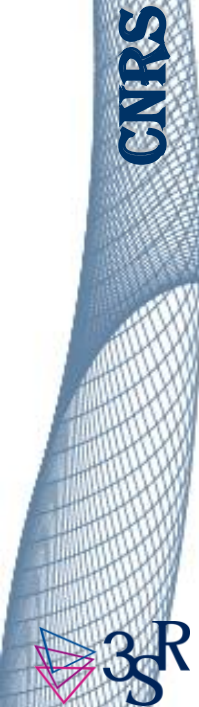
Pore pressure profiles
at ($x_2=10$ m)



Case (1)



Case (2)



Thermo-poroelasticity – Thermal to mechanical loading

Case definition	$\Delta p_\theta / \Delta p_\sigma$	$\Delta \sigma'_{22\theta} / \Delta \sigma'_{22\sigma}$	$\Delta \varepsilon_{22\theta} / \Delta \varepsilon_{22\sigma}$
$\alpha_f=0, K_f=\infty$	0.176	0.176	13.4
$\alpha_f=0, K_f=2.2 \times 10^9 \text{ 1/Pa}$	1.15	0.115	13.4
$\alpha_f=4.2 \times 10^{-4} \text{ 1/}^\circ\text{C}, K_f=2.2 \times 10^9 \text{ 1/Pa}$	36.2	3.62	13.4
$\alpha_f=4.2 \times 10^{-4} \text{ 1/}^\circ\text{C}, K_f=\infty$	5.76	5.76	13.4

Conclusions:

1. Pore pressure is significantly affected by fluid compressibility and thermal expansion
2. Previous conclusion holds correct for the field of axial effective stress
3. No changes in the axial strain field

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Thermo-poroelasticity – Simulations by the Fortran 90 FE code

Validation of the first version of the FE code:

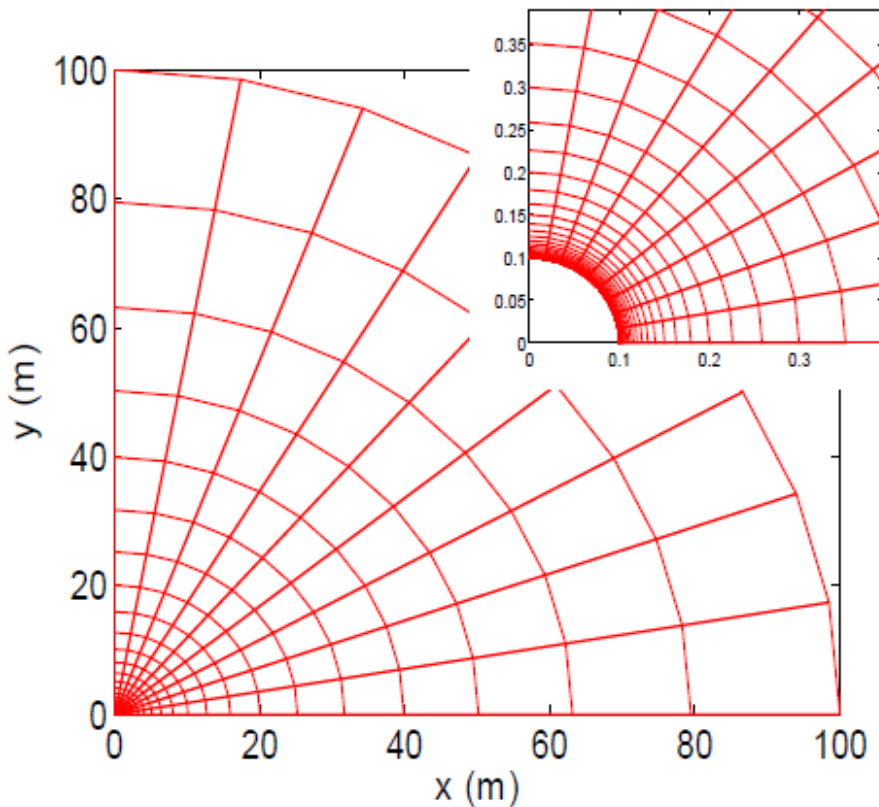
The first version of the FE code was modified by Rachel Gelet, (Gelet PhD thesis, [2012]).

The numerical responses of the FE code were correlated against two transient BVPs:

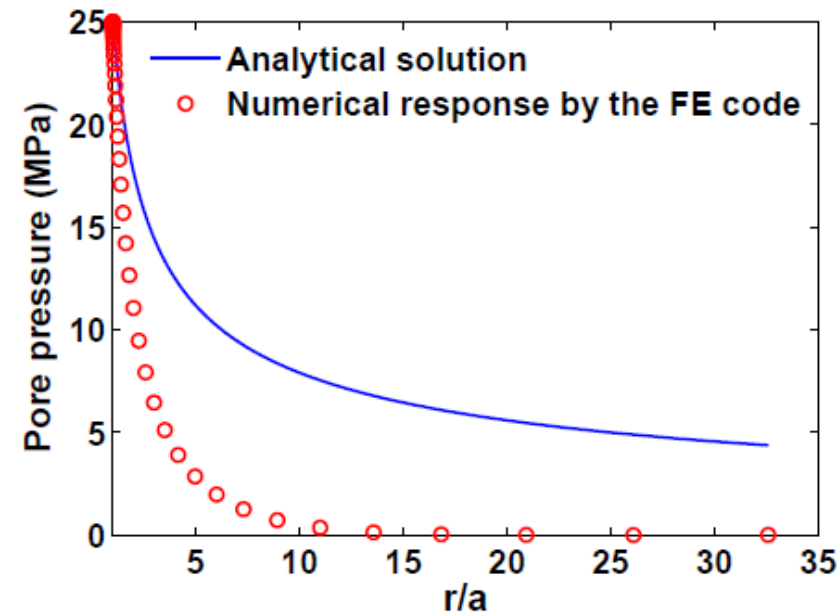
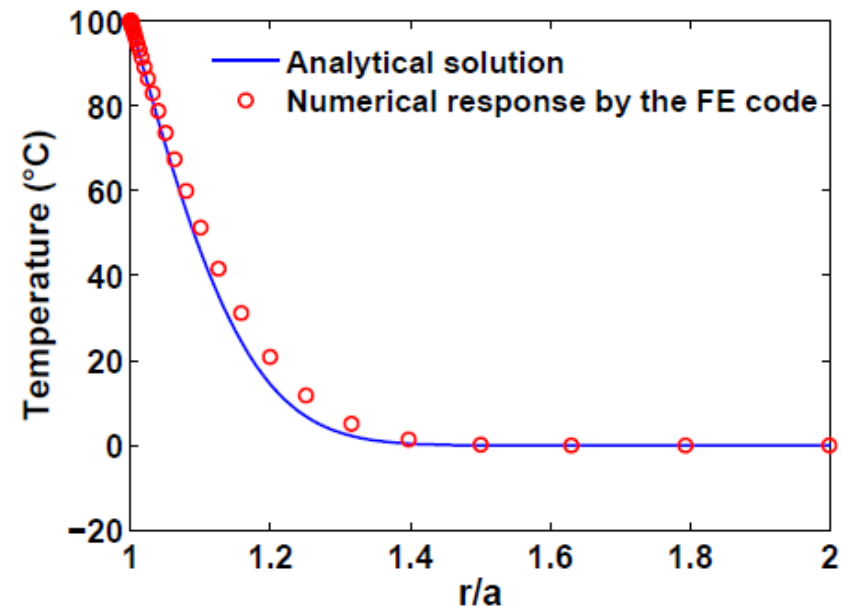
- The previously discussed 1-D column.
- A 2-D wellbore stability axisymmetric problem.

Fortran 90 code – Wellbore stability BVP

(He and Jin, [2010])



Radial distributions at $t = 280$ s



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Fracture evolution – Fracturing criterion

DDFM: Directionally Distributed Fracture Model

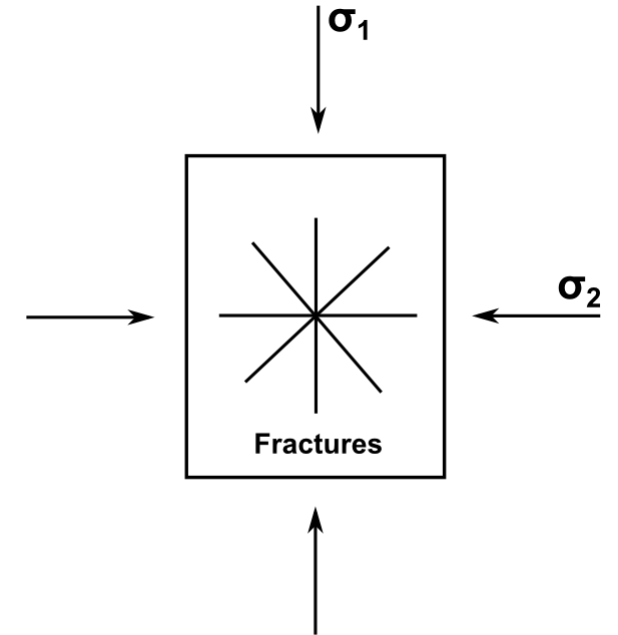
Modes I and II with all possible fracture orientations (Shao et al., [2005])

Characteristics of the model:

- A phenomenological including relevant micromechanical features
- Working in the frame of LEFM

Assumptions for opting this model:

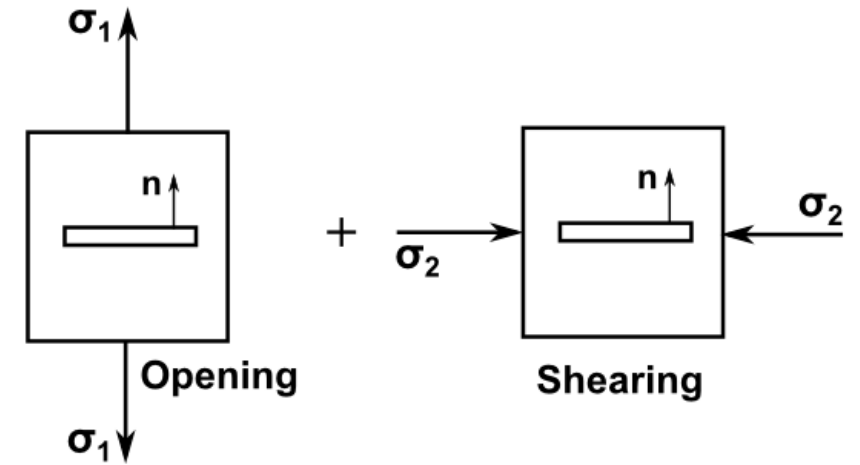
- No fracture Interaction before the onset of fracture evolution
- Initial isotropy
- Mechanical behavior before macroscopic failure
- Penny-shaped fractures embedded in an infinite body



Fracturing criterion - Fracture evolution (r)

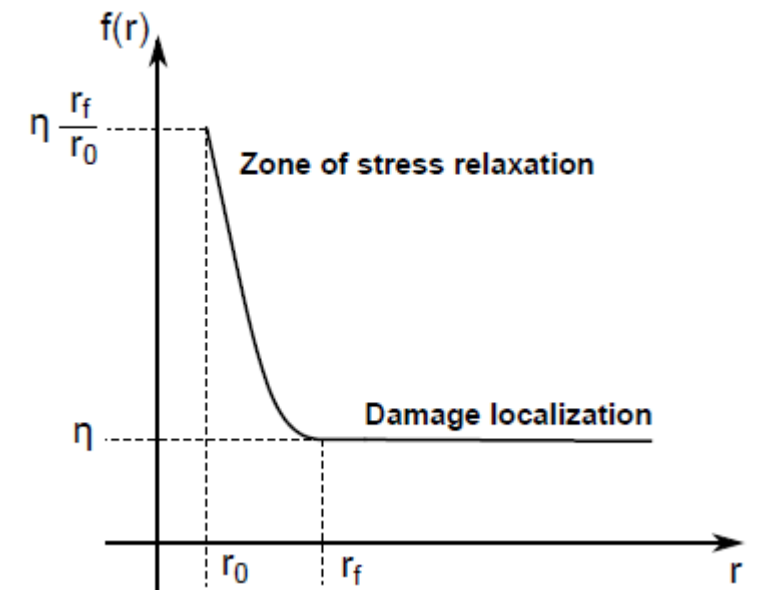
For a group of fractures in a specific direction \mathbf{n} , the following forces are sovereign:

- The stress normal to the fracture surface σ'_n
- The stress applied to the fracture plane $\langle \sigma_n^{\prime d} \rangle$



$$F(\boldsymbol{\sigma}', r, \mathbf{n}) = \sqrt{r} \left[\sigma'_n \left(\frac{f_{c,t}}{f_{c,t} + \langle -\sigma'_n \rangle} \right)^m + 3 \underbrace{f(r)}_{\text{red circle}} \langle \sigma_n^{\prime d} \rangle \right] - C_{rc} \leq 0$$

$$\sigma'_n = \mathbf{n} \cdot \boldsymbol{\sigma}' \cdot \mathbf{n}, \quad \boldsymbol{\sigma}'^d = \boldsymbol{\sigma}' - \left(\frac{\text{tr} \boldsymbol{\sigma}'}{3} \right) \boldsymbol{\delta}, \quad \sigma_n^{\prime d} = \mathbf{n} \cdot \boldsymbol{\sigma}'^d \cdot \mathbf{n}$$



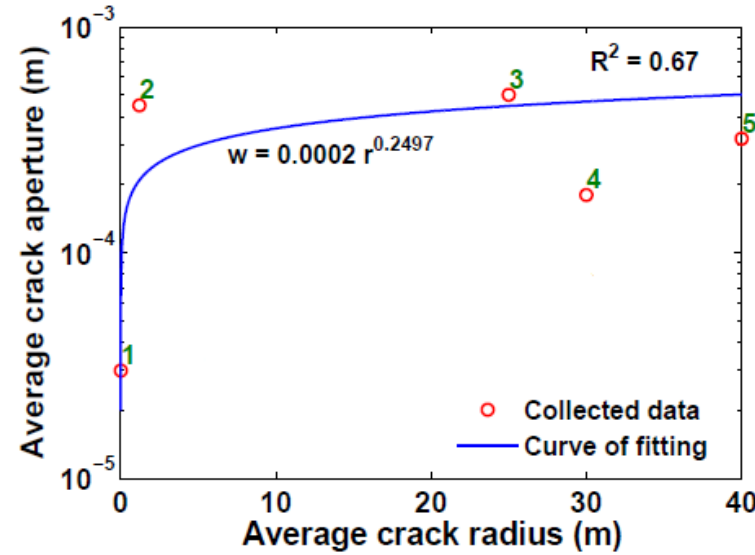
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Fracturing criterion - Fracture aperture (w) change

Fracture aperture (w) is related to fracture face mismatch and local grain matrix interaction:

$$w = 0.0002 r^{0.25}$$



- 1: Shao et al., [2005]
- 2: Papanastasiou and Thiercelin, [1993]
- 3: Bruel, [2002]
- 4: Bruel and Rejeb, [2001]
- 5: Kohl and Mège, [2007]

Crack aperture reduction: Barton's hyperbolic closure model

$$w = w_0 \left(1 - \frac{\langle -\sigma'_n \rangle}{w_0 k_{n0} + \langle -\sigma'_n \rangle} \right)$$

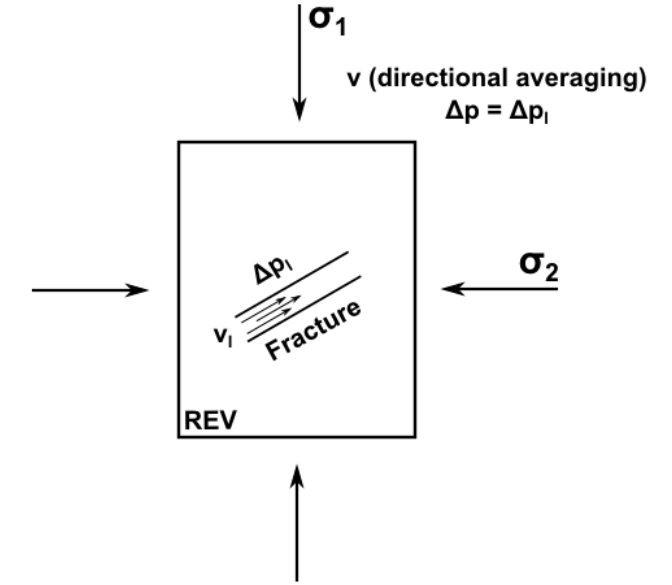
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Fracture evolution – Permeability tensor

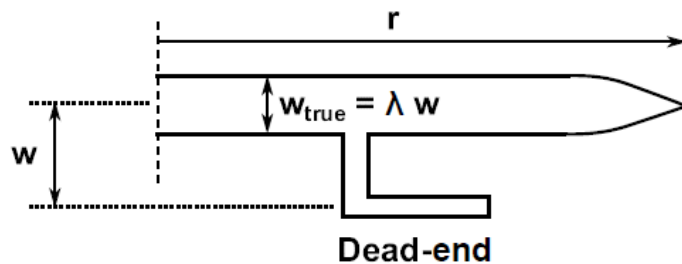
Inside a given fracture of orientation \mathbf{n} :

- Flow: Navier-Stokes equation for laminar flow
- Macroscopic velocity field: Directional averaging
- Fracture permeability tensor is obtained from the macroscopic velocity field:



Fracture density

$$k_c = \frac{N}{\Omega} \frac{\lambda}{48} \int_S R(\mathbf{n}) w(\mathbf{n})^3 r(\mathbf{n})^2 (\delta - \mathbf{n} \otimes \mathbf{n}) dS$$



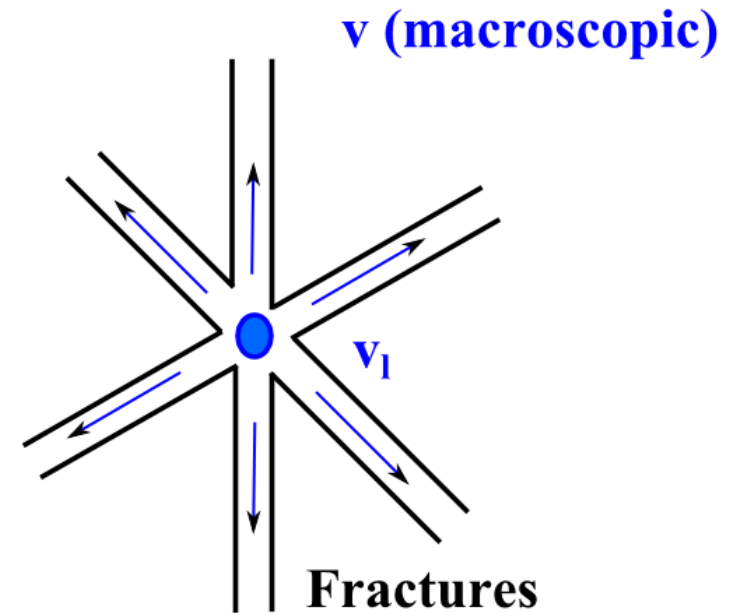
$$R(r(\mathbf{n})) = t_1 \left(\frac{r(\mathbf{n}) - r_0}{r_f - r_0} \right)^{t_2}$$

Fracture evolution – Permeability tensor

Assumptions for calculating the permeability tensor:

- Fractures are interconnected and/or dead channels
- No local pressure fluctuations
- Permeability tensor is anisotropic in nature
- Permeability tensor is contributed by two porosities:
 - Initial porosity k_0
 - Fracture induced permeability k_c

$$k = k_0 + k_c \text{ (for parallel flow)}$$



Fracture evolution – Numerical and experimental results

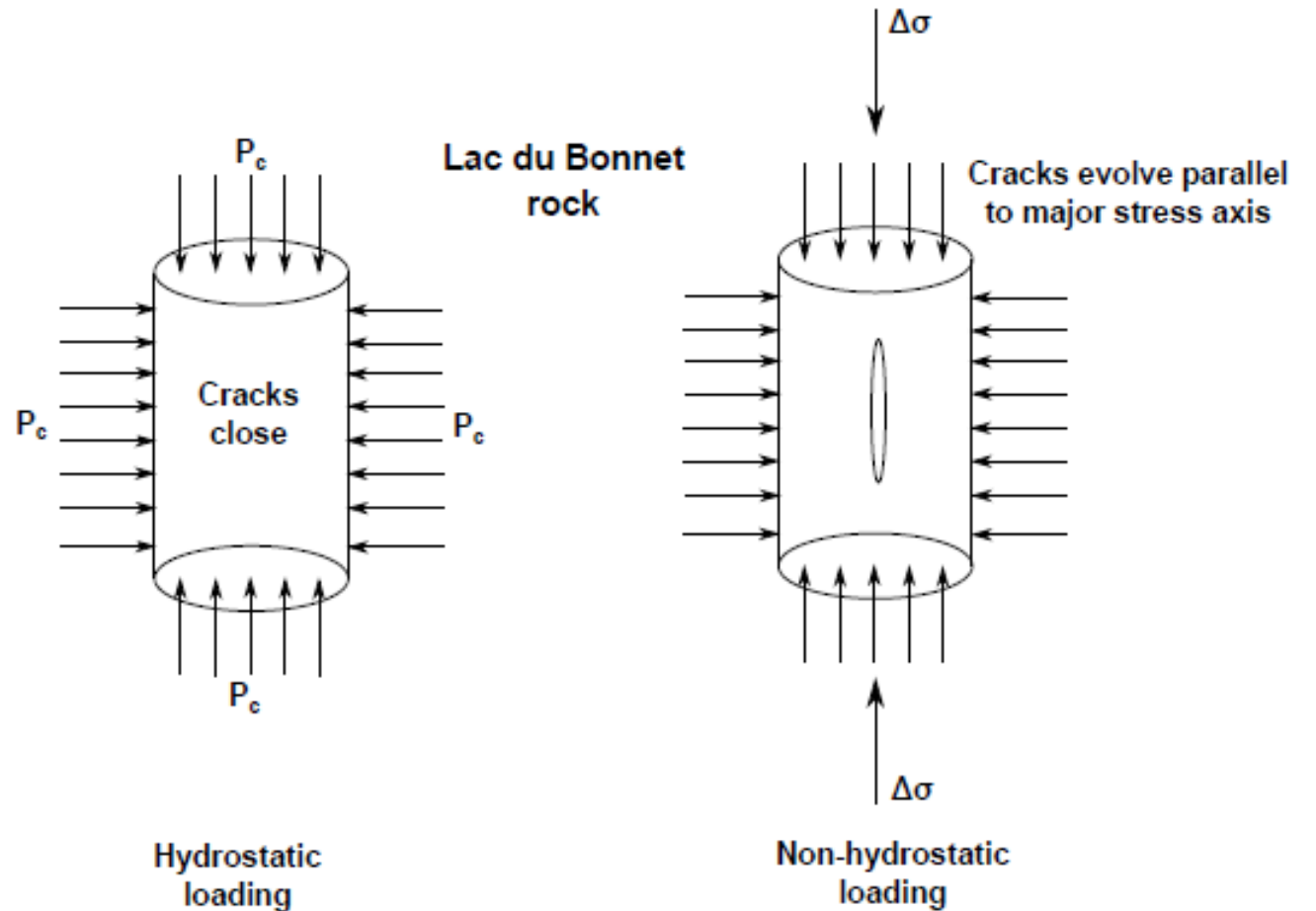
Application to Lac du Bonnet granite:

$$P_c = -10 \text{ MPa}$$

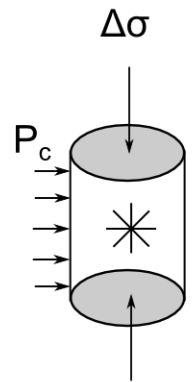
Onset of fracture evolution ($\Delta\sigma = -190 \text{ MPa}$)

$$r_0 = 3 \text{ mm and } r_f = 9 \text{ mm}$$

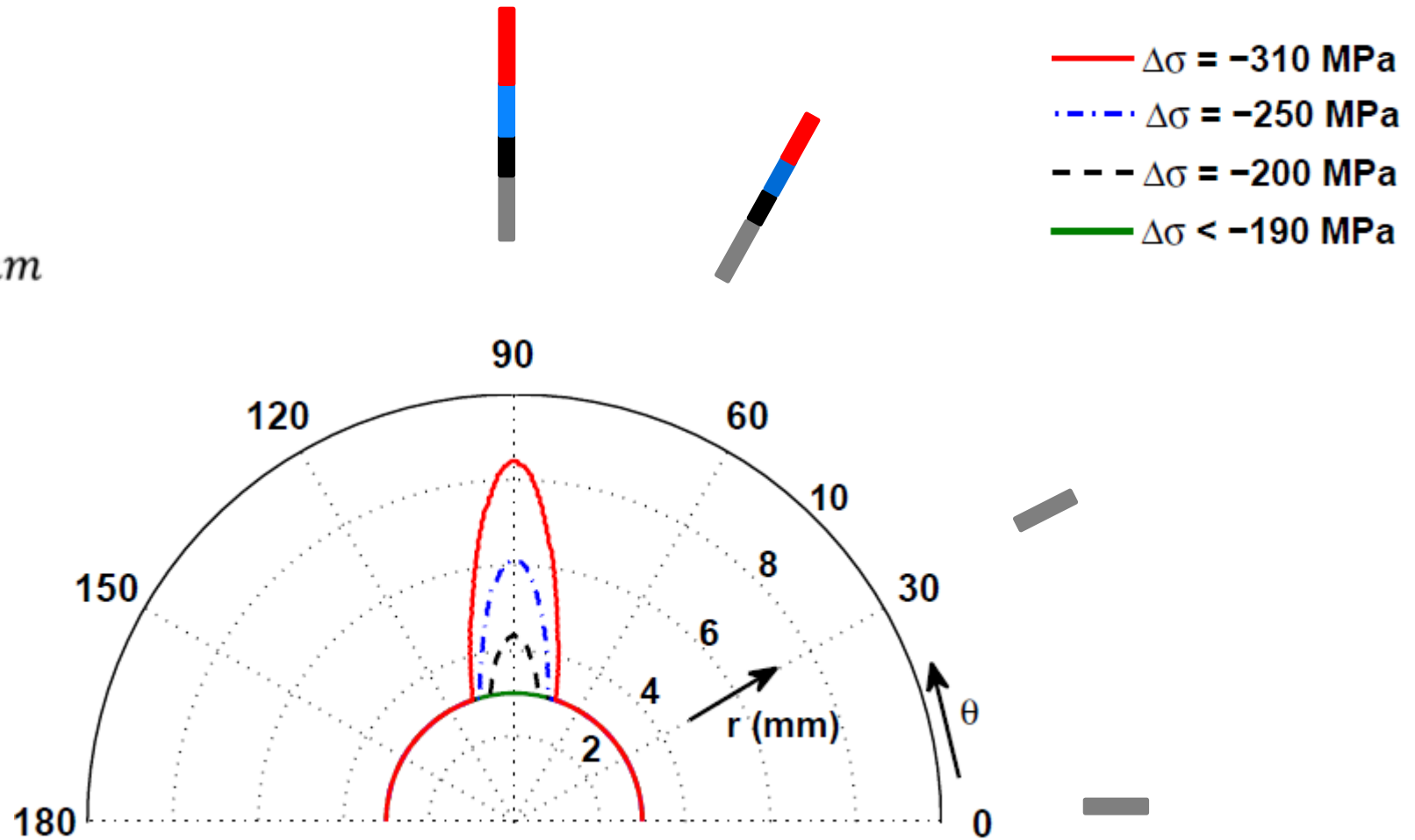
$$w_0 = 15 \text{ }\mu\text{m}$$



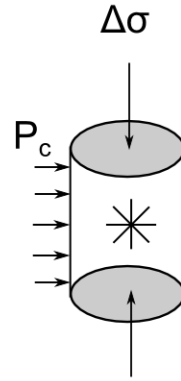
Numerical and experimental results – Fracture radius (r) evolution



$r_0 = 3 \text{ mm}$

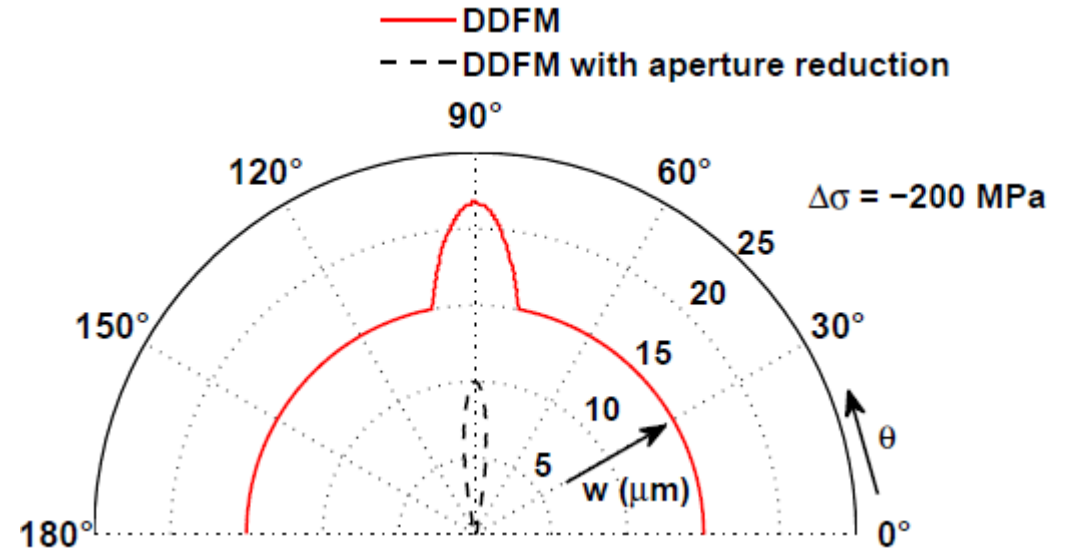
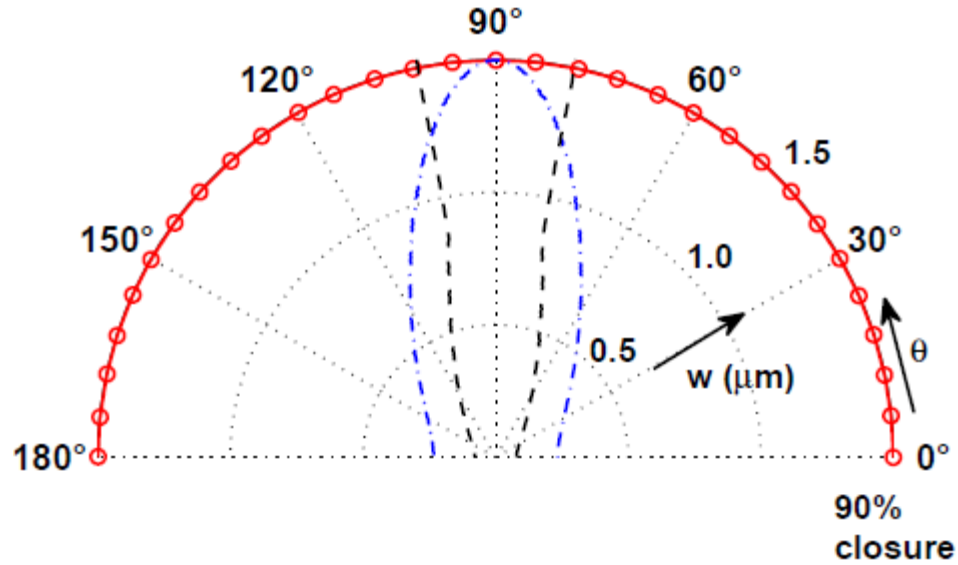


Fracture evolution – Fracture aperture (w) reduction



$$w_0 = 15 \mu m$$

- $\Delta\sigma = -200 \text{ MPa}$
- - - $\Delta\sigma = -60 \text{ MPa}$
- $\Delta\sigma = 0 \text{ MPa}$

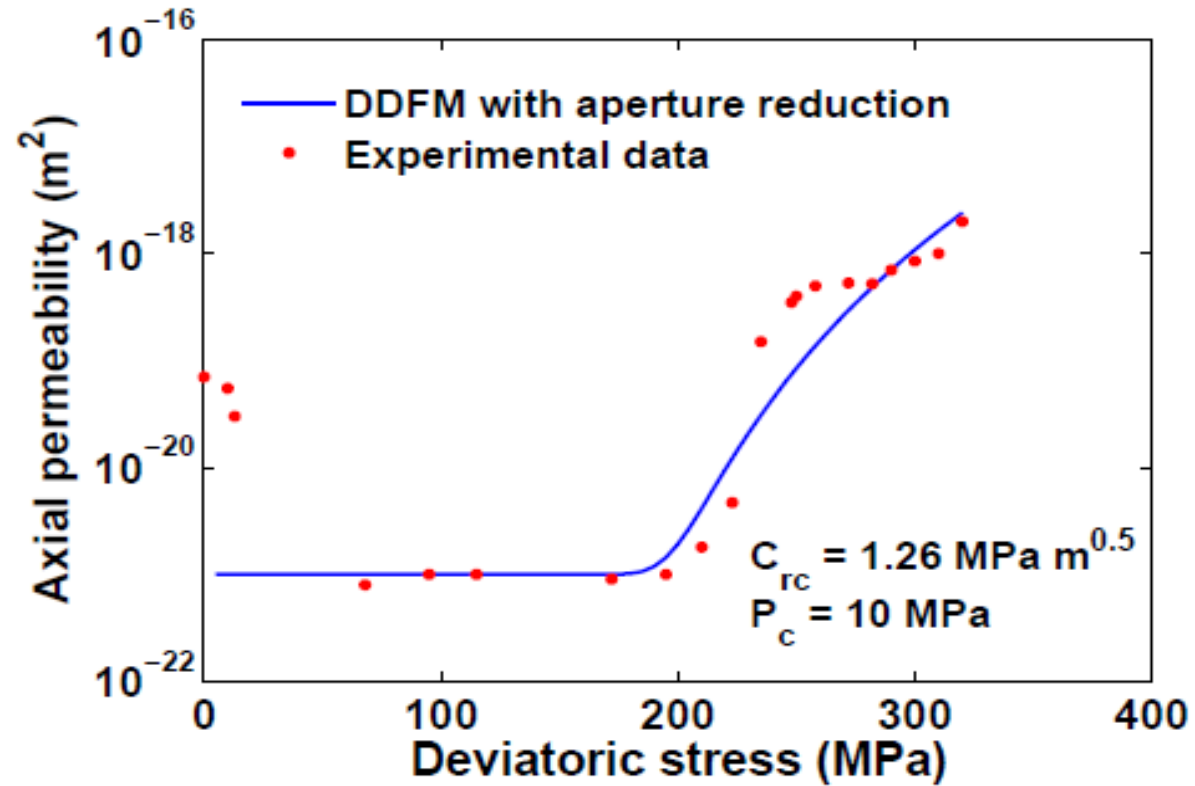


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Fracture evolution – Correlation & validation

Validation of the DDFM against experimental records: (Souley et al., [2001])



Thermo-poroelasticity and Fracturing– Summary

Reflections and Conclusions:

1. Thermo-poroelasticity

- Constitutive and balance equations
- Simulations by ABAQUS and Domestic FE code

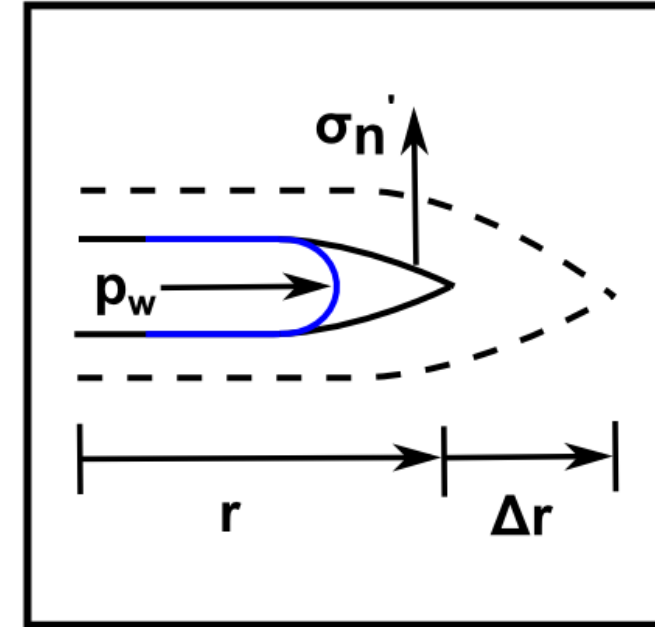
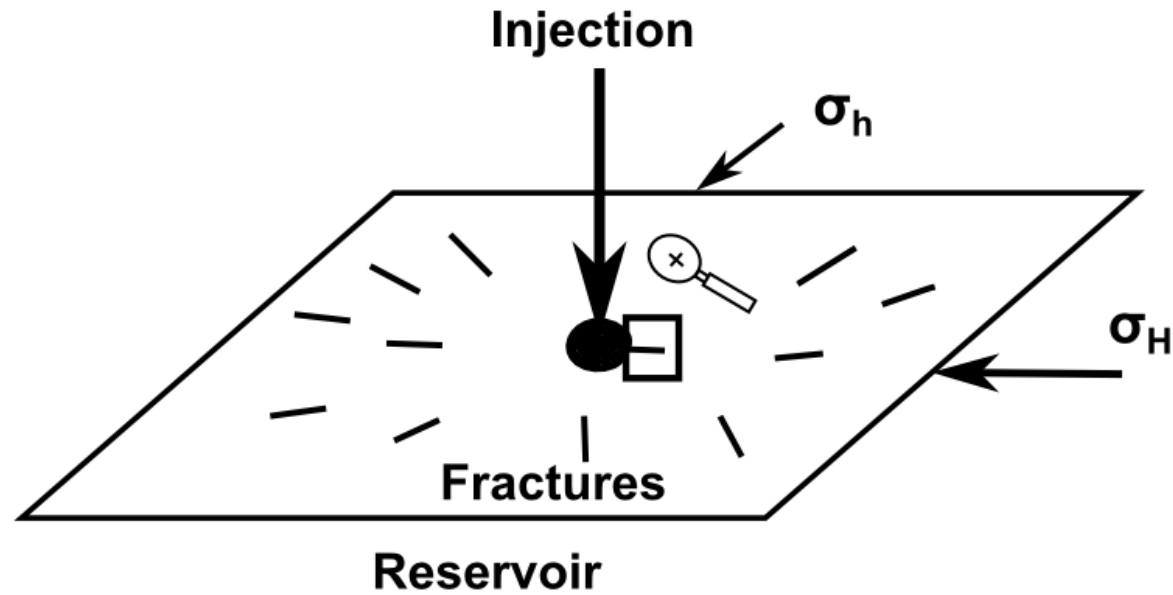
2. Permeability enhancement

- Fracturing model (r and w)
- Anisotropic permeability tensor
- Validation of the model

Hydraulic Fracturing (HF)

Definitions:

- Tensile failure of boreholes

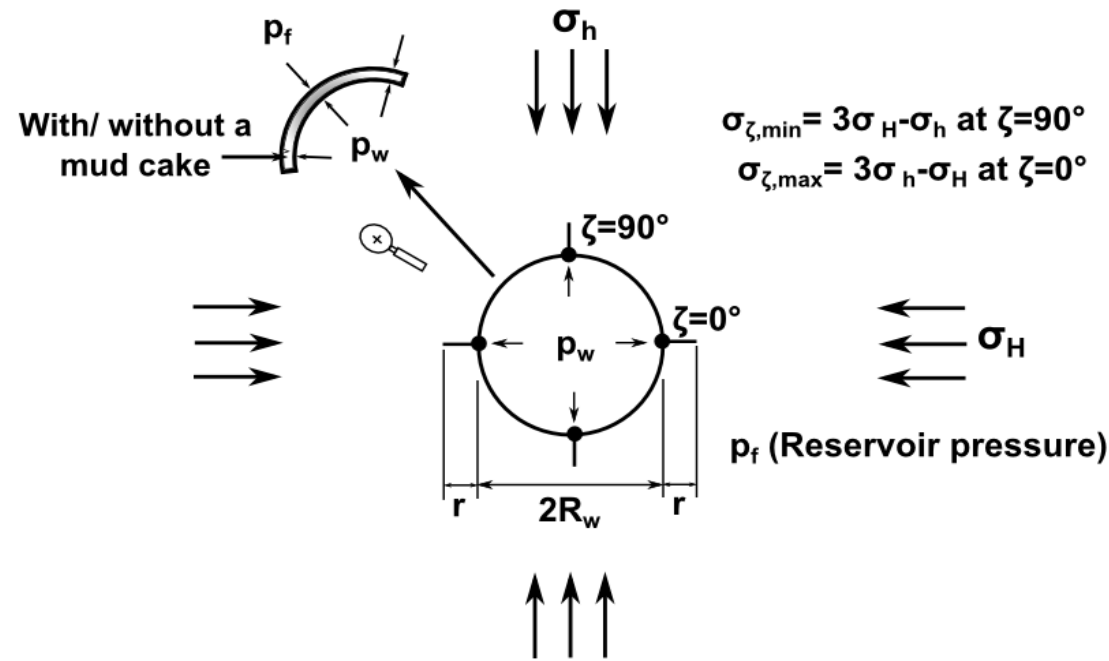


Effect of thermal loading on HF:

Thermal strain tensor

$$\sigma + \kappa p \delta = E : (\varepsilon - \varepsilon^\theta)$$

Hydraulic Fracturing – Borehole stability (tensile failure)



Continuum approaches for HF:

$$\text{With a mud cake: } p_w^f = - \left[(3\sigma_h - \sigma_H) + p_f - \frac{E \alpha_s \theta}{3(1 - \nu)} - T_c \right]$$

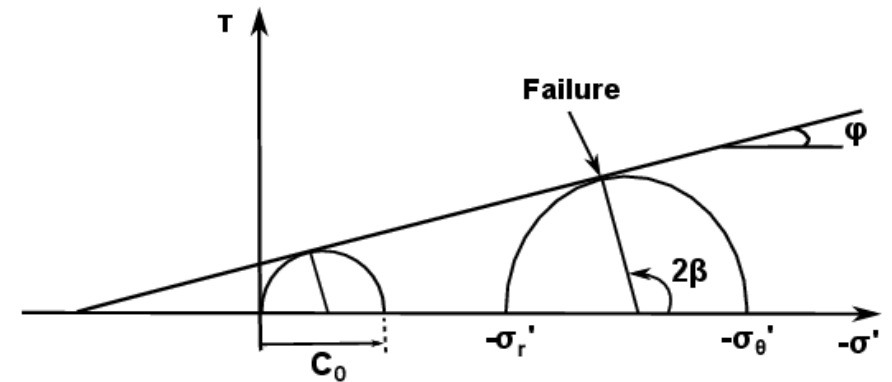
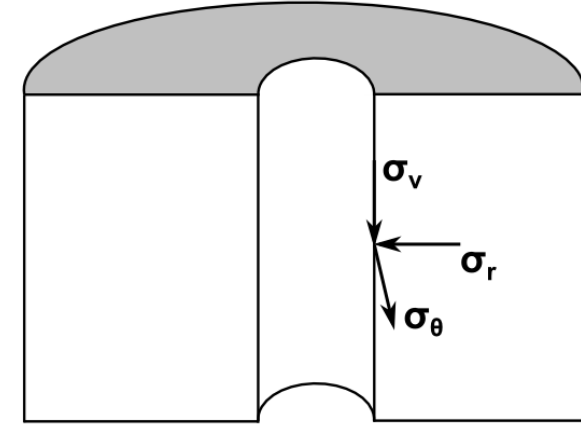
$$\text{Without a mud cake: } p_w^f = - \left[(1 - \nu)(3\sigma_h - \sigma_H) + (1 - 2\nu)p_f - \frac{E \alpha_s \theta}{3} - (1 - \nu)T_c \right]$$

Hydraulic Fracturing – Borehole stability (shear failure)

Borehole shear failure criteria

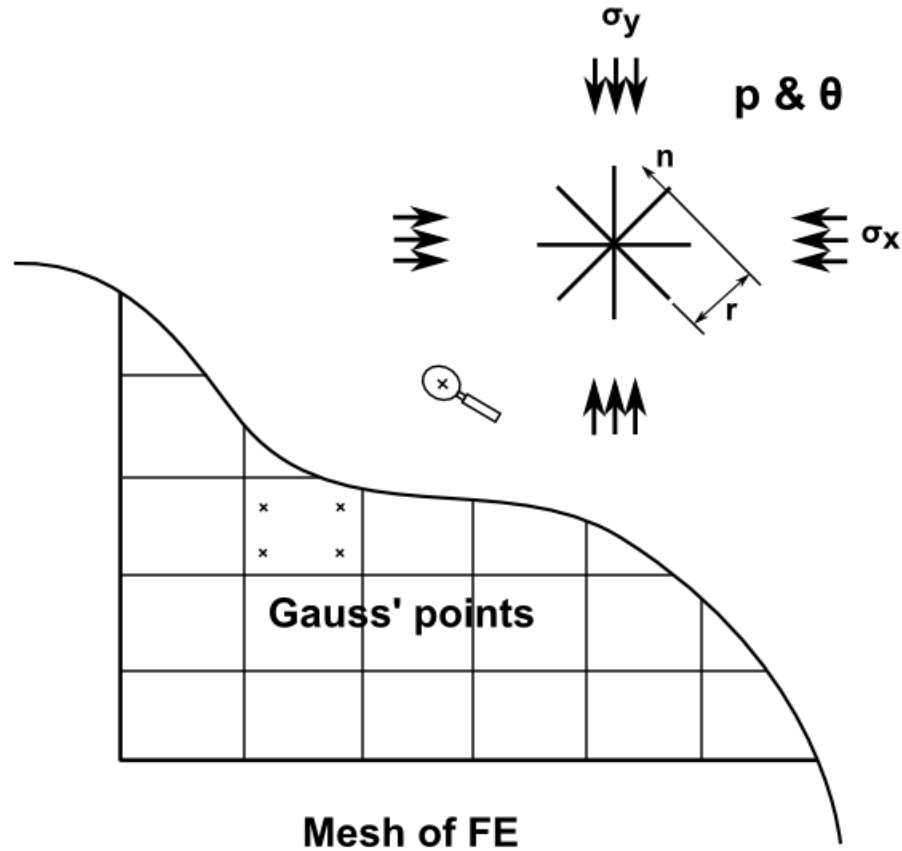
- Stress concentration at the borehole wall
 - Analytical stress expressions at the borehole wall
 - Two most observed stress states corresponding to shear borehole failure
-
- Mohr-Coulomb failure criterion:
 - Two expressions for minimum borehole pressure at shear failure

Shear borehole failure is not likely to happen during HF.



Hydraulic Fracturing – Fracture mechanics

From continuum mechanics to fracture mechanics:



Thermo-poroelasticity



Fracturing criterion (DDFM)



Fracture radius (r) and aperture (w)



Permeability tensor

Hydraulic Fracturing – Fracturing model

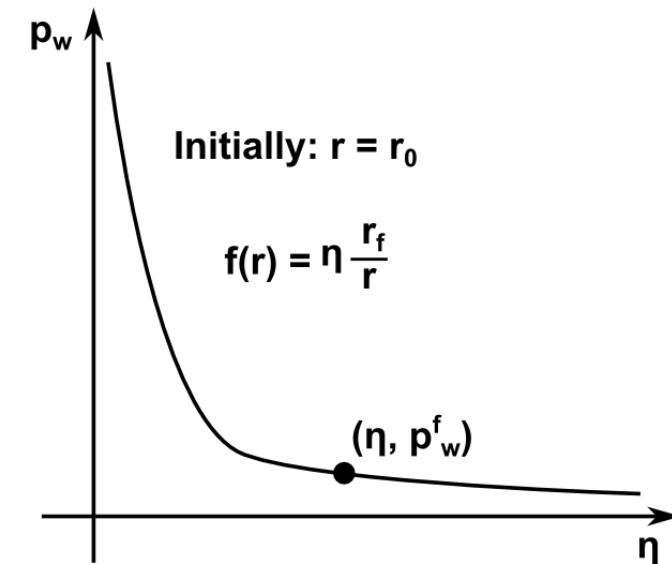
Hydraulic Fracturing Model (HFM)

Only **mode I** of fracture evolution

Starting from the DDFM:

$$F(\sigma'_n, r) = \underbrace{f(r)} \sigma'_n \sqrt{\pi r} - K_{Ic}$$

Parameterization of the model so that fractures propagate at p_w^f

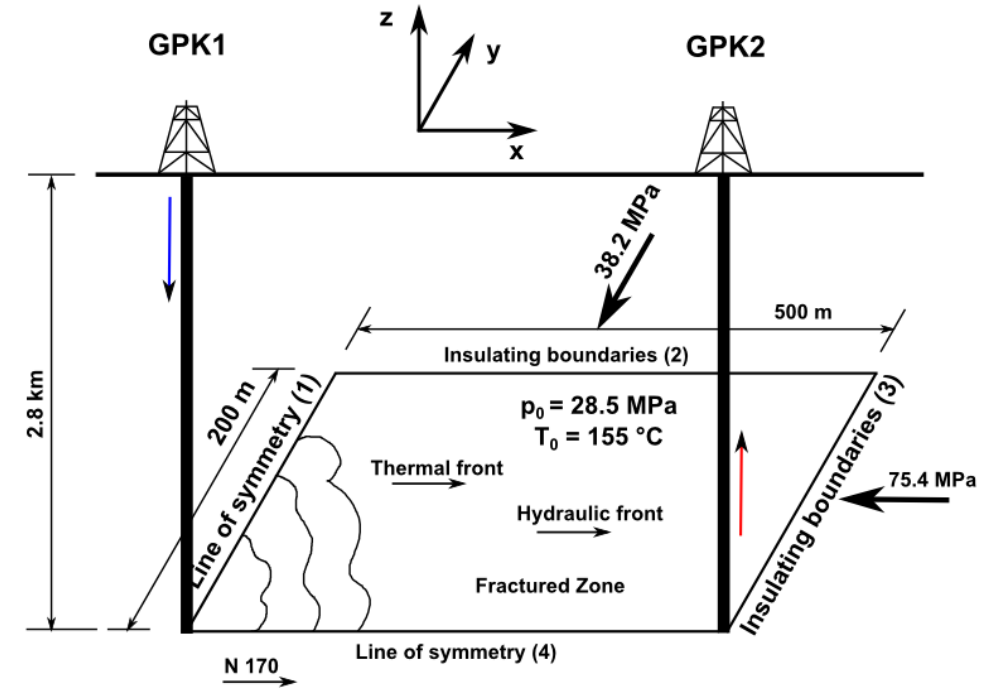
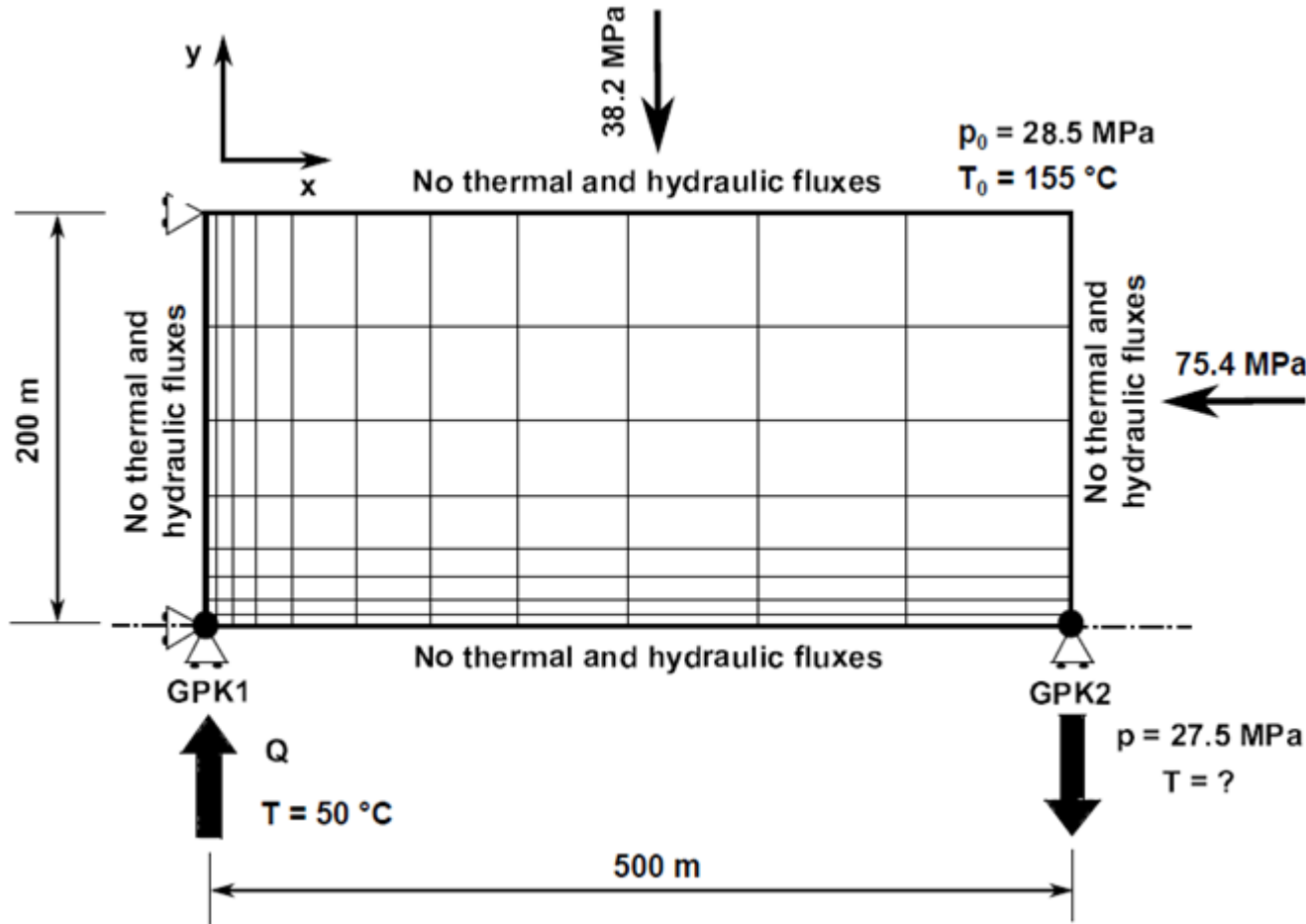


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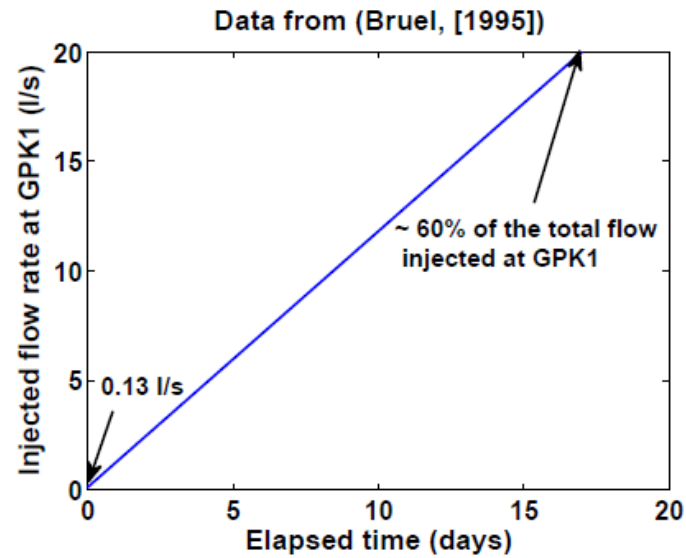
Hydraulic Fracturing – Circulation tests

Stimulation tests of Soultz–Sous–Forêts HDR reservoir: Phase 1 injection test at GPK1



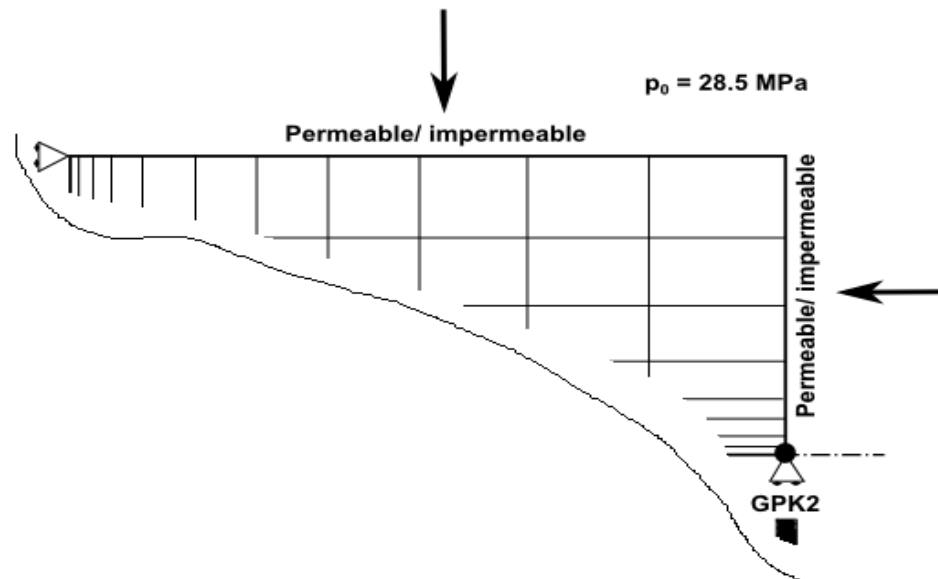
Circulation tests – Flow logging 1993 – Injected flow

Applied flow at GPK1:



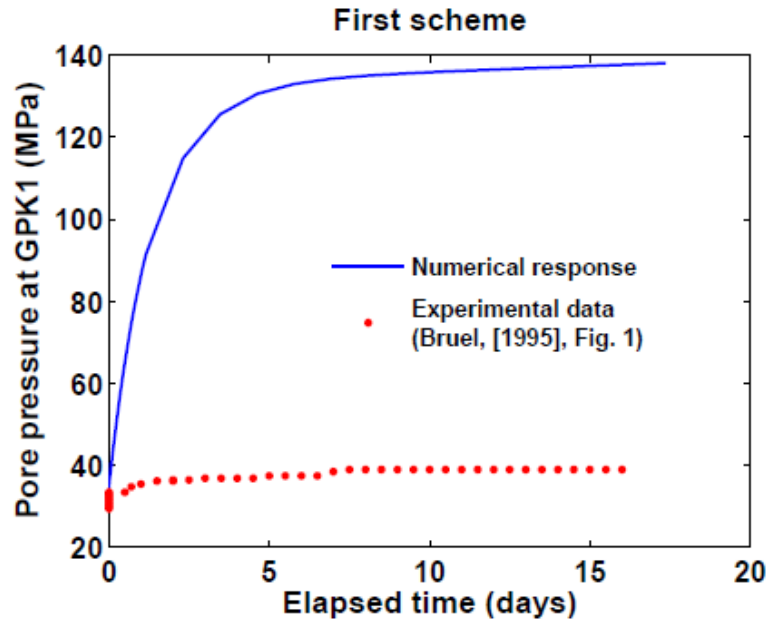
Strategy of the simulations:

- Scheme 1
- Scheme 2

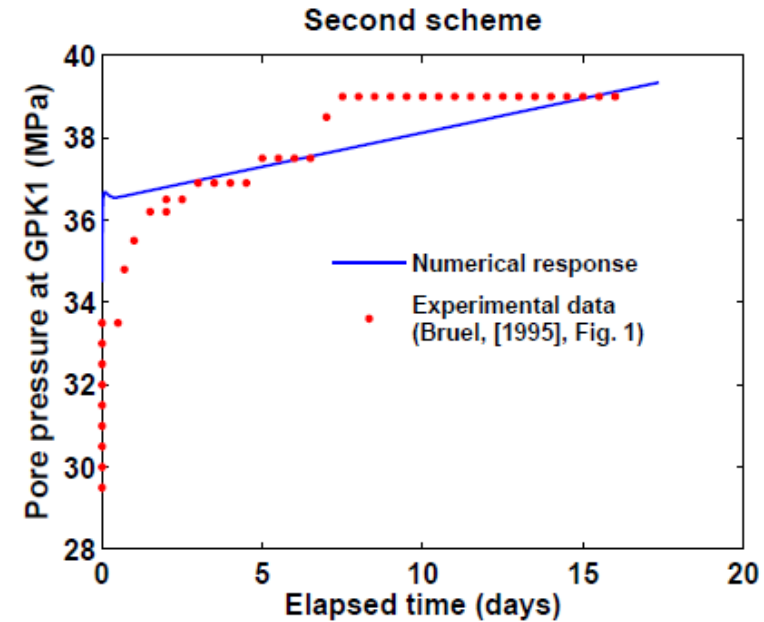


Circulation tests – Flow logging 1993 - Correlations

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(a) Impermeable boundaries



(b) Permeable boundaries

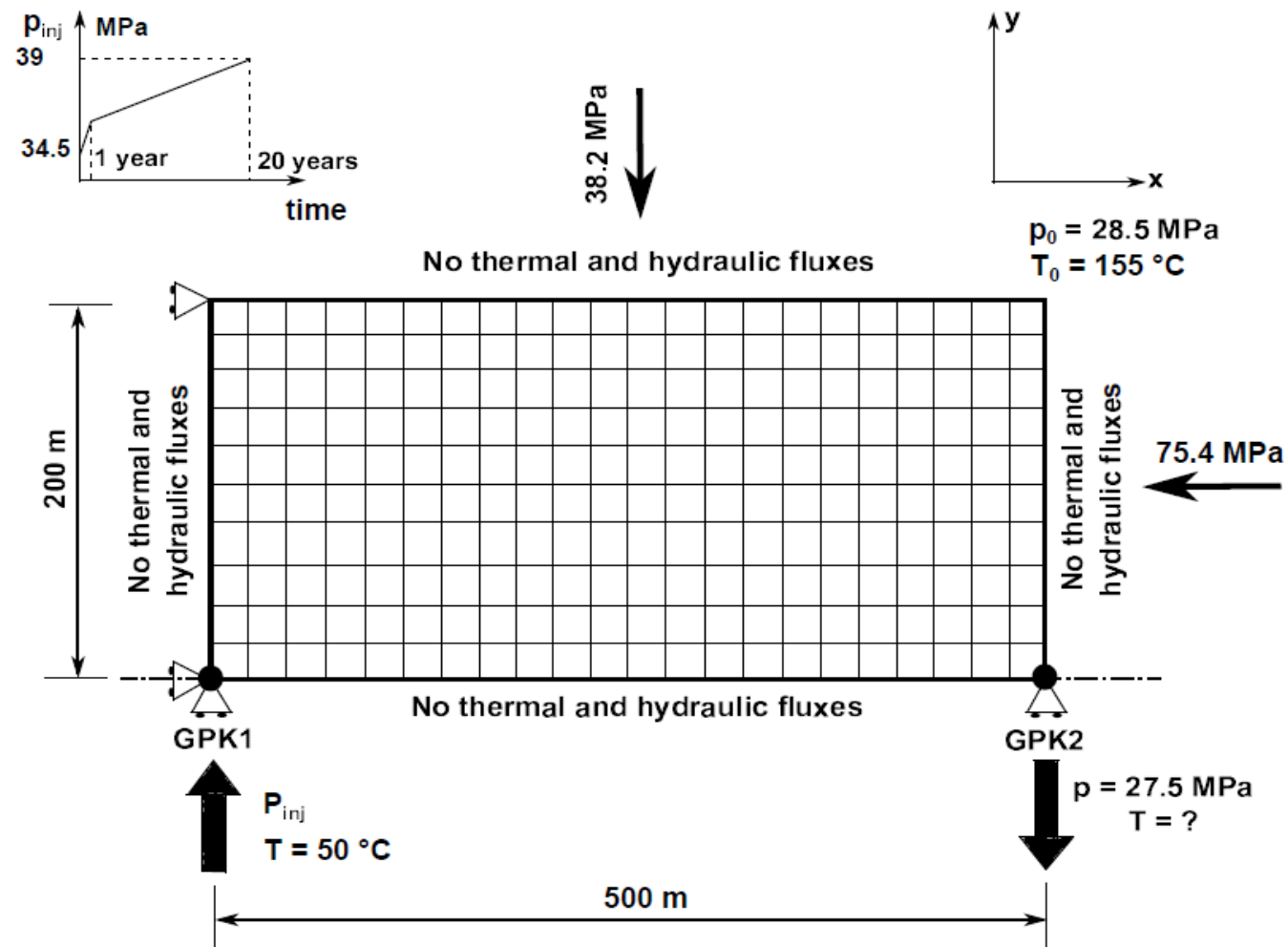
Conclusions:

1. Asymptotic plateau for turbulent flow
2. More effective HF for impermeable boundaries



Circulation tests – Permeability enhancement

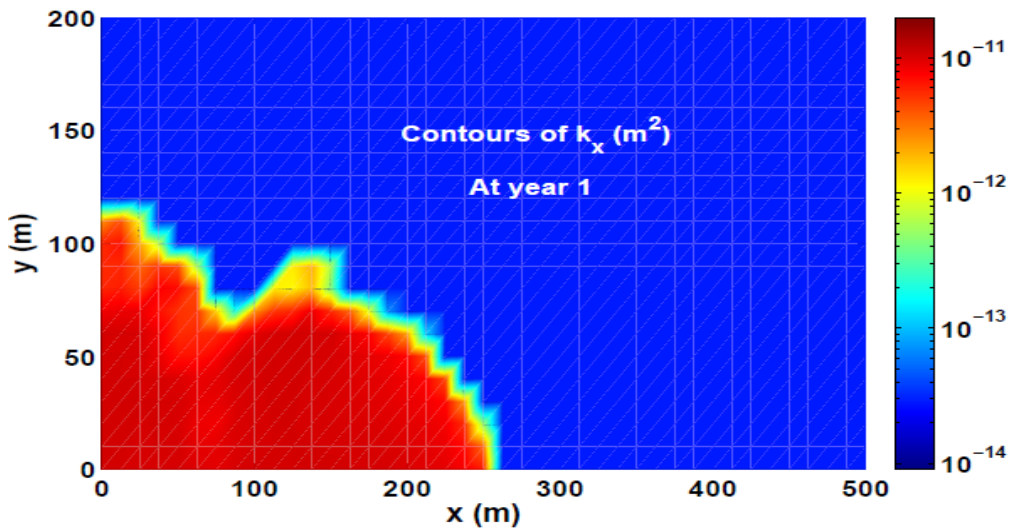
Phase 1 injection test at GPK1 1993: Modeling



Permeability enhancement – Simulations

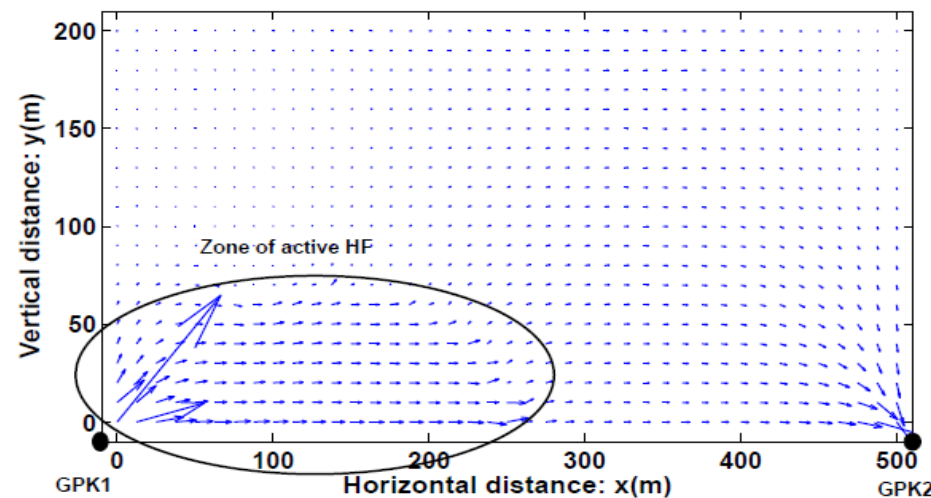


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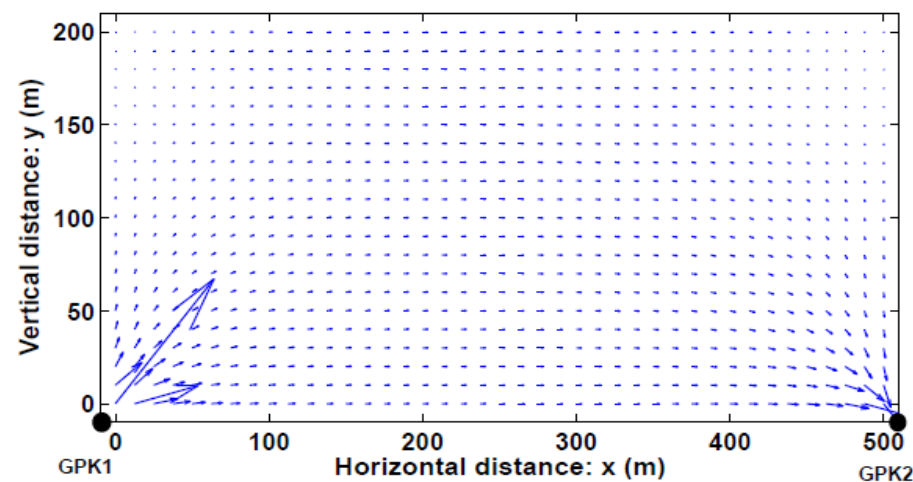
Longitudinal permeability component k_x

Seismic record (Bruel, [1995])



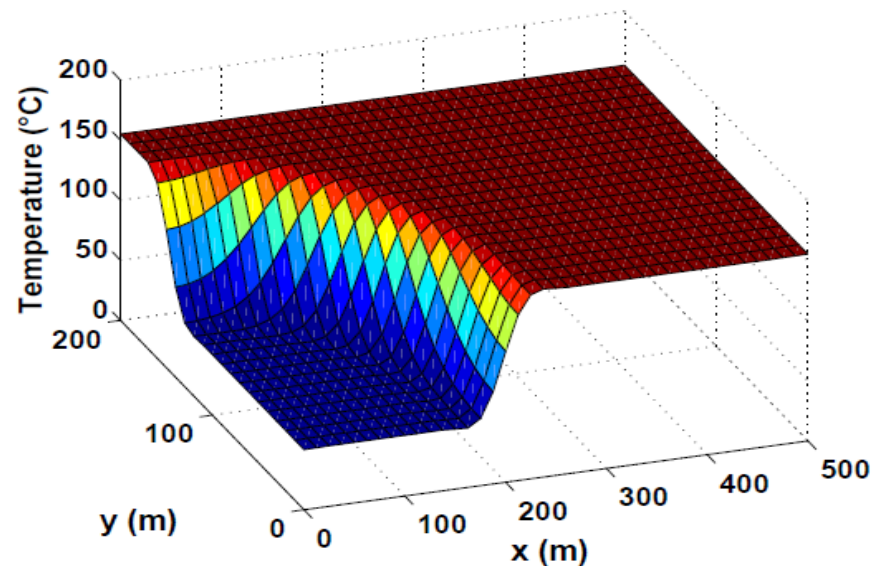
With HF

Fluid velocity vectors at year 1

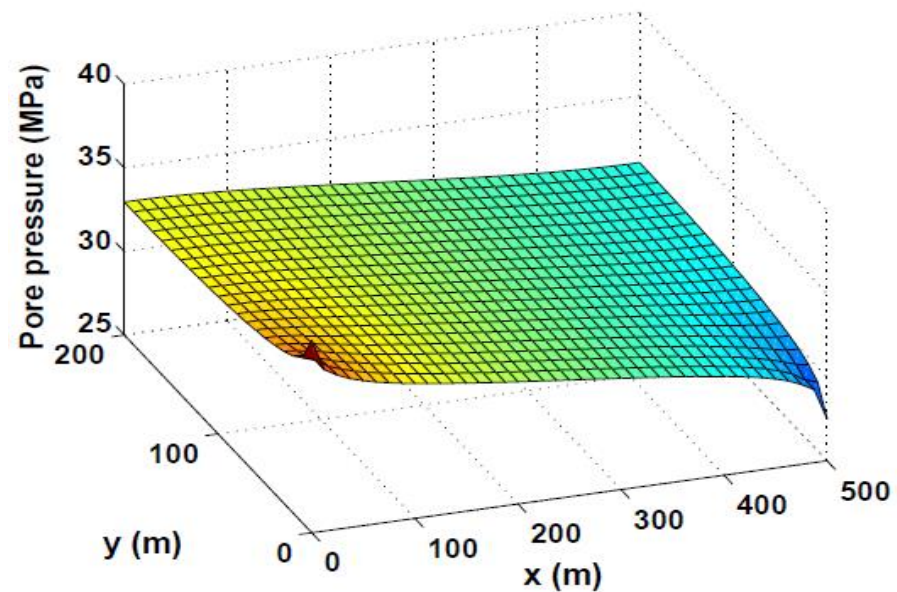


Without HF

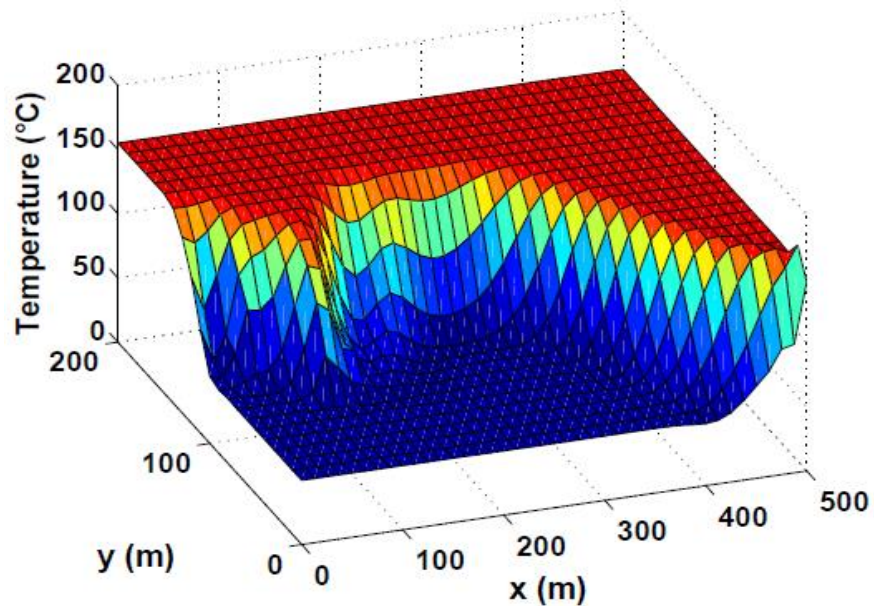
Simulations – Temperature and pressure



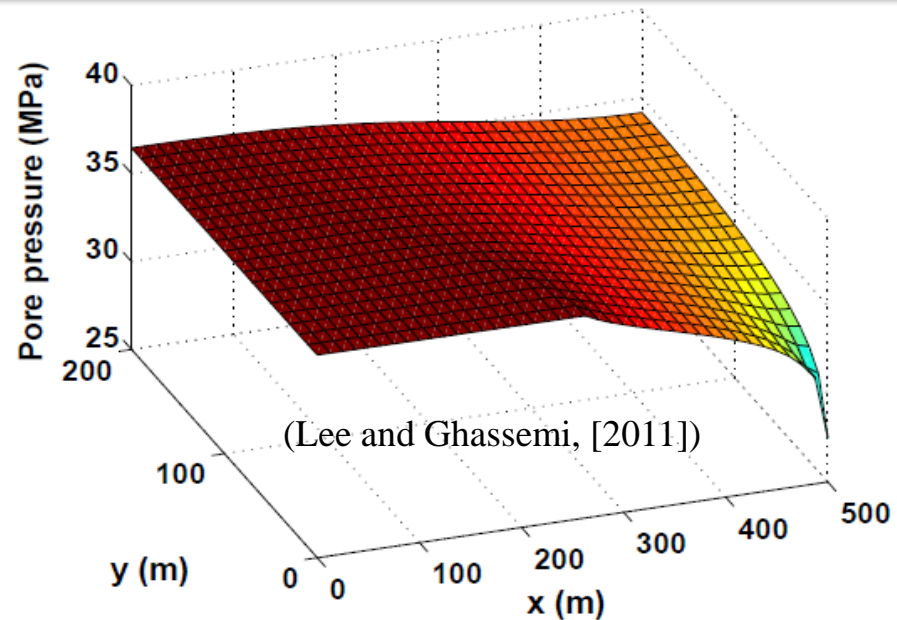
Without HF



At year 5

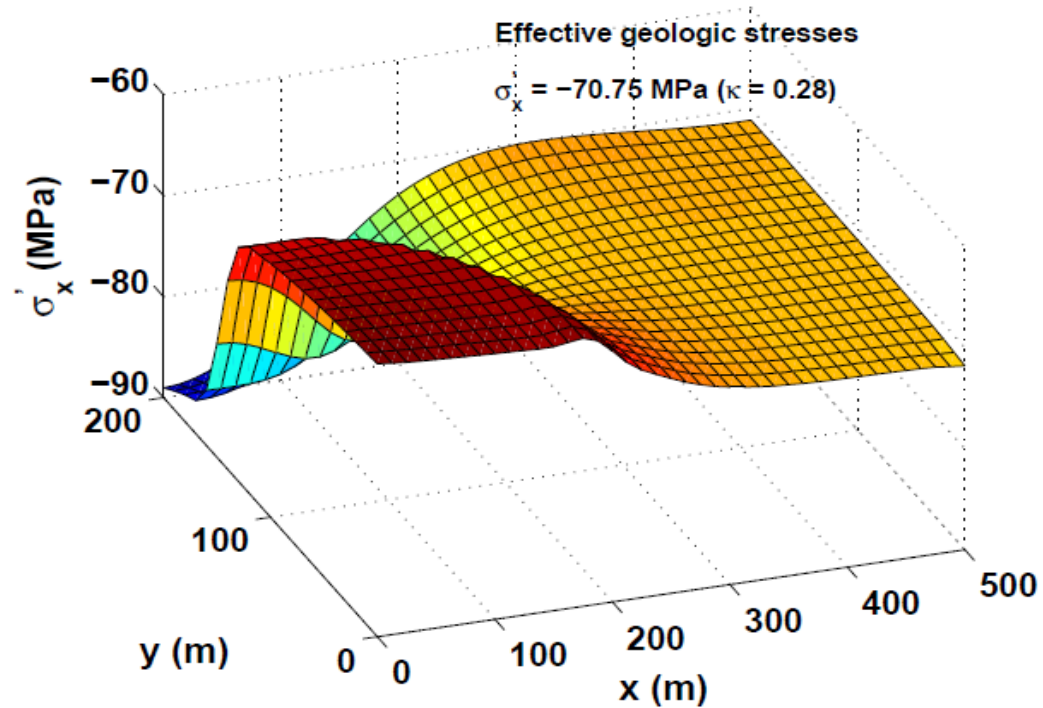


With HF

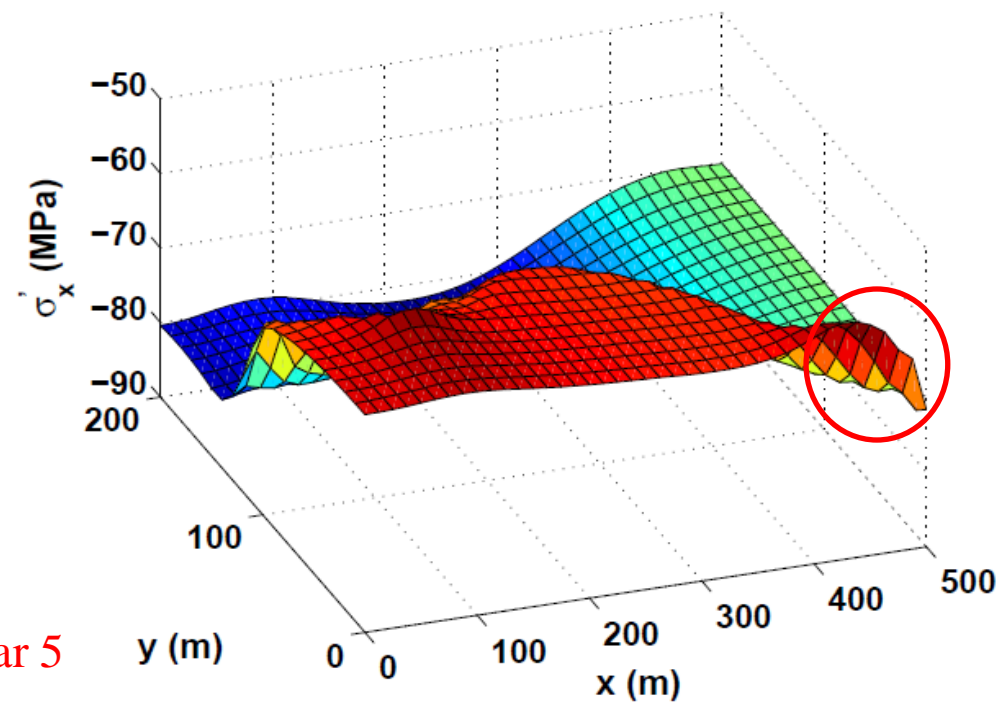


(Lee and Ghassemi, [2011])

Simulations – Longitudinal stress



Without HF



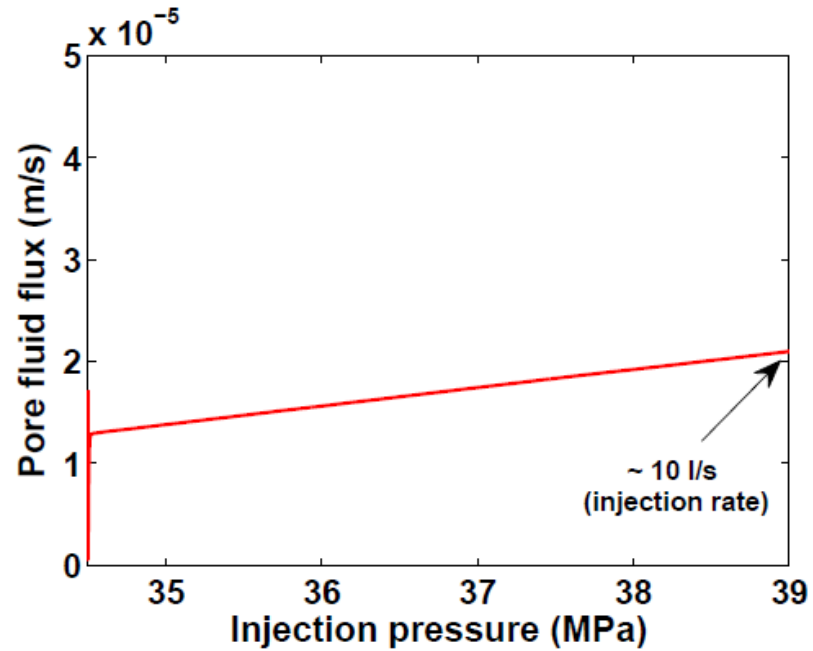
At year 5

with HF

Wiggles due to heat convection: DCM and SGS

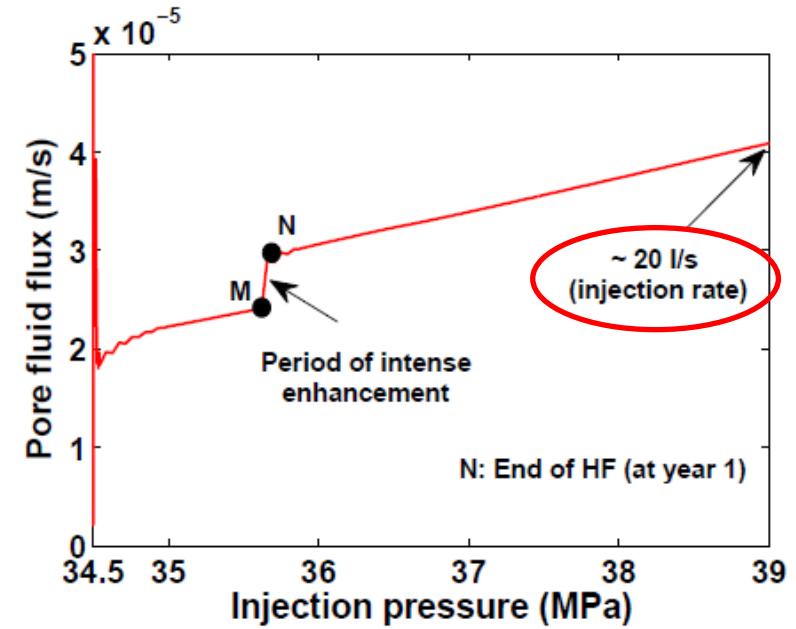
(AbuAisha thesis, [2014], ch. 6)

Simulations – Injection schedule



Without HF

At injection well GPK1



With HF

(Bruel, [1995])

Non-linear relation in injection logging with HF

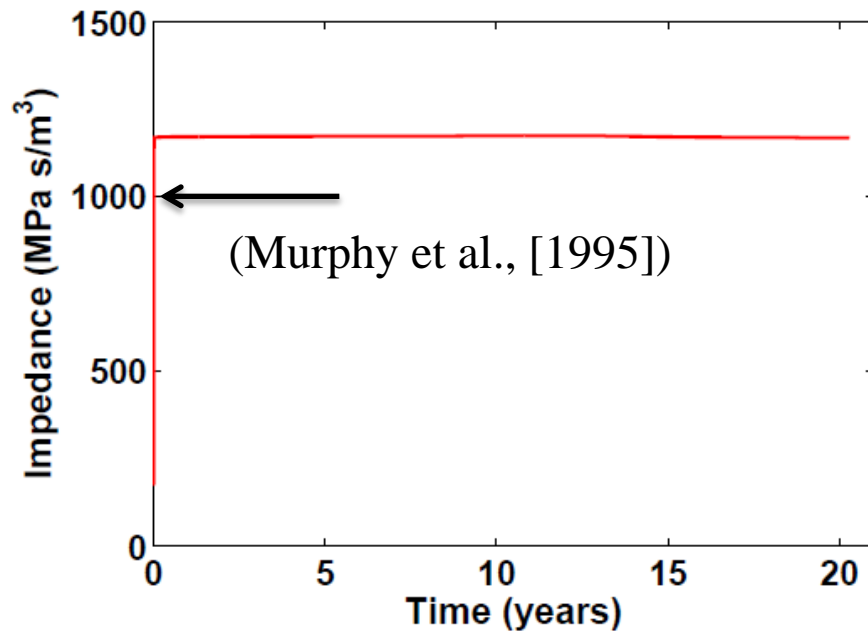
Termination of HF at injection pressure of 35.9 MPa

Injection rate of 20 l/s at injection pressure of 39 MPa

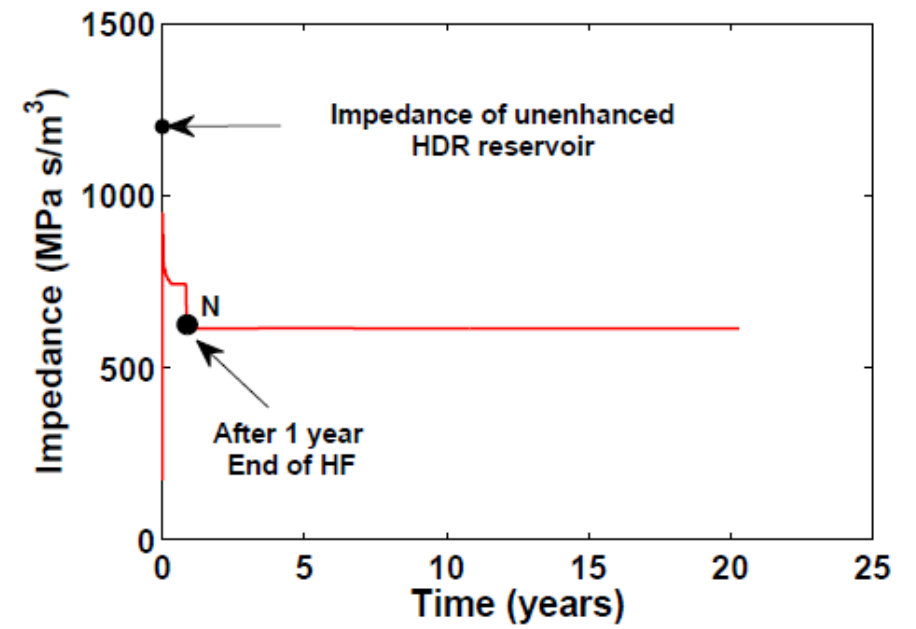
Simulations – Impedance and efficiency

Designer point of view

$$Z = \frac{P_{inj} - P_{pro}}{Q}$$



Without HF

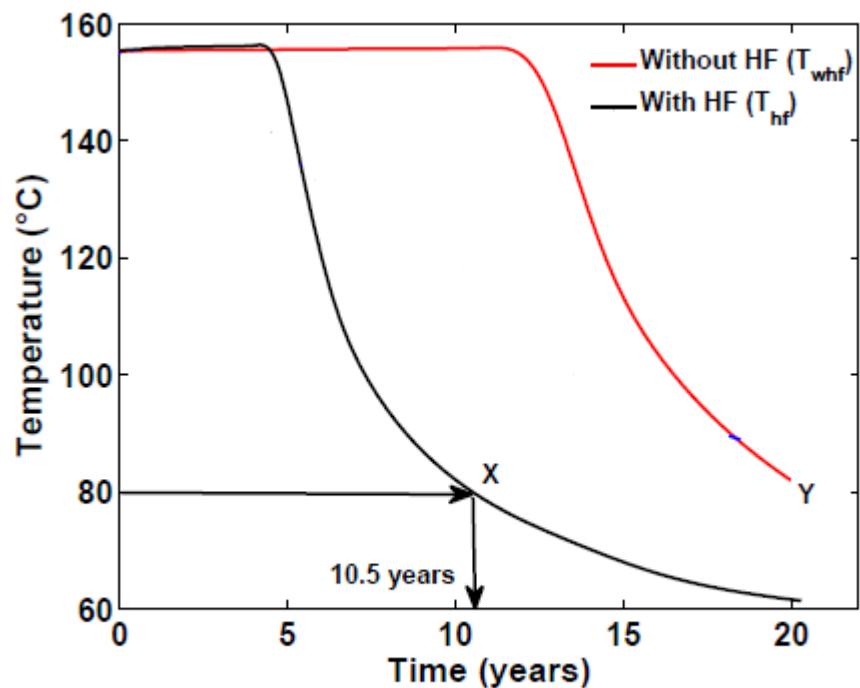


With HF

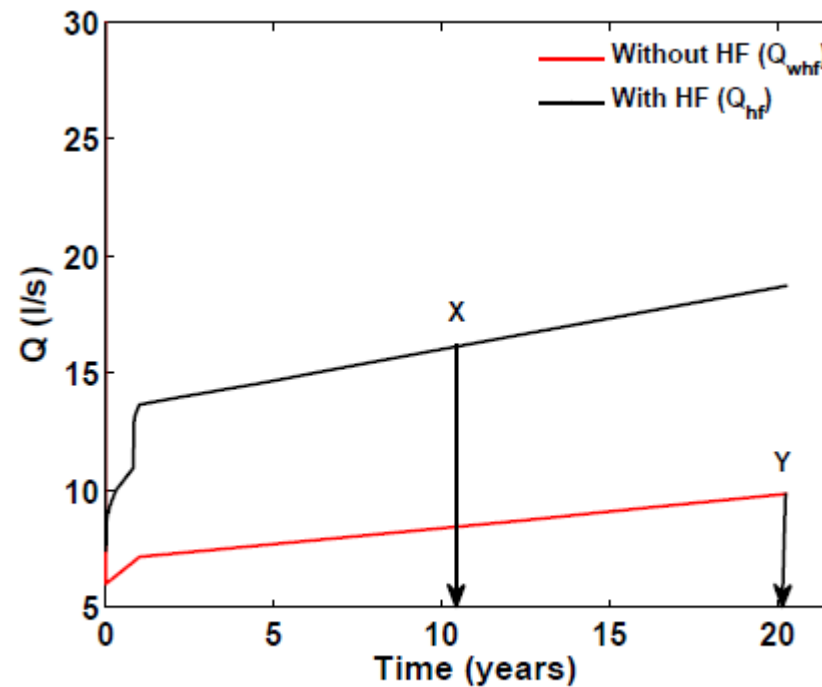
Efficiency enhanced by about 50%

Simulations – Impedance and efficiency

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Profiles of produced fluid temperature



Profiles of produced flow rate (Q)

Efficient fluid with HF is 4.922 Million m^3

Efficient fluid without HF is 5.364 Million m^3



Permeability enhancement – Summary

Reflections and Conclusions:

1. HFM for mode I of fracture evolution
 - Validated against field data
 - Used in doing the stimulation of Soultz–Sous–Forêts HDR reservoir
2. HF increased the efficiency of the reservoir by 50%
3. 7% to 8% of the produced efficient fluid is lost over the effective age of the reservoir

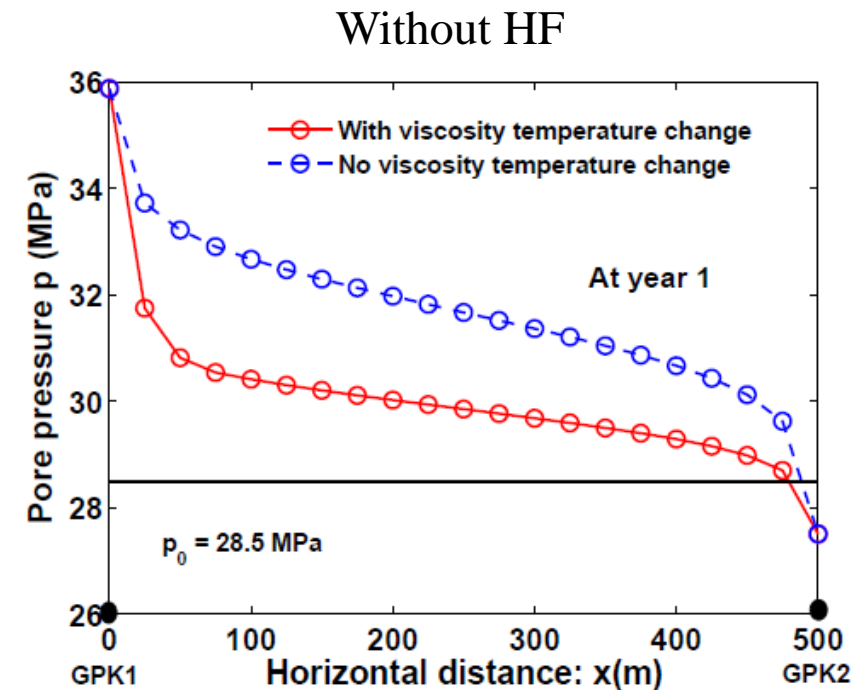
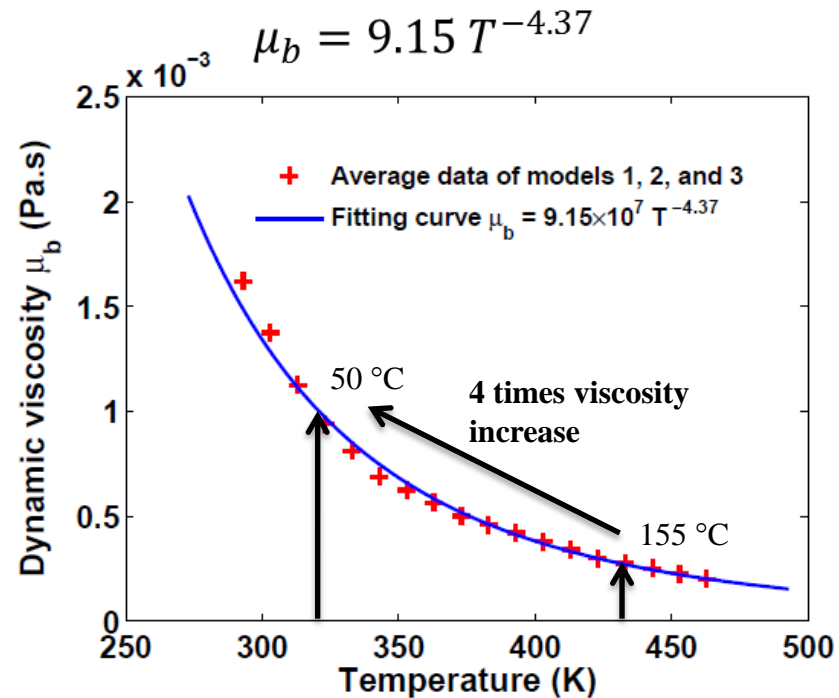
Permeability enhancement – Viscosity temperature change

Phase 1 injection test at GPK1 1993: Simulations with viscosity-temperature change

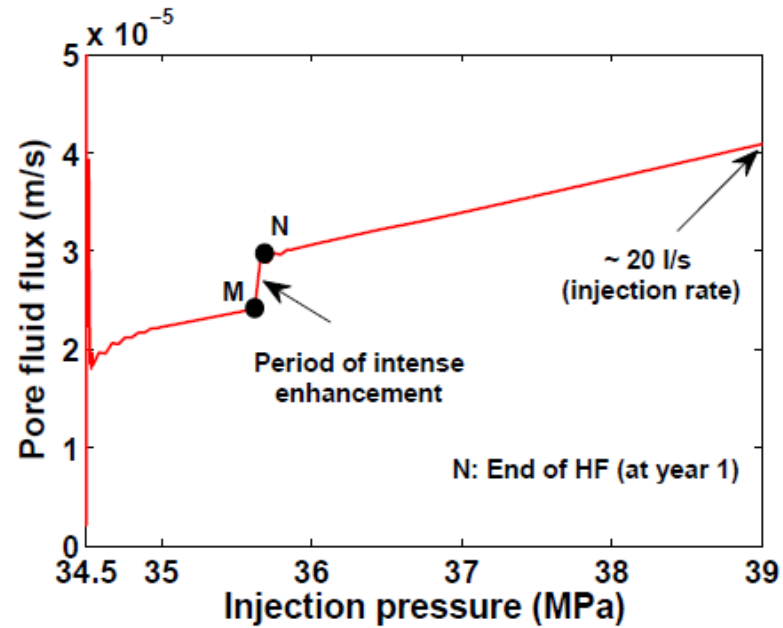
Brine used:

Models of (Francke and Thorade, [2010])

Brine of NaCl (22.5% concentration) at pressure range of 0.01 to 50 MPa



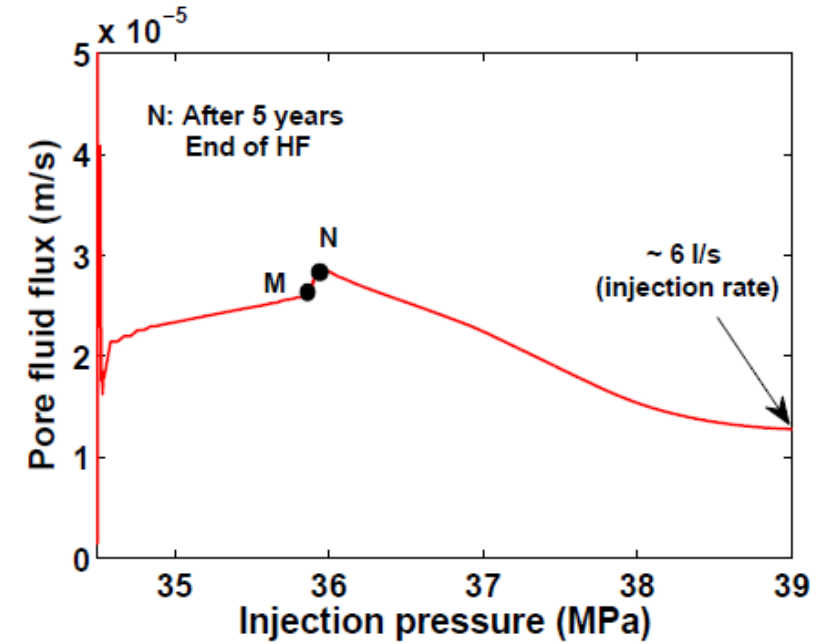
Viscosity temperature change – Injection schedule



No viscosity change

At injection well GPK1

With HF

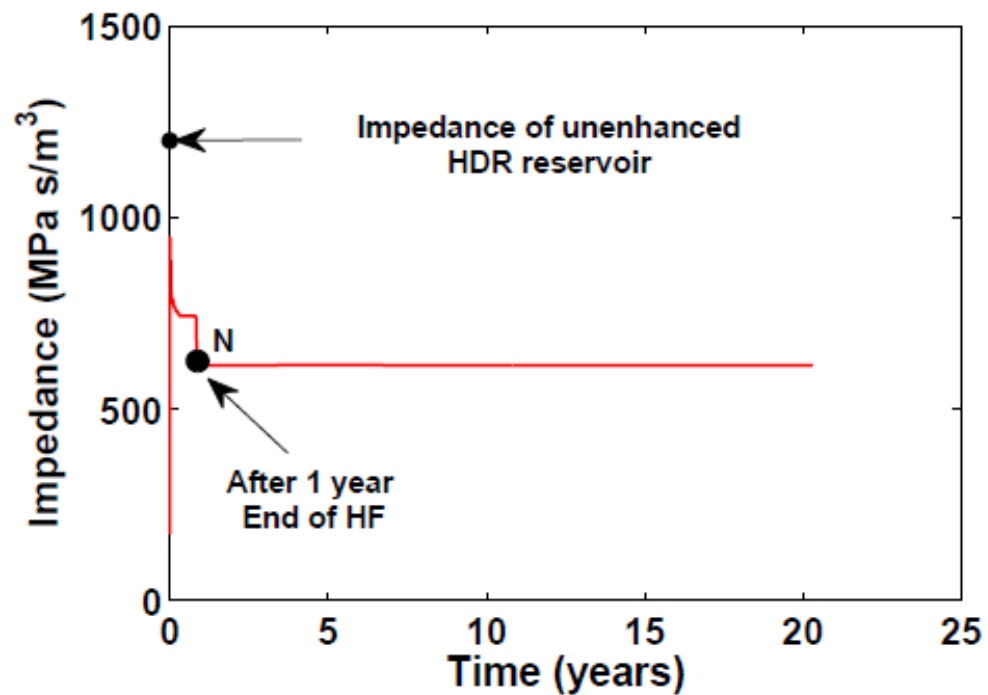


With viscosity change

Termination of HF after 5 years with viscosity change

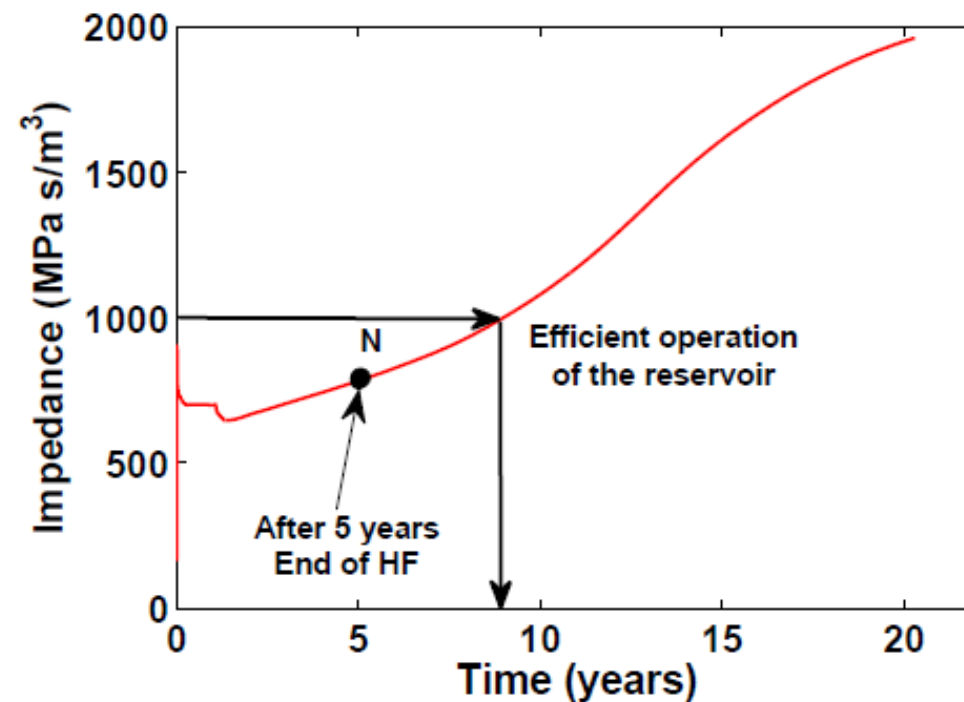
HF counteracts the hindrance due to viscosity increase

Viscosity temperature change – Impedance and efficiency



No viscosity change

With HF



With viscosity change

Longer but inefficient longevity of the reservoir

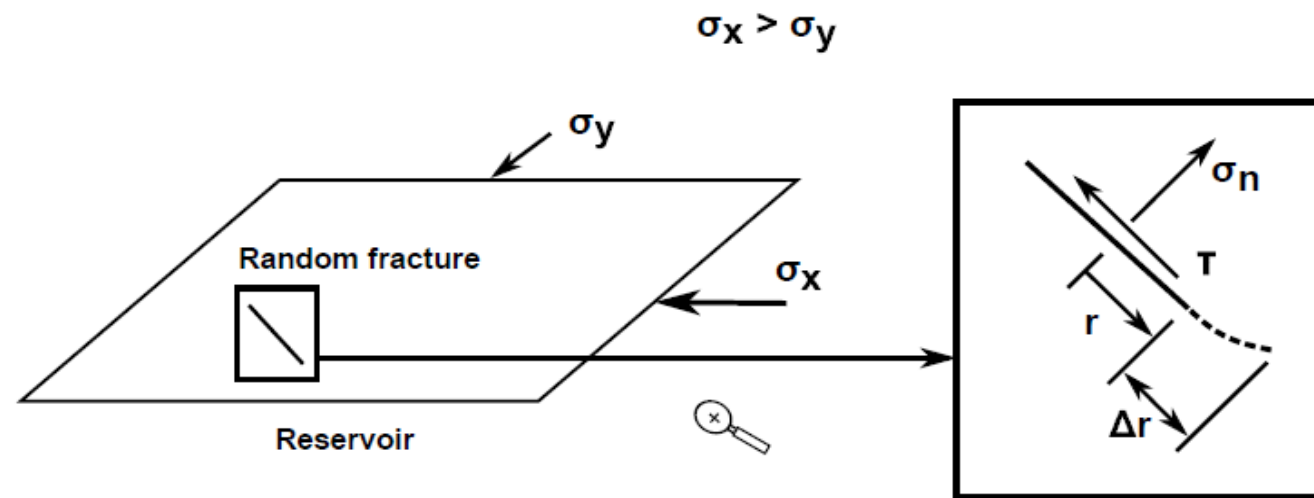


Hydraulic Fracturing – Permeability enhancement HFM2

Hydraulic Fracturing Model (HFM2)

Modes I and II of fracture propagation

Shear slippage of inclined fractures



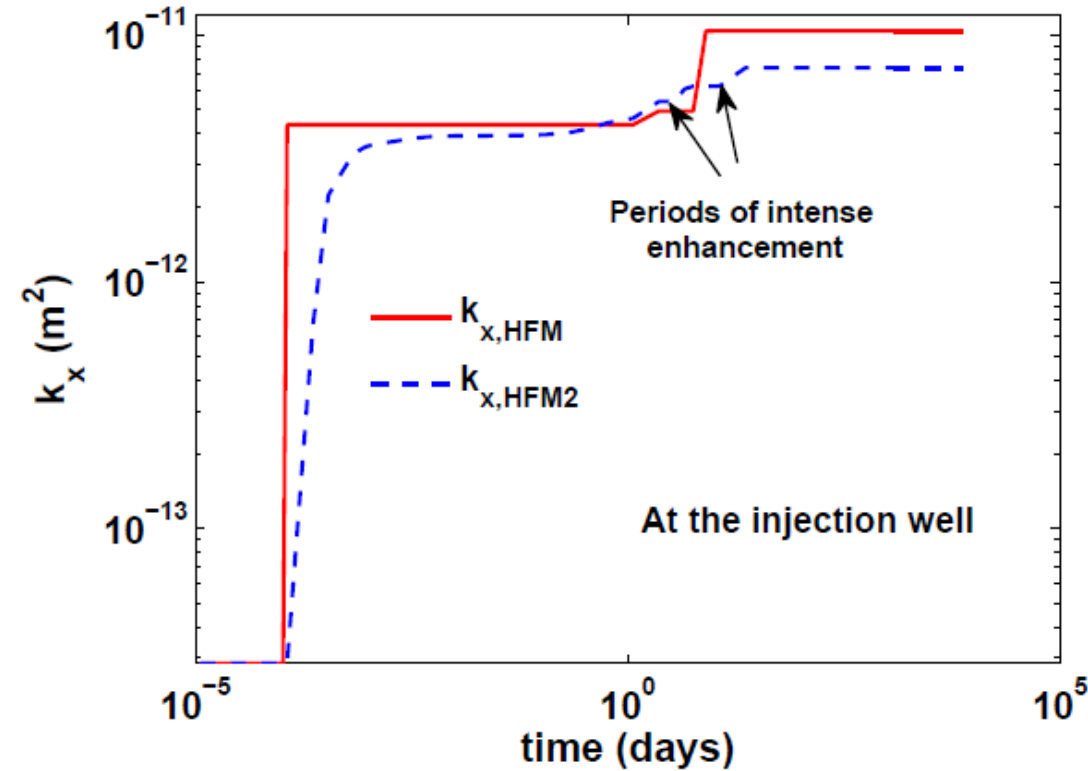
$$F(\sigma', r, n) = \sqrt{r} \left[\sigma'_n + 3 f(r) \langle \sigma'_n{}^d \rangle \right] - C_{rc} \leq 0$$

Permeability enhancement HFM2 – Permeability history at GPK1

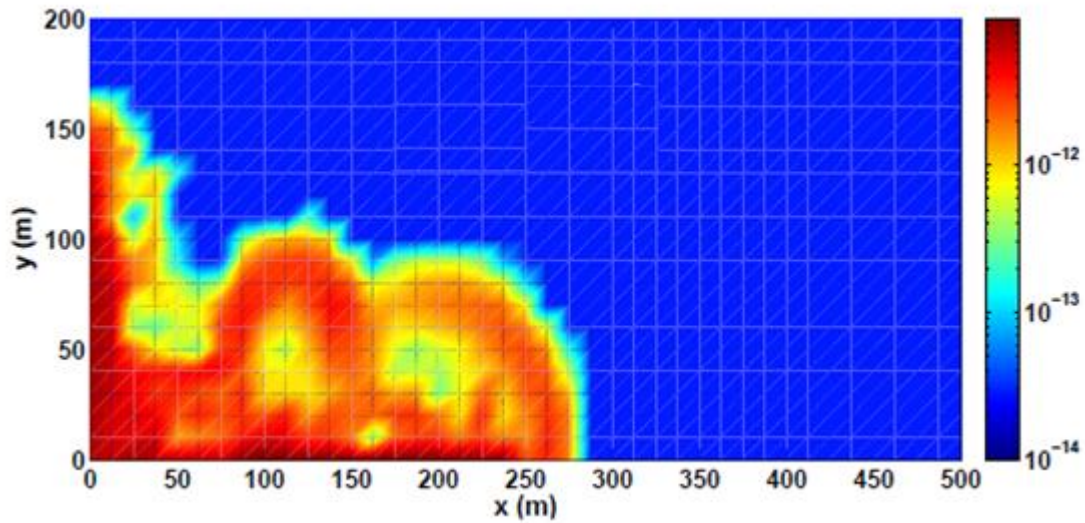
Phase 1 injection test at GPK1 1993: Stimulations using HFM2

k_x at the injection well GPK1

Stabler growth of fractures



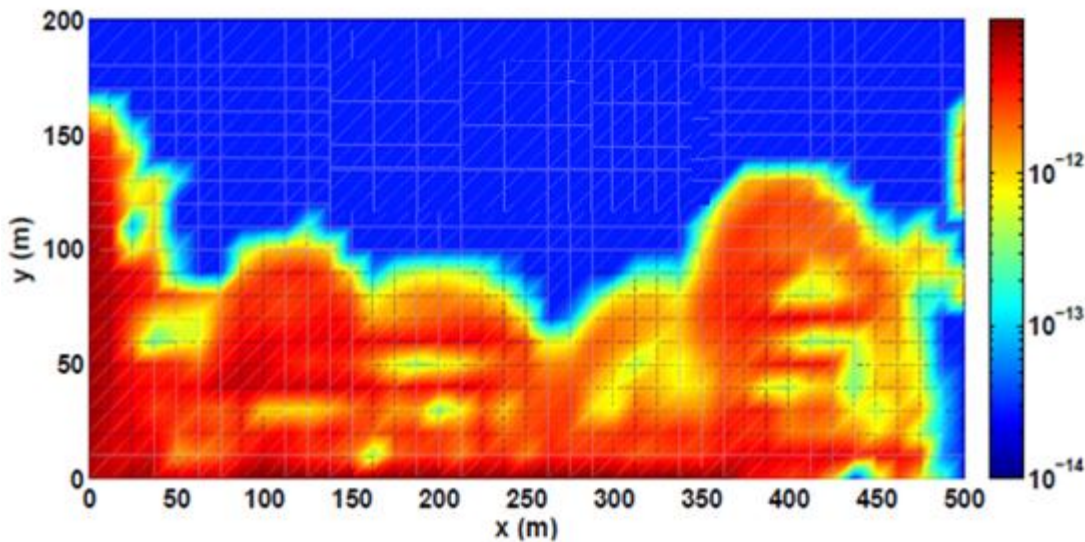
Permeability enhancement HFM2 – Permeability contours



At year 1

Longitudinal permeability contours

HF while accounting for modes I & II



At year 2

Overview of the research:

- **Thermo-poroelasticity**
 - Mathematics
 - Simulations by ABAQUS and FE domestic code
- **Fracture evolution and permeability enhancement**
 - Fracturing criterion:
 - ❖ Evolution of fracture radius
 - ❖ Fracture aperture change
 - Anisotropic permeability tensor
- **FE simulations of Hydraulic Fracturing (HF)**
 - Circulation tests without and with considering HF
 - Designing HDR reservoirs: Impedance, efficiency and life-time
- **Convection of heat – Stabilization**
- **Conclusion**

Convection of heat – Definition

Fluid velocity multiplied by the gradient of its temperature: $v \cdot \nabla \theta$

Solving the equation of balance of energy with dominant convection of heat – Difficulties

Heat waves striking suddenly stiff boundaries: $\left[(\partial \theta / \partial t) + v \cdot \nabla \theta \right]$

Bubnov-Galerkin methods are not efficient – Alternatives:

1. Subgrid Scale (SGS) method
2. Streamline-Upwind Petrov-Galerkin (SUPG) method
3. The Discontinuity Capturing Method (DCM)

Convection of heat – SGS Method

Application of the SUPG method is inefficient at small time steps and when activating HF.

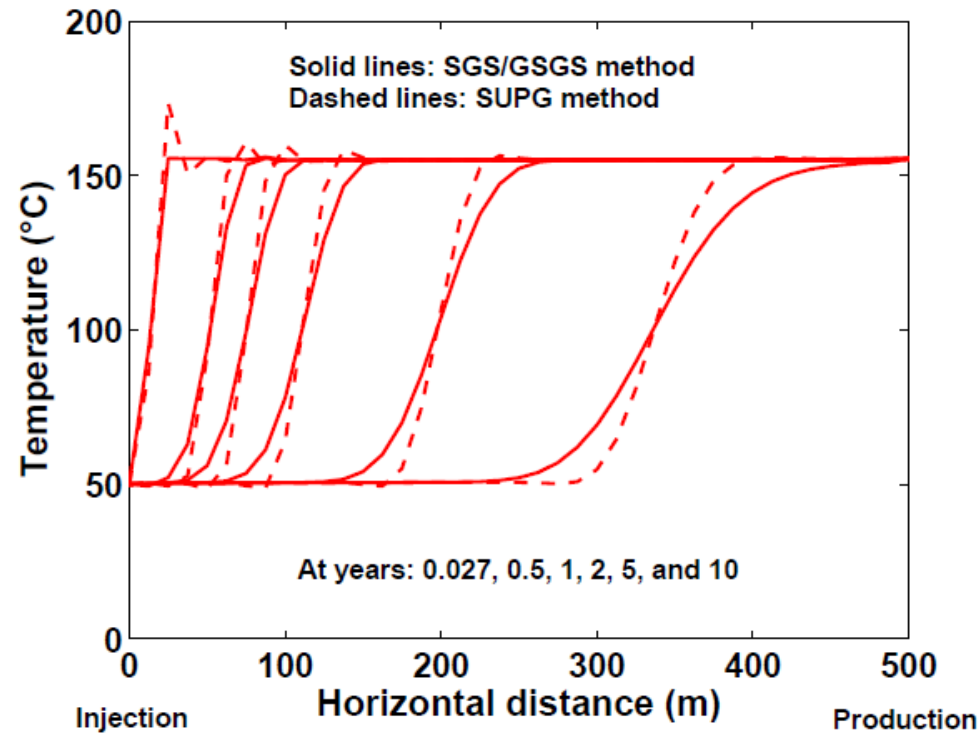
SGS: The transient term of a transient diffusion problem can be transformed into a reaction term by first discretizing in time instead of the conventional method of first discretizing in space.

$$\int_V w^h \left(\mathcal{N} \varphi_{n+1}^h - F_{n+1} \right) dV + \sum_{e=1}^{N_{el}} \int_{V^e} \left(-\mathcal{N}_* w_{n+1}^h \right) \tau_{00}^e \left(\mathcal{N} \varphi_{n+1}^h - F_{n+1} \right) dV^e \\ + \sum_{e=1}^{N_{el}} \int_{V^e} \nabla \left(-\mathcal{N}_* w_{n+1}^h \right) \tau_{11}^e \nabla \left(\mathcal{N} \varphi_{n+1}^h - F_{n+1} \right) dV^e = 0,$$

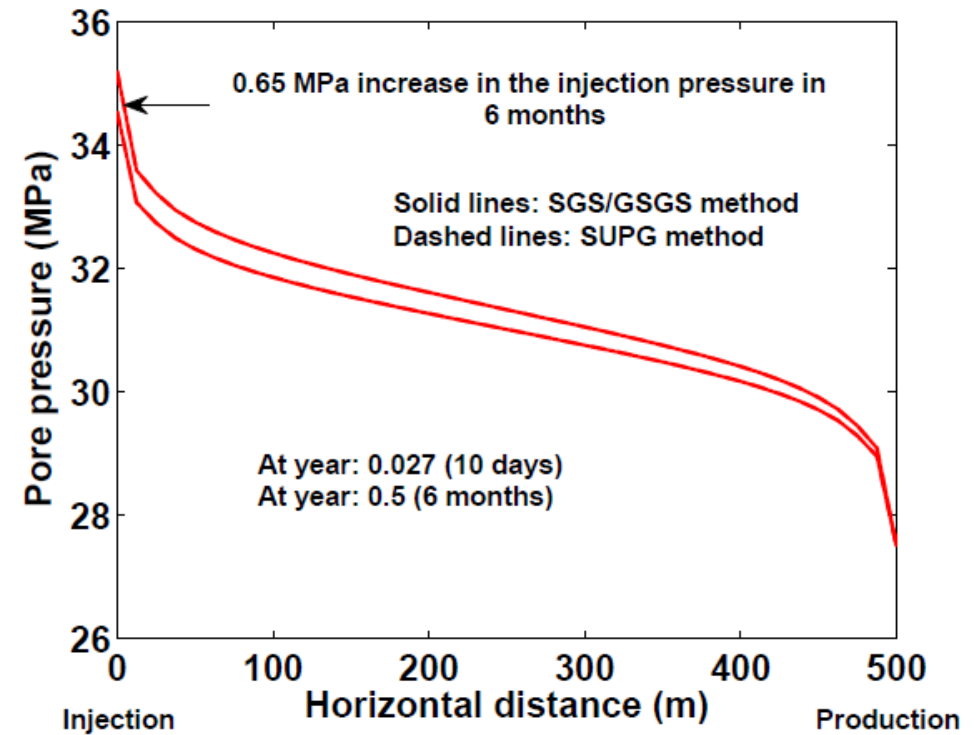
where τ_{00}^e (s) and τ_{11}^e ($\text{m}^2 \text{s}$) are the stabilization parameters.

SGS Method - Simulations

Stabilization at early and intermediate time intervals:



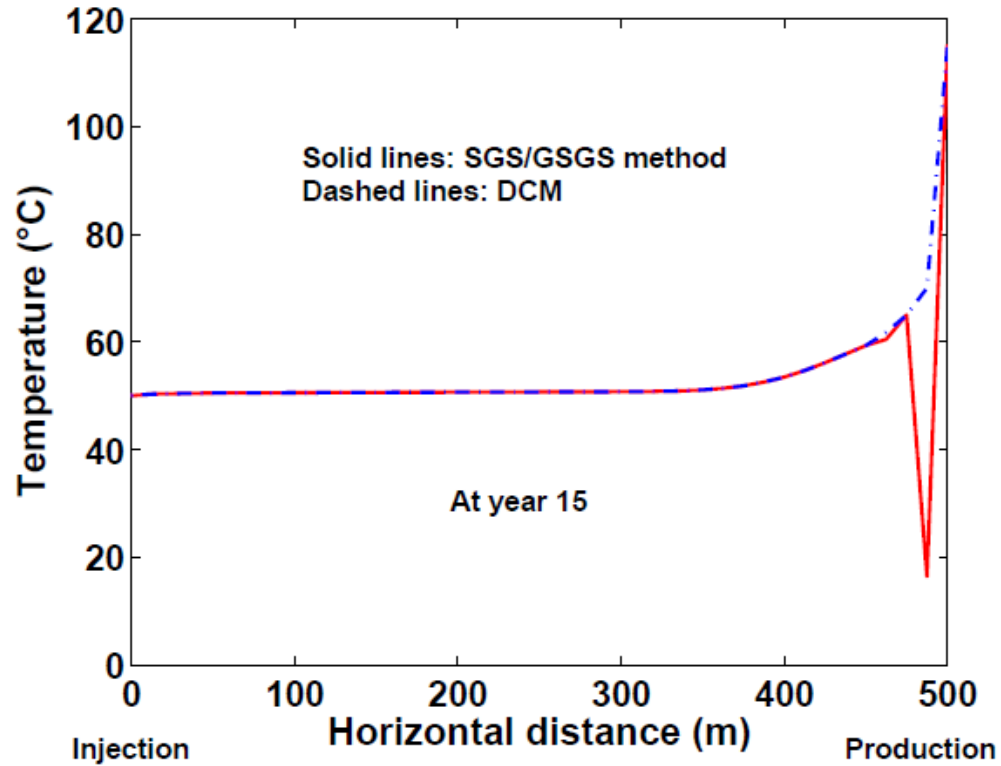
(a) Temperature profiles



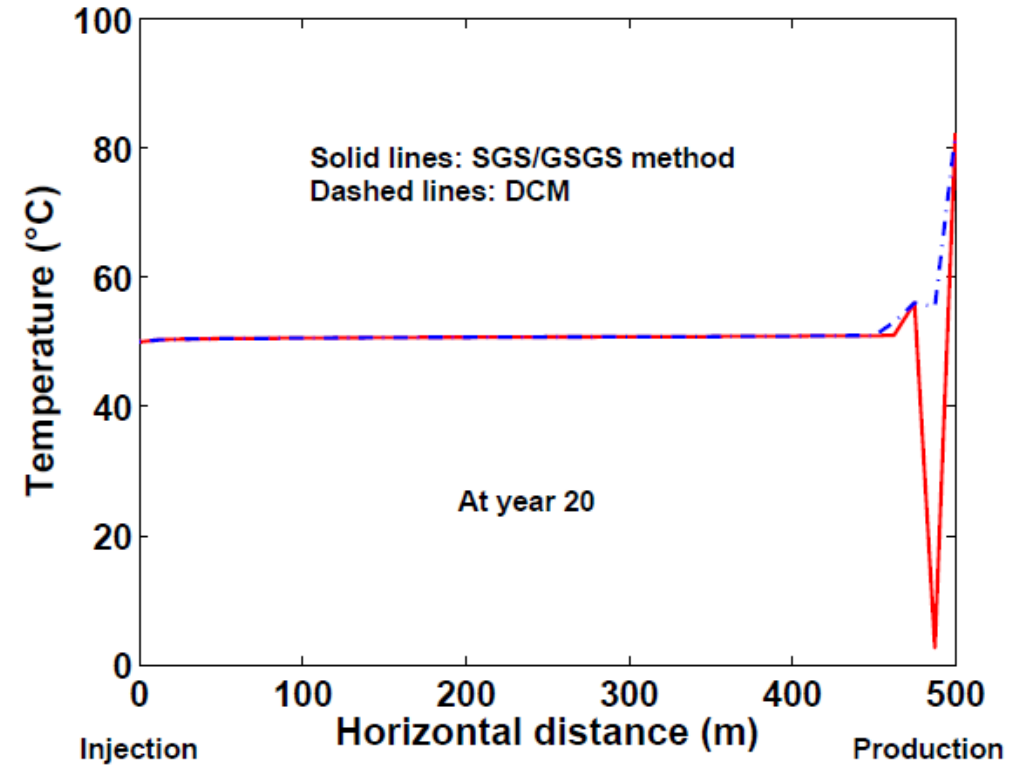
(b) Pore pressure profiles

DCM- Simulations

Stabilization at late time intervals:



(a) Temperature profiles at year 15



(b) Temperature profiles at year 20

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 - Fracturing criterion:
 - ❖ Evolution of fracture radius
 - ❖ Fracture aperture change
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- **Conclusion**

Conclusion

Building a frame work capable of describing permeability enhancement in a THM framework with:

- fully integrated mechanical ingredients to describe HF (HFM and HFM2),
- a computational aspect to implement HF models and thermo-poroelasticity

Reflections and perspectives

1. Investigating large and small scale heterogeneities of geothermal systems
2. Fracture slippage and permeability reduction under compressive stresses
3. Experimental laboratory tests
4. Impact of temperature change on the viscosity of Non-Newtonian fluids
5. Non-Darcian flow to describe inertial effects due to high fluid velocities
6. Chemical enhancement of EGS
7. HF in a dual-porosity thermo-poroelastic framework
8. CO₂-based EGS



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