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COMSOL CONFERENCE ROTTERDAM 2013

Simulation of Flow, Thermal and Mechanical Effects in COMSOL for Enhanced Geothermal Systems

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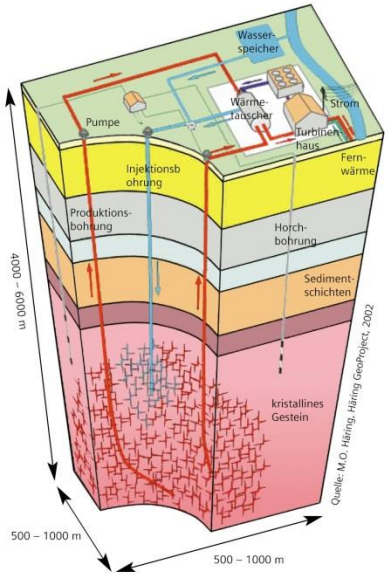
Enhanced Geothermal Systems

- Enhanced Geothermal Systems: technology where a hot (>100°) but relatively impermeable ($\kappa < 10^{-16}$ m^2) rock at depth (often > 2-3 km) is hydraulically stimulated.
- Shear failure on pre-existing fracture network, giving increased permeability; enabling flow between wells to exchange heat

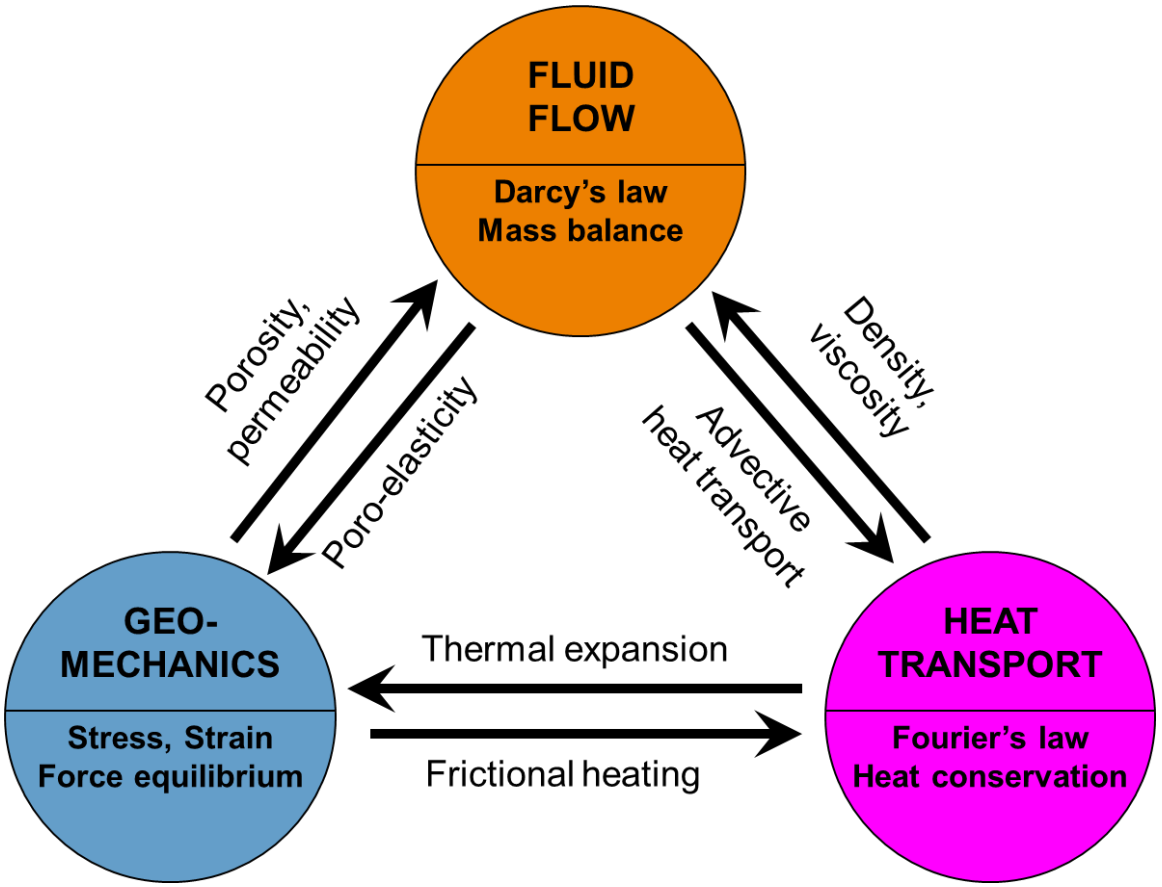


- Mechanisms of shear failure (Majer et al., 2007)
  - Pore pressure ↑ Effective normal stress ↓
  - Temperature ↓ Effective normal stress ↓
  - Chemical reaction may reduce coefficient of friction

Mohr-Coulomb

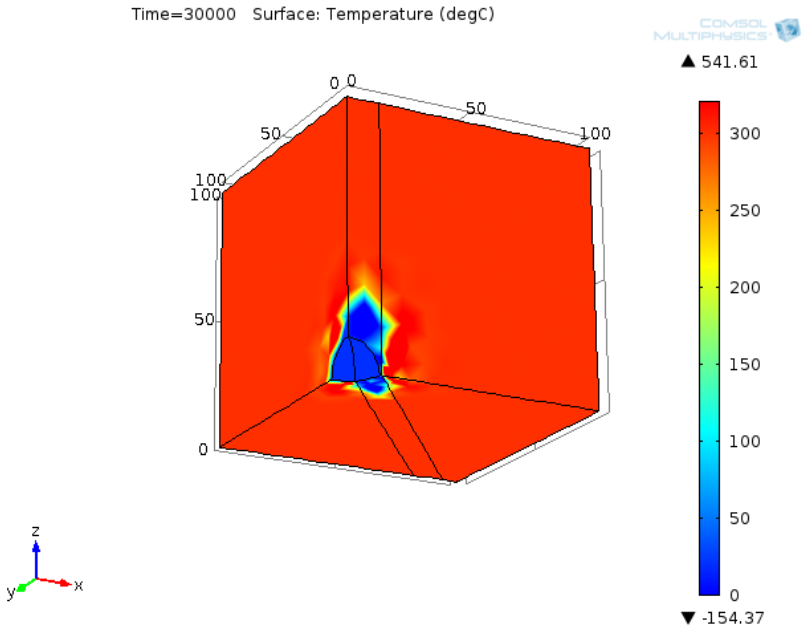
$\tau = S_0 + \mu(\sigma_n - p_f)$

Full Coupling of Flow, Mechanics and Heat Transport



The Model

- Inspired by field case (Soult-sous-Forêts)
- 3D rock mass of 100x100x100 m^3
- Fracture zone with dip of 60°
- Impermeable matrix of granite
- Fracture zone
  - 20 m thickness
  - Initial permeability of 500 mD
- Vertical injection well
- Injection of cold water (20°C)

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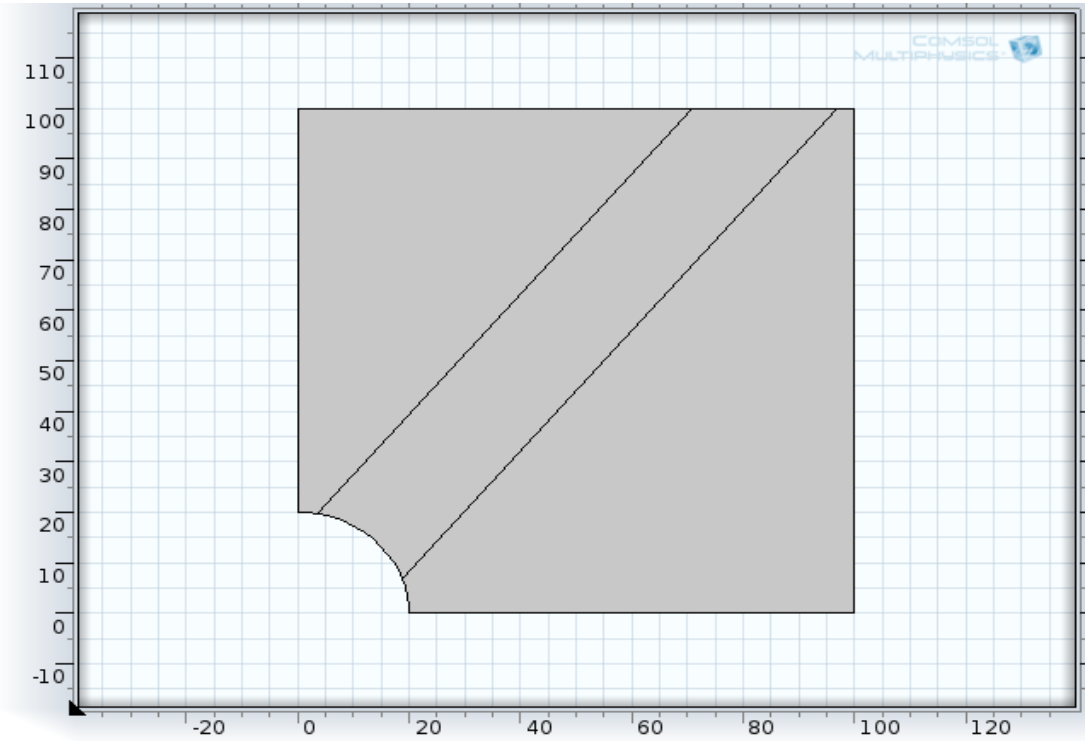
2D Model

Sensitivities using 2D cross section

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Coupled Processes and COMSOL Multiphysics

- **Flow** in porous medium
  - Darcy's law
  - Continuum equation
  - Fracture Permeability according to the cubic law (Poisseuille flow)
  - Porosity change due to volumetric strain
  - Viscosity change due to temperature
- **Mechanics**
  - Rock matrix: Linear Elastic
  - Fracture zone: Mohr-Coulomb Model
  - Poro-elastic stresses
  - Thermo-elastic stresses
- **Heat Transfer**
  - Conduction & Diffusion: Heat equation
  - Convection: Darcy velocity field


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Equation

Show equation assuming:

Study Poro-elastic, Time Dependent

$$-\nabla \cdot \sigma = Fv, \quad \sigma = s$$

$$s - S_0 = C : (\epsilon - \epsilon_0 - \epsilon_{inel}) - (\text{trace}(C : (\epsilon - \epsilon_0 - \epsilon_{inel}))/3 + p_w)I - \alpha_B pf I$$

Modelled as initial stress

$$\epsilon = \frac{1}{2}\left[(\nabla u2)^T + \nabla u2\right]$$

$$\rho S \frac{\partial pf}{\partial t} + \nabla \cdot (\rho u) = Q_m - \rho \alpha_B \frac{\partial e_{vol}}{\partial t}$$

Has to be modelled in Darcy Law as a source term

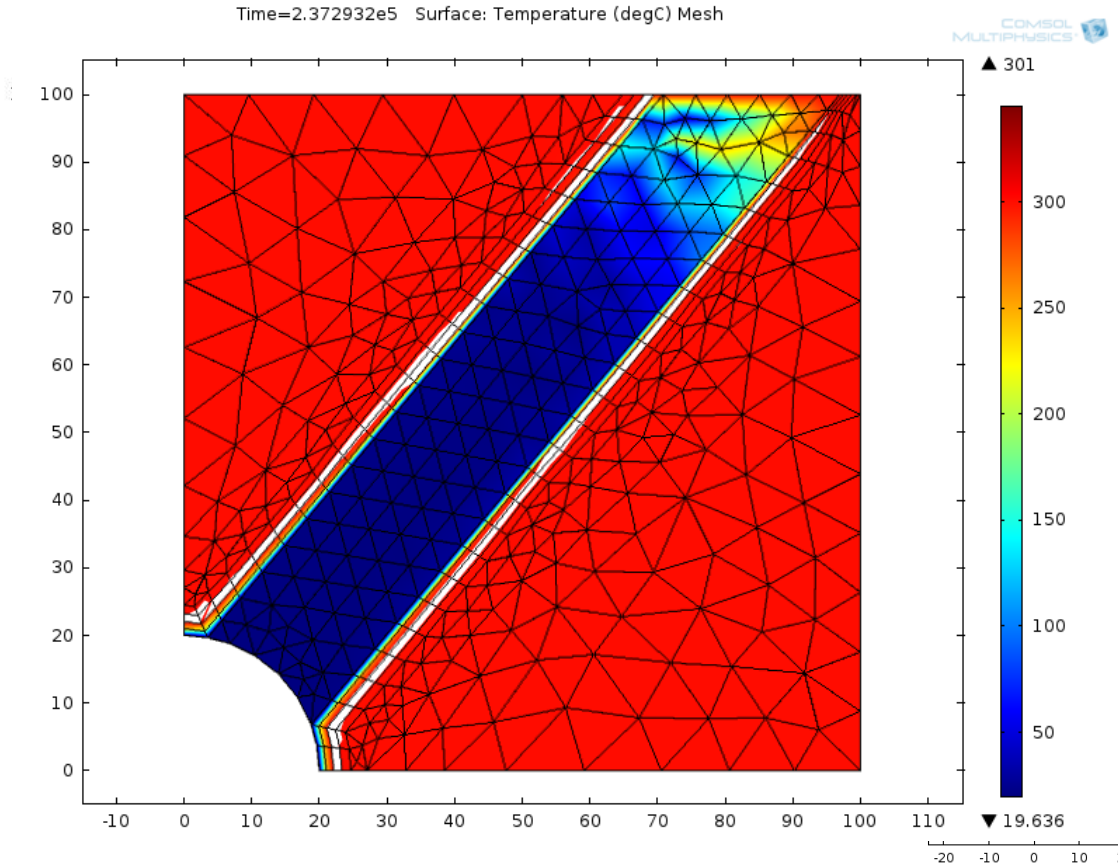
$$u = -\frac{\kappa}{\mu} \nabla pf$$

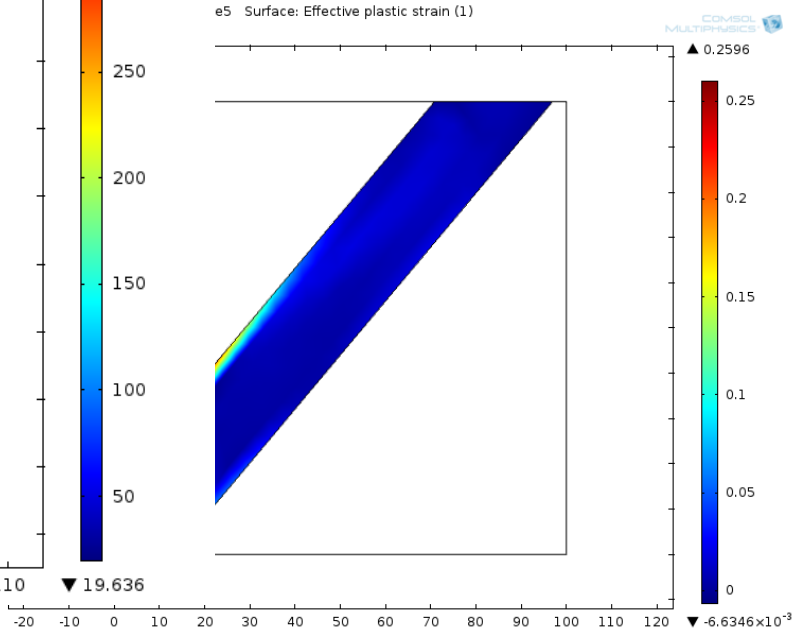
$$S = \epsilon_p \chi_f + \frac{(\alpha_B - \epsilon_p)(1 - \alpha_B)}{K}$$

storage has to be calulated

Model Inputs

Sensitivity to meshing





Temperature case 1 after 55 hours of injection.

- T_{matrix} = 300°C
- T_{fluid} = 20°C

Effective plastic strain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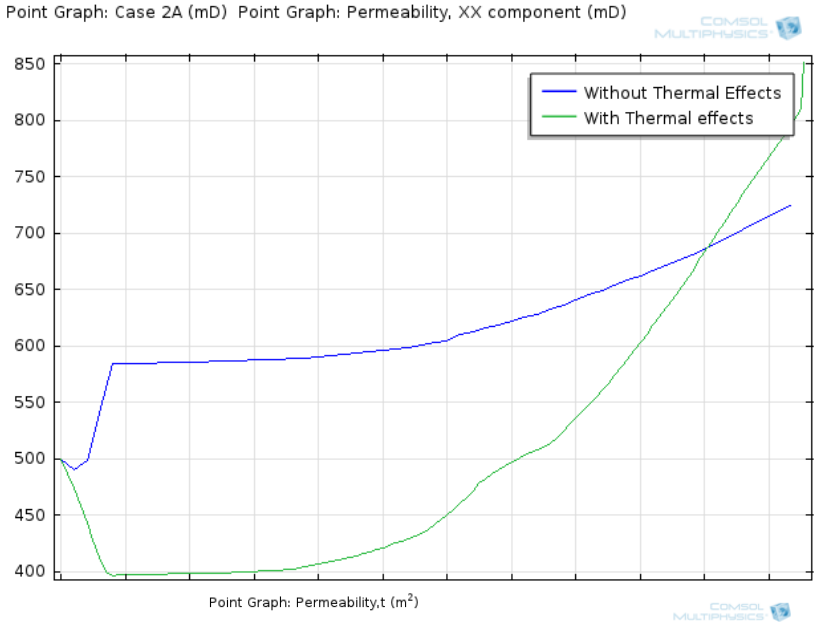
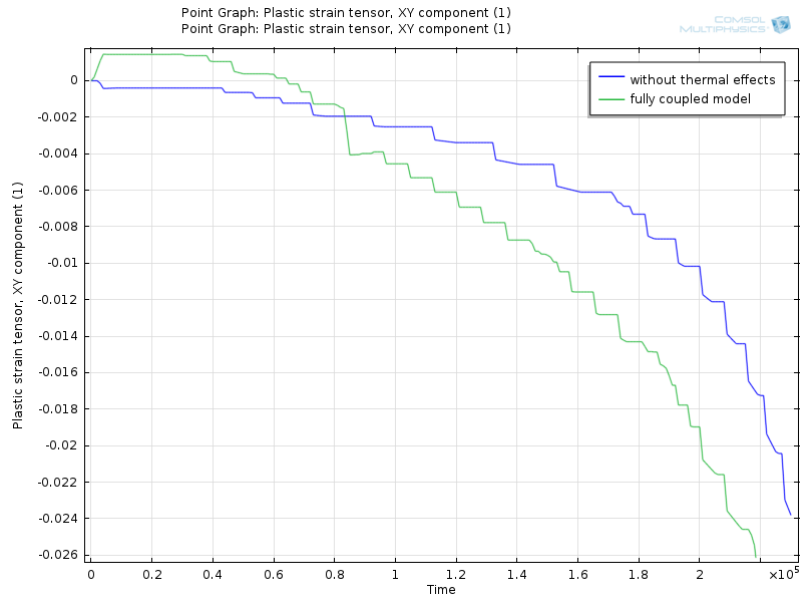
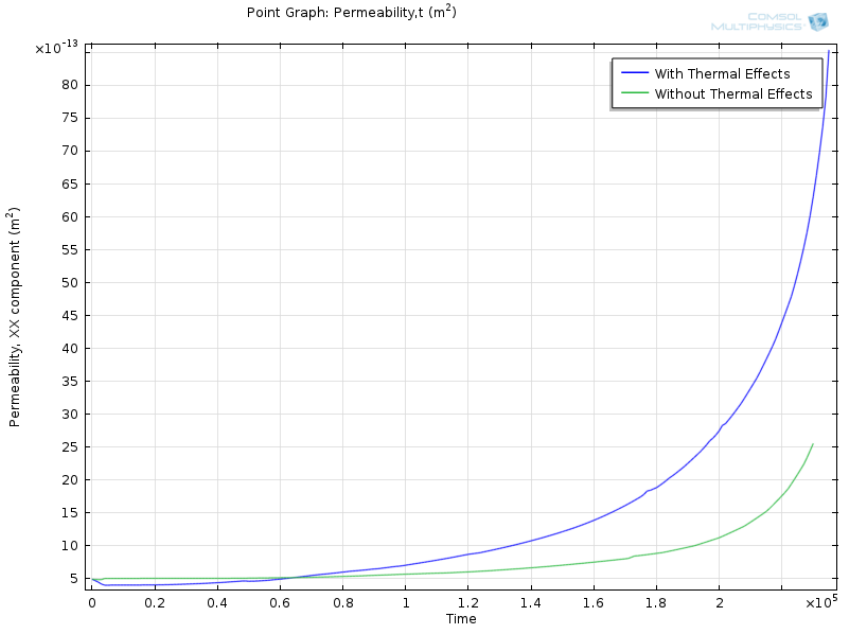
Thermal Effects

Neglecting thermal effects is not justified

- different behaviour of permeability
- shear strain changes sign

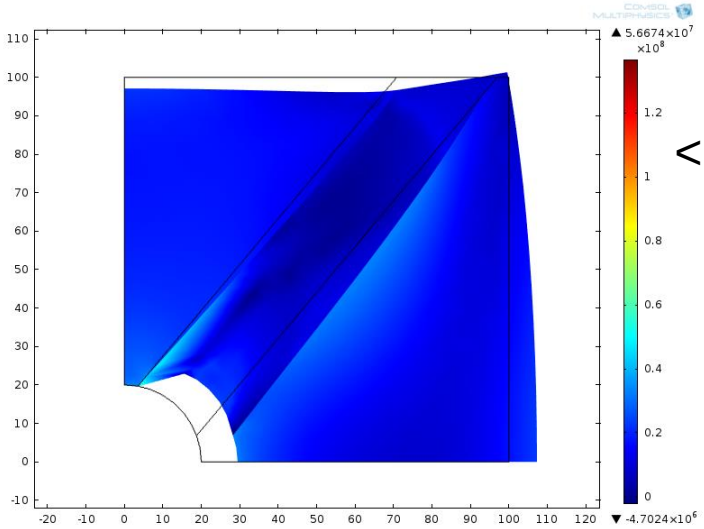






Thermal Effects

Von Mises stress



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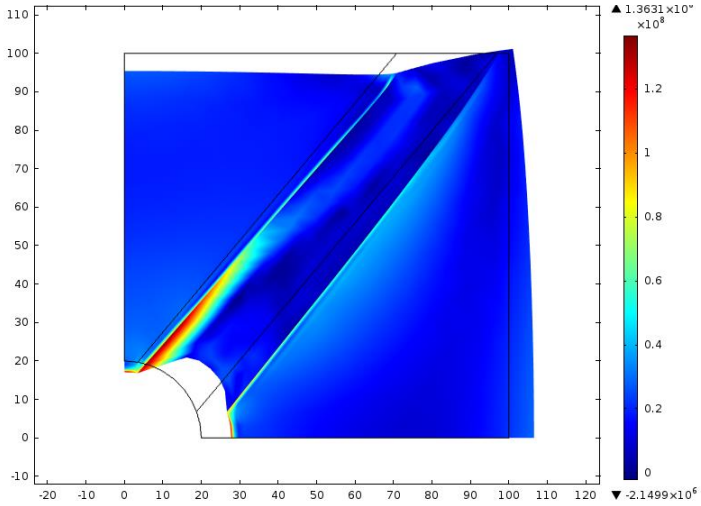

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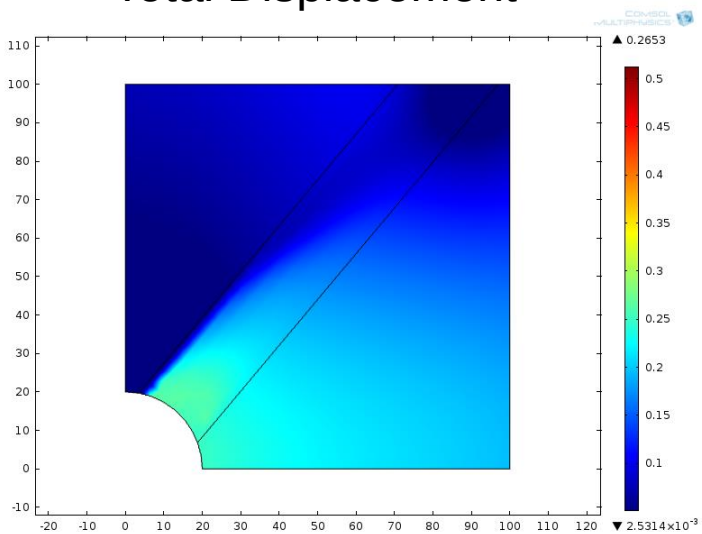
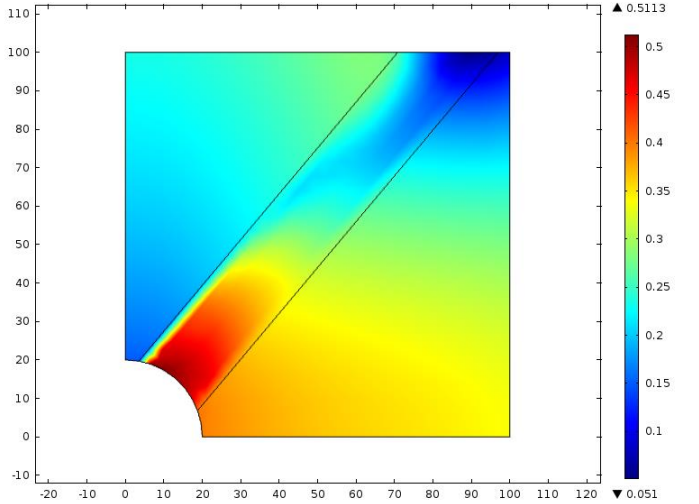
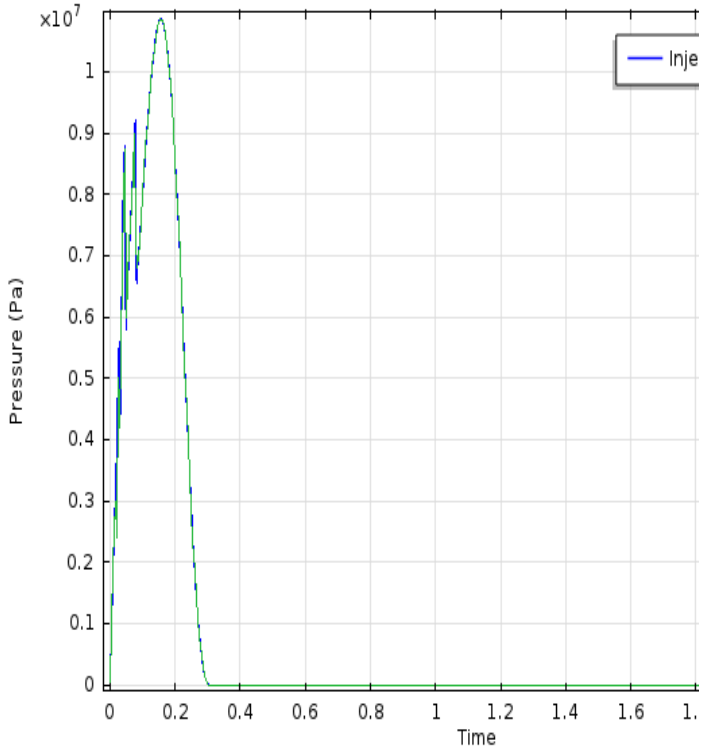
Total Displacement

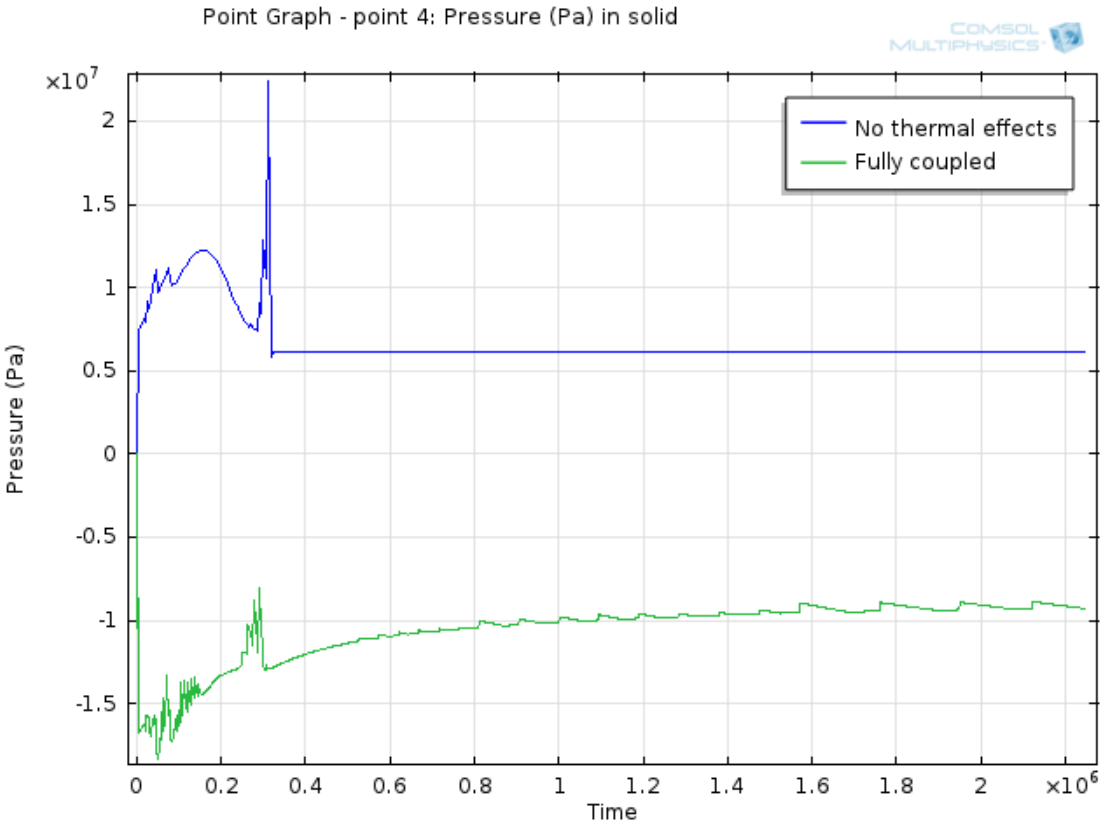




Effect of stopping injection

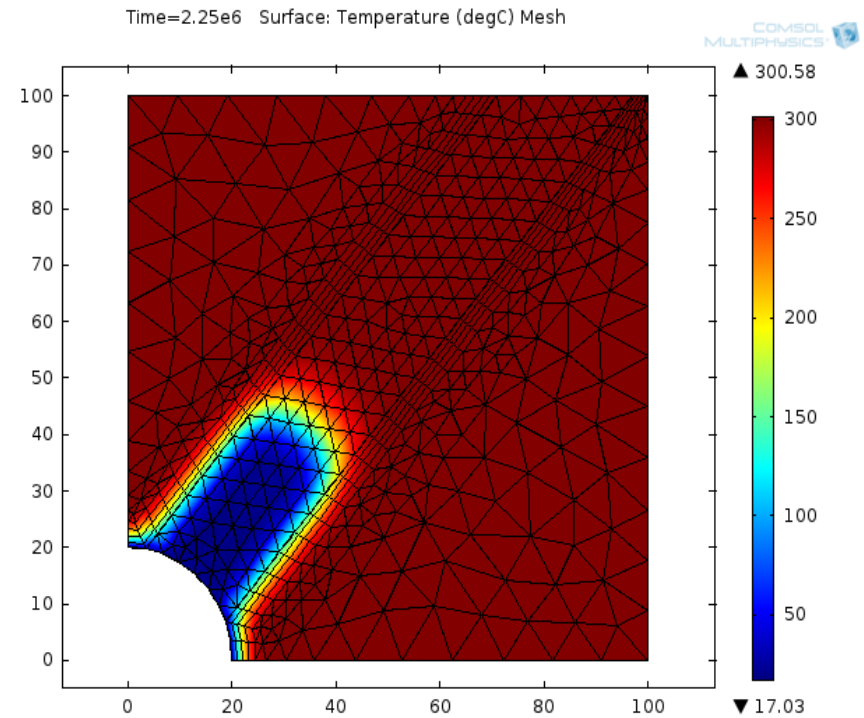
- Well pressure (actual injection scheme)
- Pressure in solid
  - Cooling reduces pressure
  - Continued effect





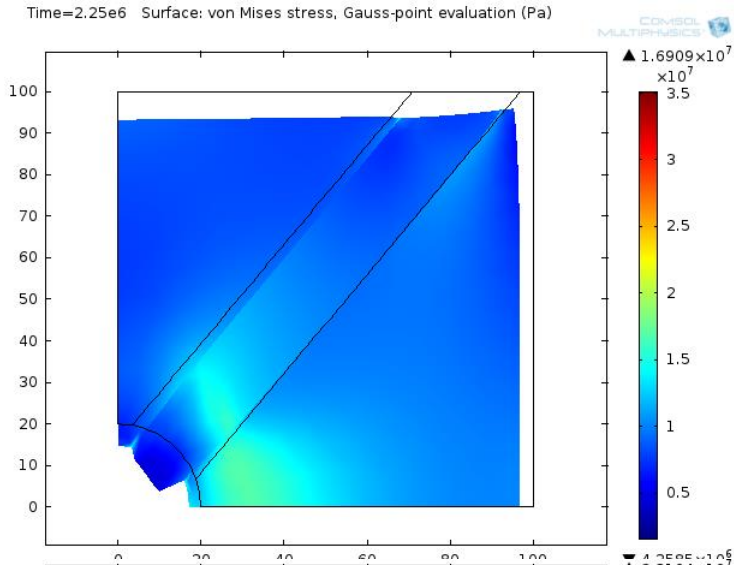
Temperature effects after shutdown

- Temperature

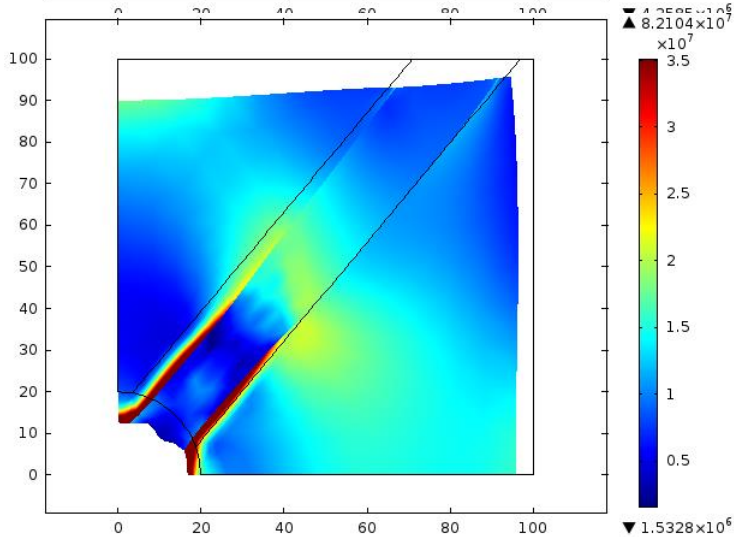


- Von Mises stress

- No TE effects

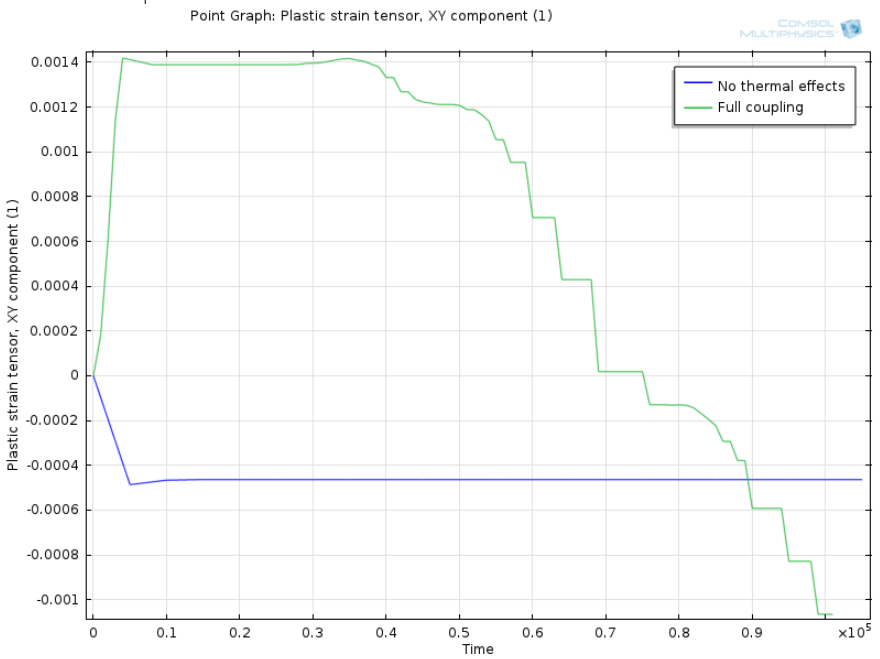


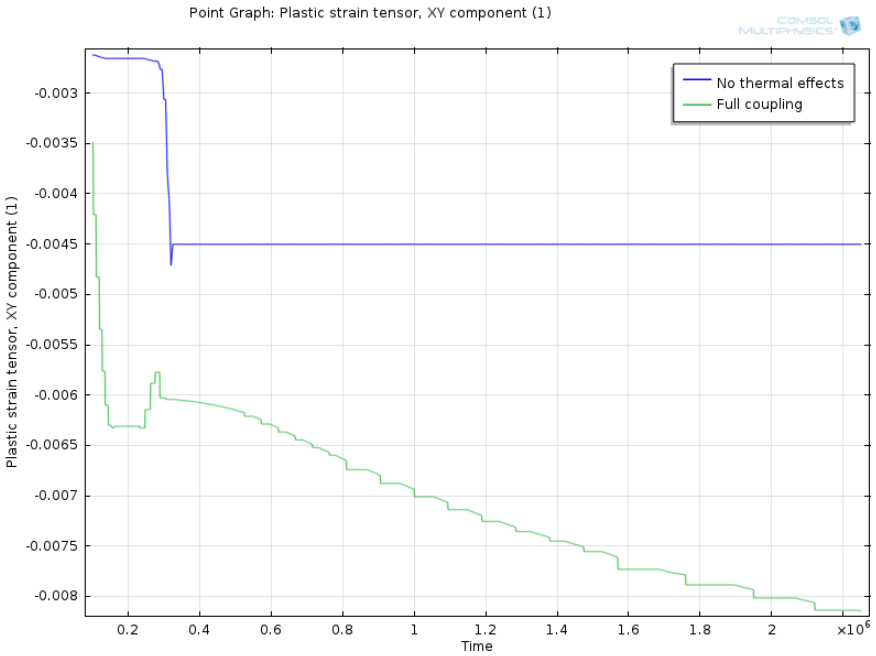
- With TE effects



Plastic Strain:

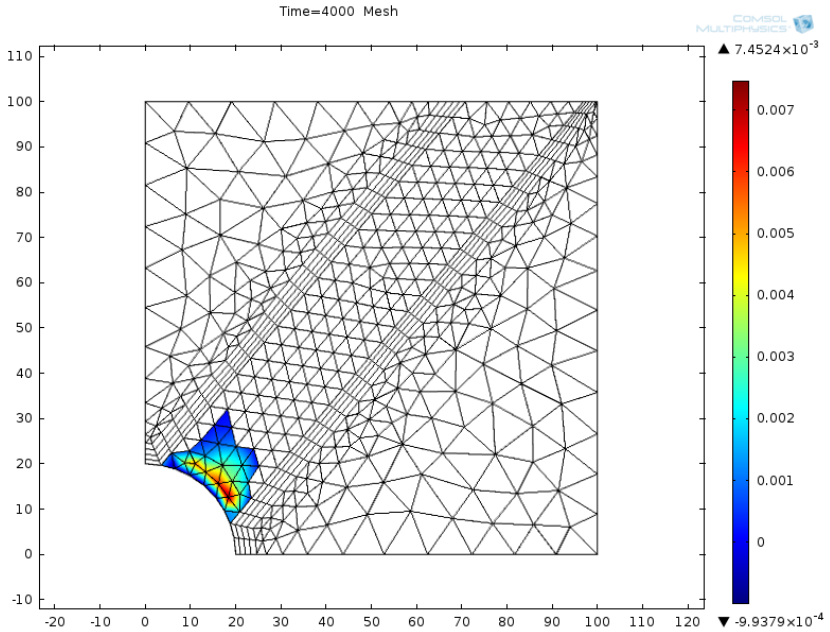
Evolution during injection time and after shutin





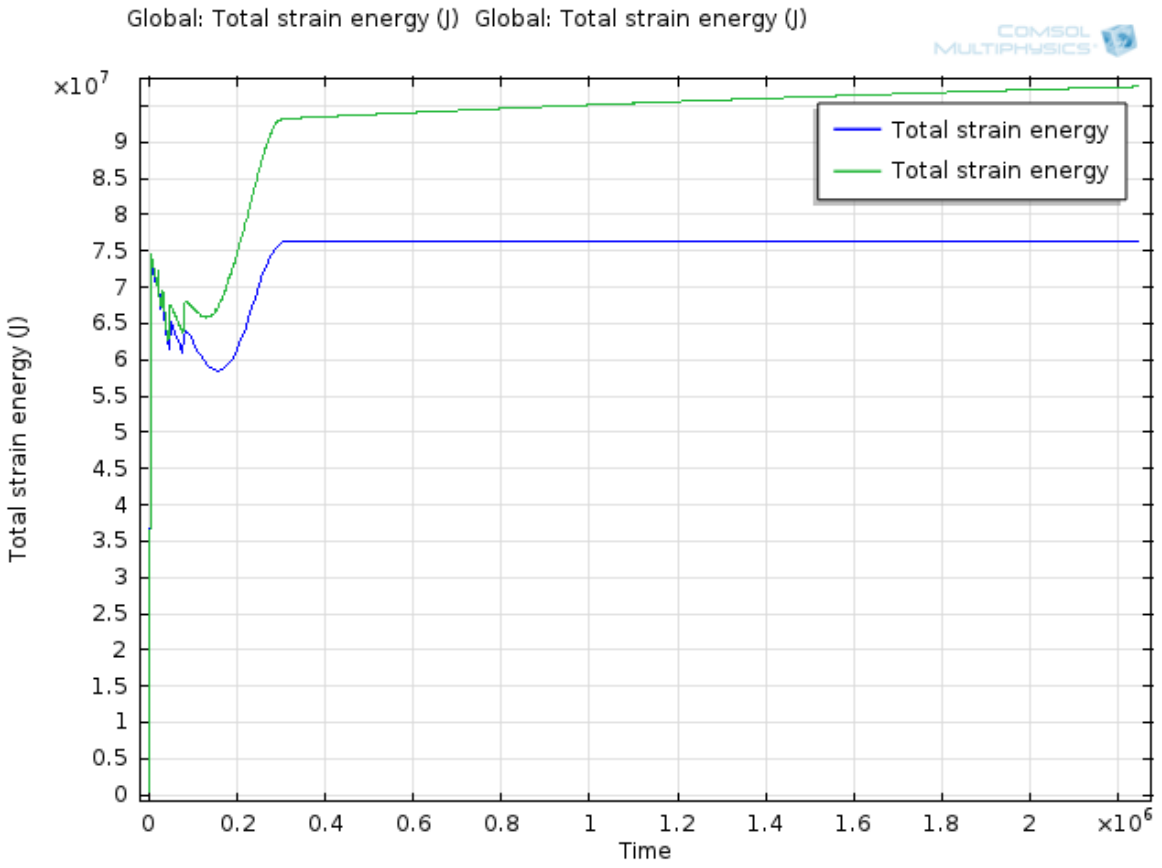
Induced seismicity

- M = G d A
- Shear displacement = shear strain * H
- Failing area: 3rd dimension is missing – estimation of H=10 or 20m

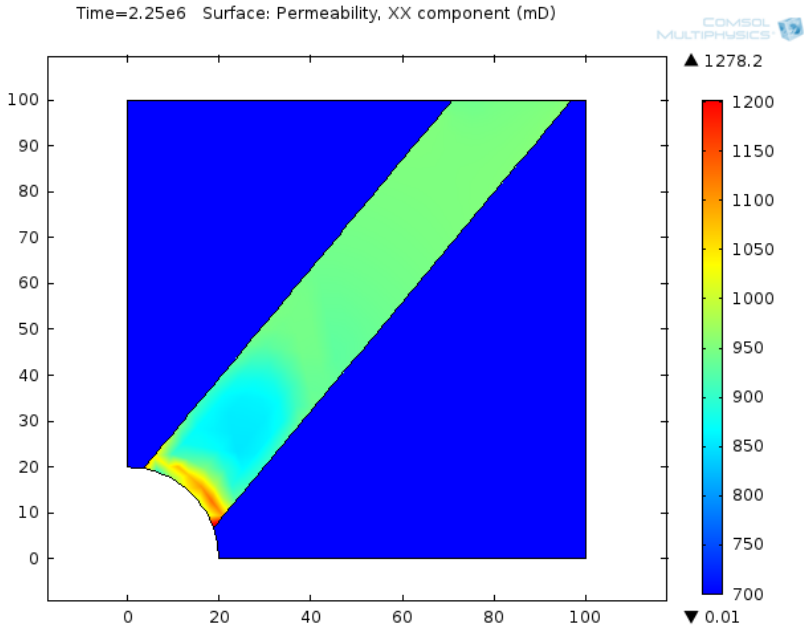


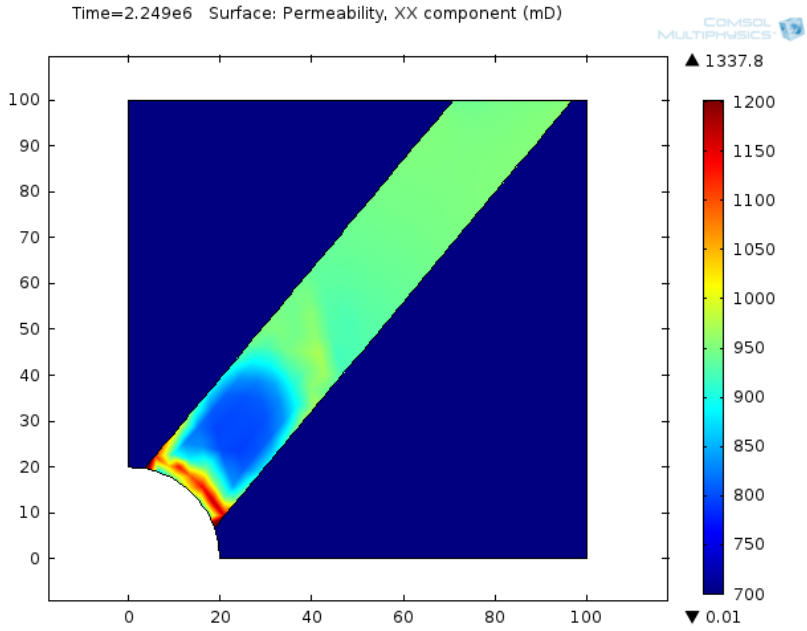
Effective plastic strain > 0
Failing patch
Shear strain

Strain Energy



Injection of warmer water vs. injection of cold water – comparison with a field case (Iceland)





Injectivity_cold/ Injectivity_warm=1.45 Modeling result

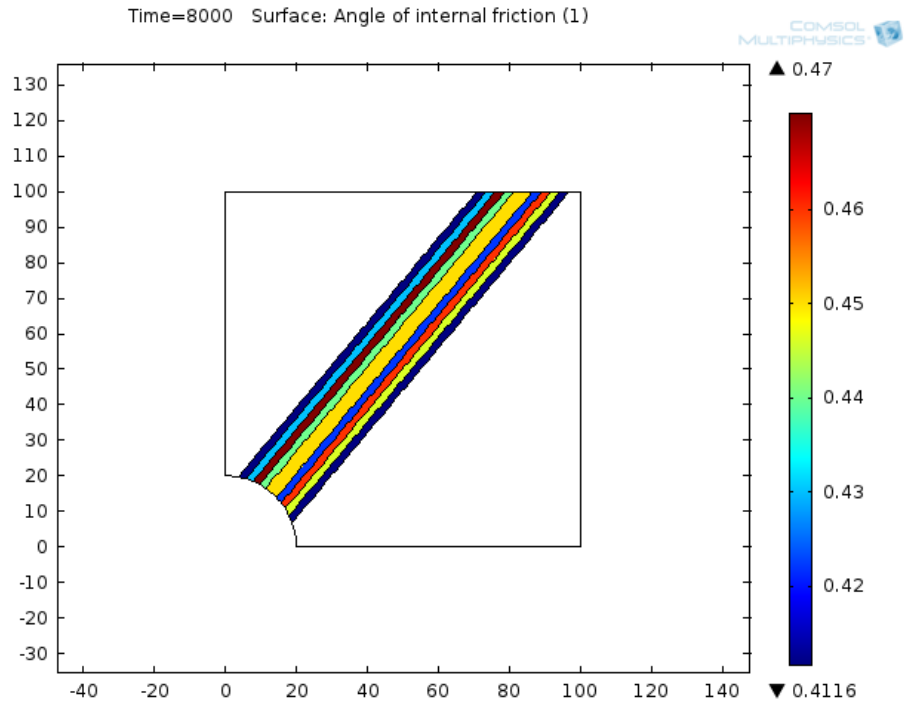
Injectivity_cold/ Injectivity_warm=5.85 at well NH-09

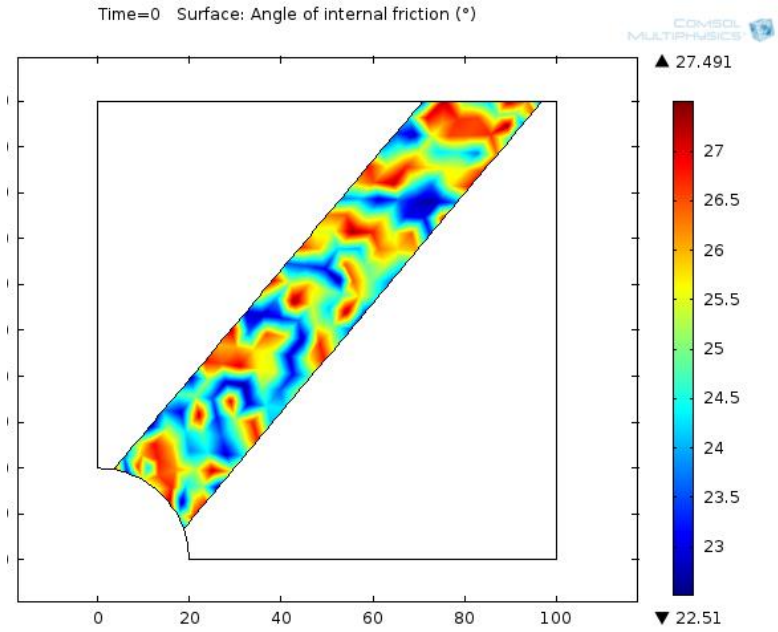
Injectivity_cold/ Injectivity_warm=3.3 at well NH-12

In Iceland geothermal field

Uncertain parameter: friction angle in Mohr-Coulomb shear failure

Uniform vs. 9 domains vs. random






Conclusion & Discussion

- COMSOL is suitable as tool for sensitivity analysis – strong in coupled modelling; issues remain with stability for 3D models
- Thermal stresses can instantly change permeability and plastic strain, changing injectivity and induced seismicity potential
- Qualitative but not yet quantitative agreement of temperature effect on injectivity for Iceland geothermal field
- Identified factors relevant for the induced seismicity – calibration still required


Future Work

- Shear weakening
- Healing
- Heterogeneity
- Influence of geometry on injectivity and seismicity
- Probabilistic modelling with a proxy model