THMS Simulation of Enhanced Geothermal System via an Adaptive Hybrid Numerical Method

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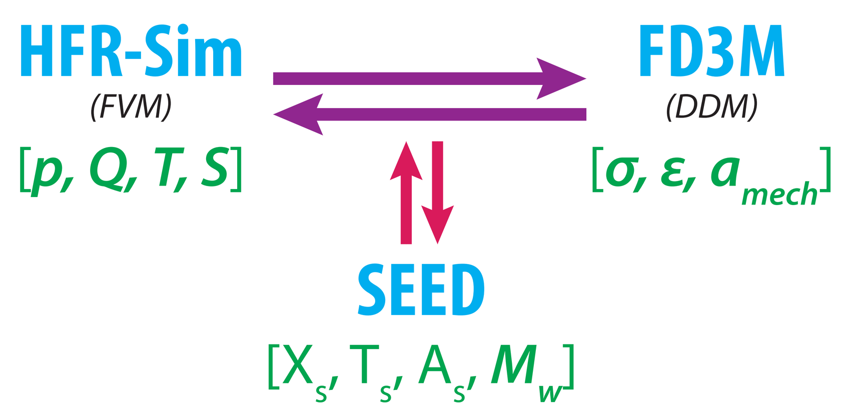
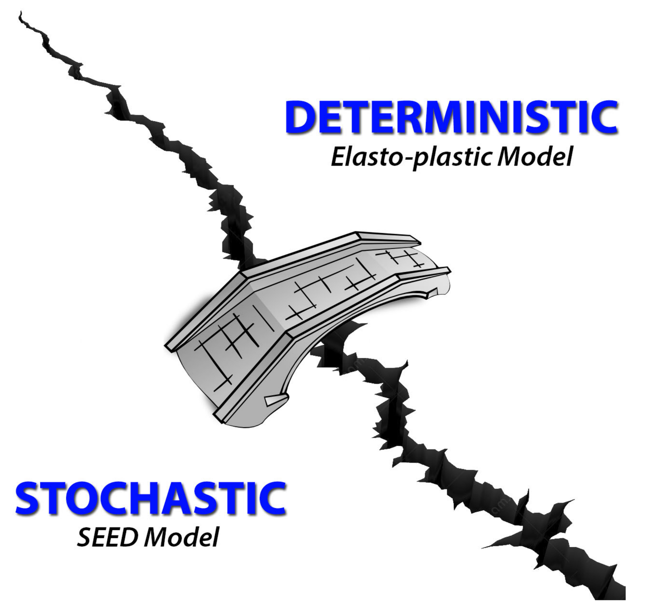
Research Goals

- Moving toward an approach which could clarify the physics of *Thermo-Hydro-Mechanic-Seismicity* (THMS) processes in fractured crystalline for the enhanced geothermal system (EGS) application
- Iterative coupling of *finite volume method* (pressure and temperature) with *displacement discontinuity method* (stress and displacement)
- Bridge between *stochastic* and *deterministic* seismic models via combination of *elasto-plastic* and *seed* models

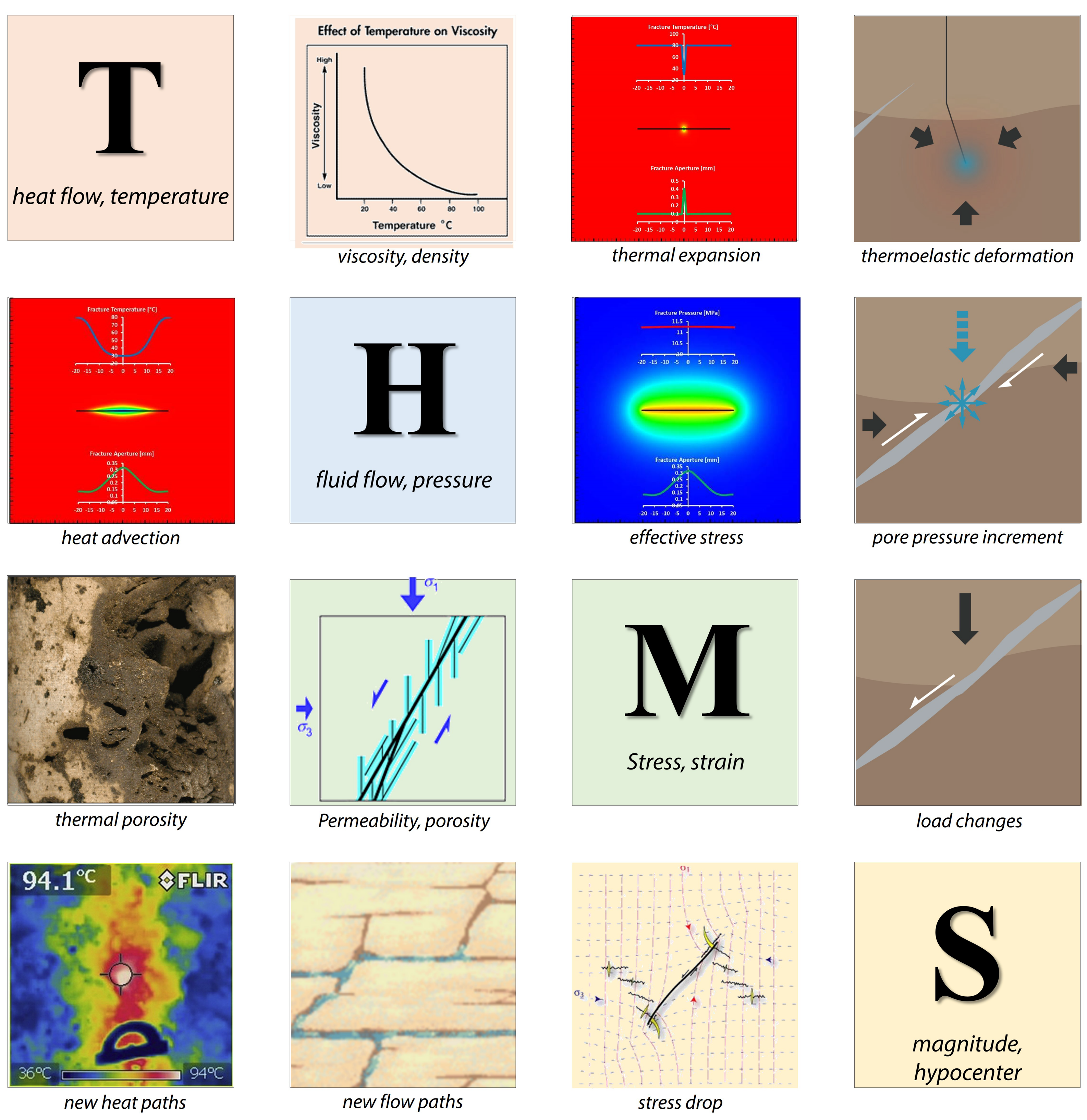




Thermo-Hydro-Mechanic-Seismicity Coupling (THMS)

The word coupling refers to combined analysis of concomitant physical processes under different levels of interaction, i.e. *explicit*, *iterative* and *fully* coupled. In this study, an iterative coupling approach is adopted between two existing codes, i.e. HFR-Sim (FVM) for pressure and temperature calculation, and FD3M (DDM) for stress and deformation estimation in fracture and matrix medium.

Approach	Advantage	Disadvantage
Explicit Coupling	▪ Effective and time-saving for subsidence problems ▪ Flexible and straightforward	▪ One-way coupling for geomechanics ▪ Stability and accuracy
Iterative Coupling	▪ Flexible in the case of numerical methods ▪ It is possible to couple conventional reservoir simulators (e.g. ECLIPSE, TOUGH2, STARS) with geomechanical modules (e.g. FLAC, UDEC, VISAGE) .	▪ Require large number of iterations (1st order convergence) ▪ Relatively small jumps in pore volume can be handled
Full Coupling	▪ The most stable approach ▪ Preserves 2nd order convergence ▪ Reliable and a benchmark for other coupling methods	▪ Difficult to couple existing modules and softwares ▪ Require more code development ▪ Slower than other coupling techniques

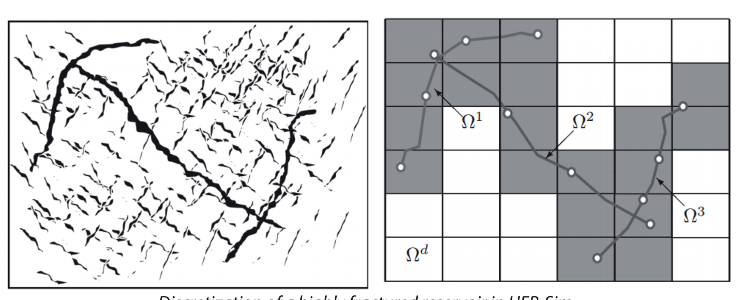


Governing Equations

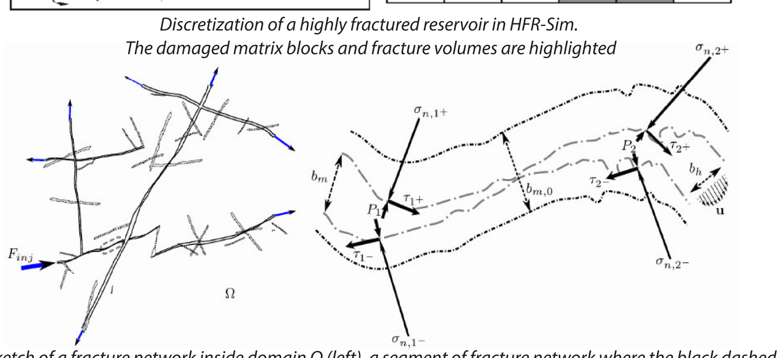
The hybrid model combines a deterministic solution of a two-dimensional stochastic discrete fracture network for flow and heat transport (*Karvounis and Wiemer, 2015*), and stress and displacement (*Jalali, 2013*) with stochastic modeling for location, time source and magniutde of induced seismicity events. The deterministic modeling is performed by HFR-Sim and FD3M, where the stochastic modeling is done with the so-called SEED model (*Goertz-Allmann et al. 2011; Gischig et al., 2014; Catalli et al., 2016; Rinaldi and Nespoli, 2016*).

	Continuum Mechanics	Heat Transfer	Fluid Flow
Governing Equation (Field Eq.)	Conservation of Momentum $div\boldsymbol{\sigma} + \rho\left(\mathbf{f} + \frac{\partial^2 \mathbf{u}}{\partial t^2}\right) = 0$	Conservation of Energy $div\mathbf{q_h} + r = 0$	Conservation of Fluid Mass $div\mathbf{q_f} + r = 0$
Neumann B.C.	Stress Vector B.C. $\mathbf{T}^d = \boldsymbol{\sigma} \cdot \mathbf{n}$	Heat Flux B.C. $q_h = \mathbf{q_h} \cdot \mathbf{n}$	Fluid Flux B.C. $q_f = \mathbf{q_f} \cdot \mathbf{n}$
Constitutive Law	Hooke's Law $\boldsymbol{\sigma} = \mathbf{C} : {}^s\nabla \mathbf{u}$	Fourier's Law $\mathbf{q_h} = -K_T \nabla T$	Darcy's Law $\mathbf{q_f} = -K_P \nabla p$

HFR-Sim



Discretization of a highly fractured reservoir in HFR-Sim. The damaged matrix blocks and fracture volumes are highlighted



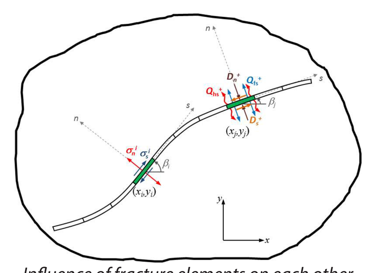
2D sketch of a fracture network inside domain Ω (left), a segment of fracture network where the black dashed line is mechanical aperture and grey dashed line is hydraulic aperture.

FD3M

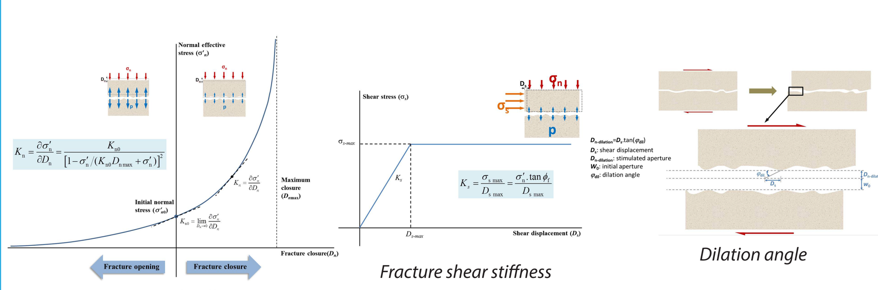
Different fracture states with their specifications used in FD3M

Fracture Status	Contact Porosity*	Stress Condition	Fracture Pressure	Fracture Properties
closed fracture	$n_c = 0$	$\sigma_n' < 0$	$p = 0$	$K_n \to \infty$, $\psi = 0$
compliant fracture	$0 < n_c < 1$	$\sigma_n' < 0$ $\lvert\sigma_s\rvert < c + \lvert\sigma_n'\rvert \tan\phi$	$0 < p < \sigma_n$	$K_n = \partial\sigma_n/\partial u_n$**, $\psi = 0$
Mohr – Coulomb Criteria ($\lvert\sigma_s\rvert = c + \lvert\sigma_n'\rvert \tan\phi$)				
sliding fracture	$0 < n_c < 1$	$\sigma_n' < 0$ $\lvert\sigma_s\rvert > c + \lvert\sigma_n'\rvert \tan\phi$	$0 < p < \sigma_n$	$K_n = \partial\sigma_n/\partial u_n$** $K_s = 0$, $\psi \neq 0$
open fracture	$n_c = 1$	$\sigma_n' \geq 0$	$p \geq \sigma_n$	$K_n = \partial\sigma_n/\partial u_n$**, $\psi = 0$

*Contact porosity is defined as the ratio of non-contacting fracture area to nominal area.
**Fracture normal stiffness is updated based on the hyperbolic model.



Influence of fracture elements on each other in a thermo-poroelastic medium



Fracture normal stiffness

Fracture shear stiffness

Dilation angle

[Jalali et al., 2015]

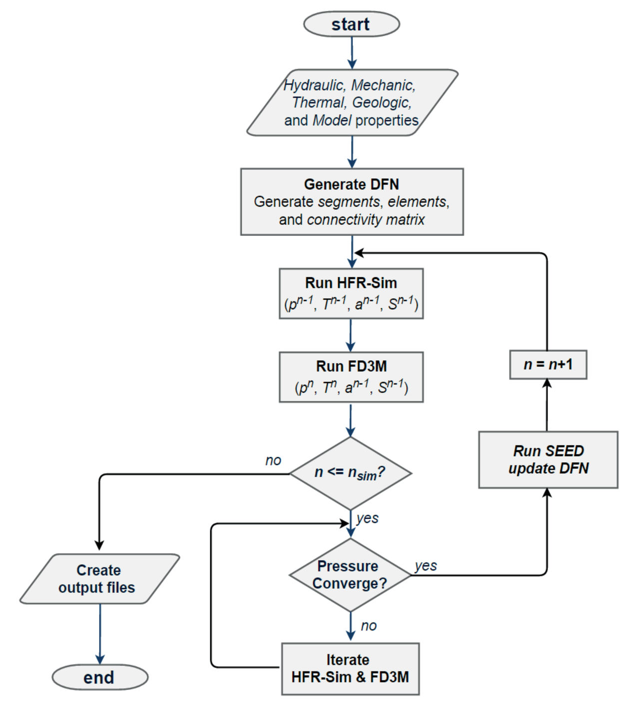
Adaptive Hybrid Numerical Method

In this method, discrete fracture network (DFN) is created stochastically based on the normal distribution of fracture orientations and power law distribution of fracture length. The HFR-Sim and FD3M are then iteratively solved together using fracture pressure, temperature and mechanical aperture as the coupling parameters.

After convergence reached, the seismic characteristics of the model for the current time step are estimated. This estimation consists of two approaches, i.e. deterministic calculation of the seismic moment via calculation of slip area and magnitude for the discrete fractures and semi-stochastic estimation of the seismic moment for the matrix, especially damaged zone around the fractures using SEED model.

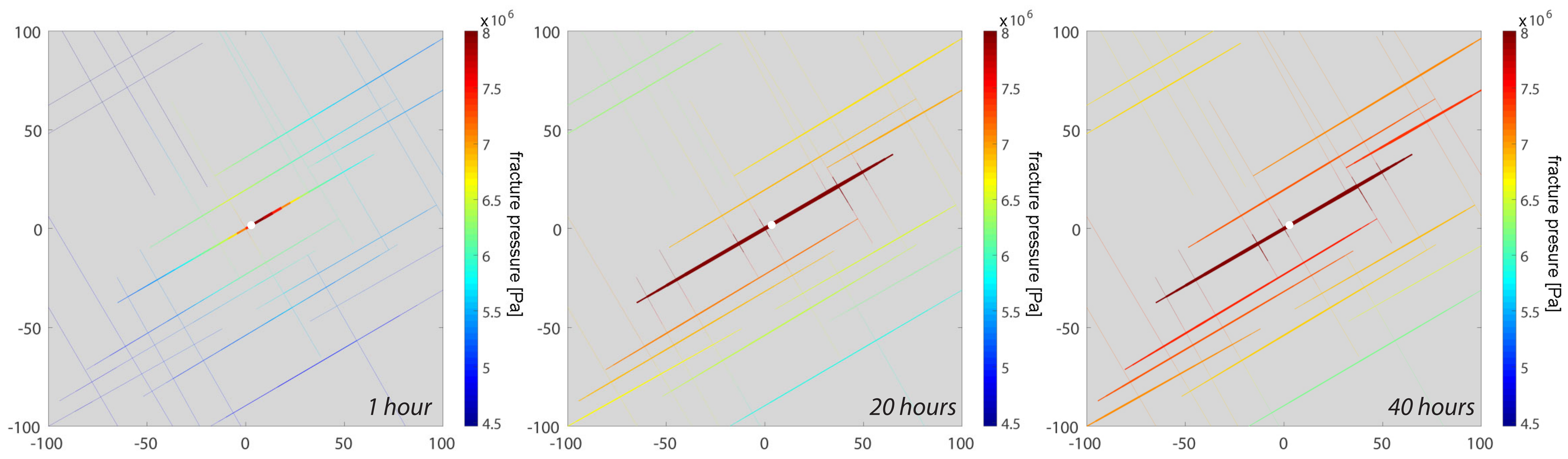
The DFN is updated then with the new triggered fractures and the above procedure is repeated for the next time step.

An adaptive time marching between flow and mechanical simulators is used in order to enhance computational time in comparison with full coupled models.

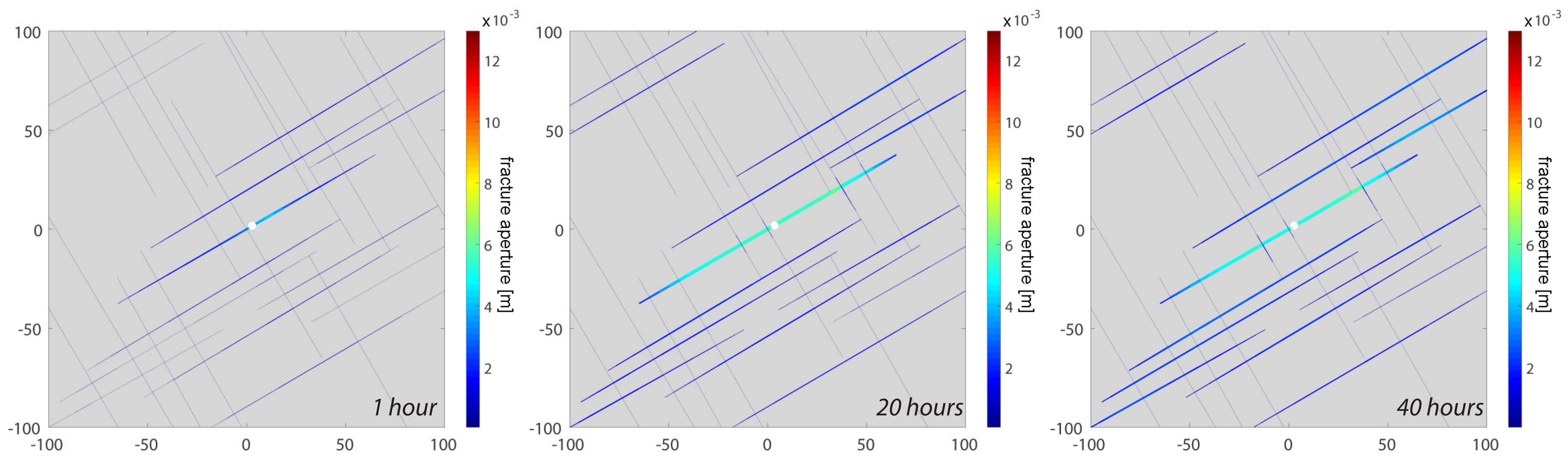


Hydraulic tomography results conducted between two injection boreholes

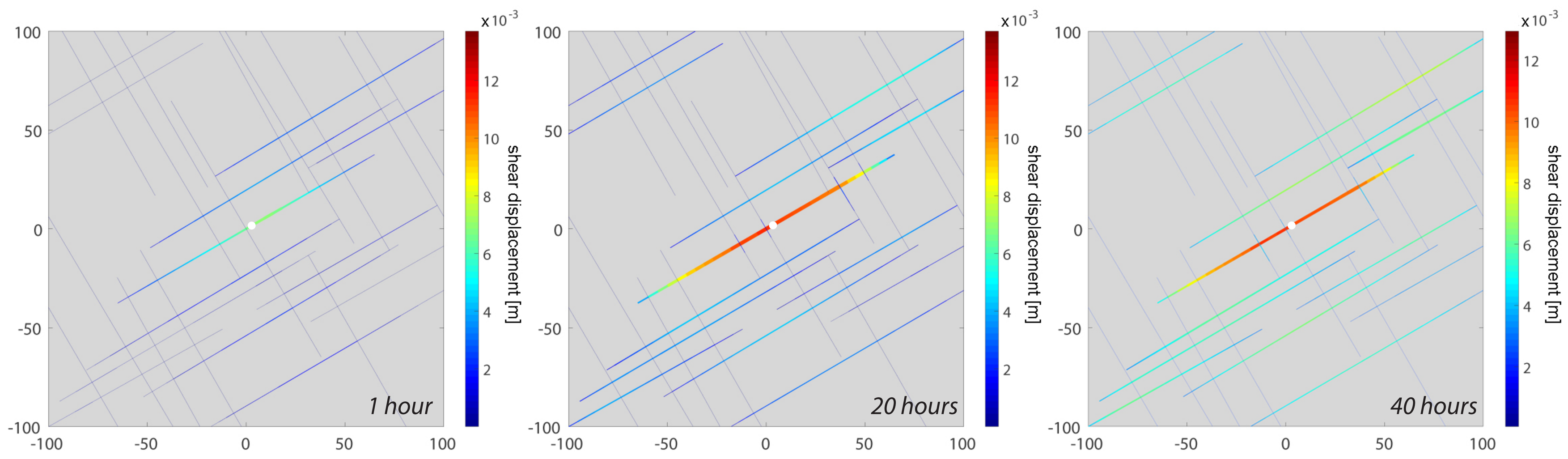
Exemplary Simulation Results



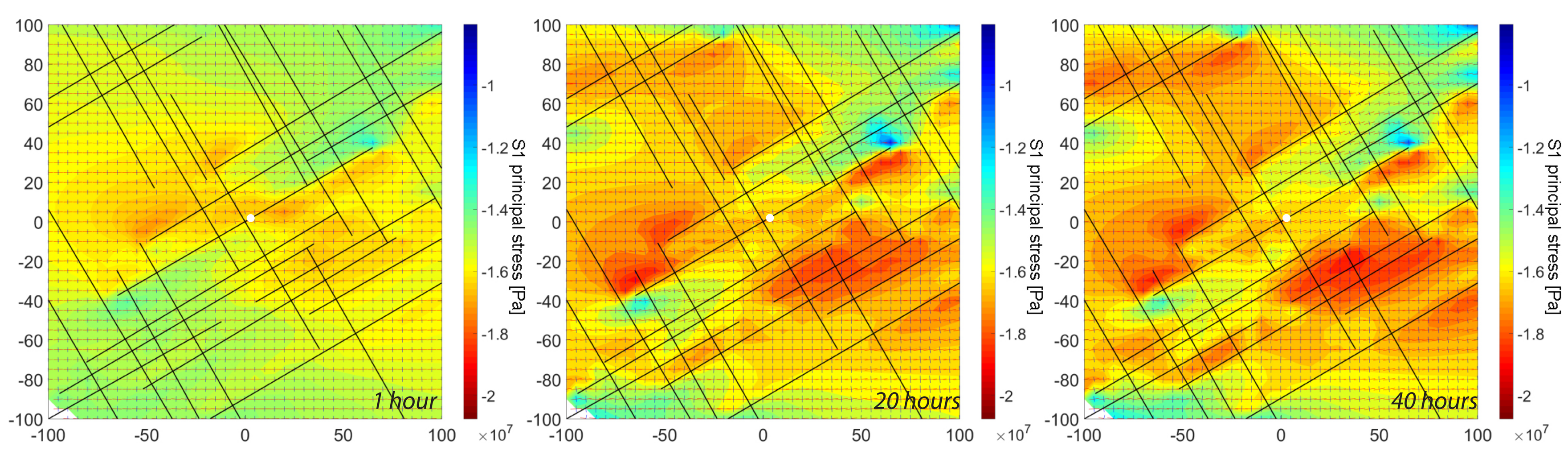
Fracture pressure propagation @ 1, 20, and 40 hours



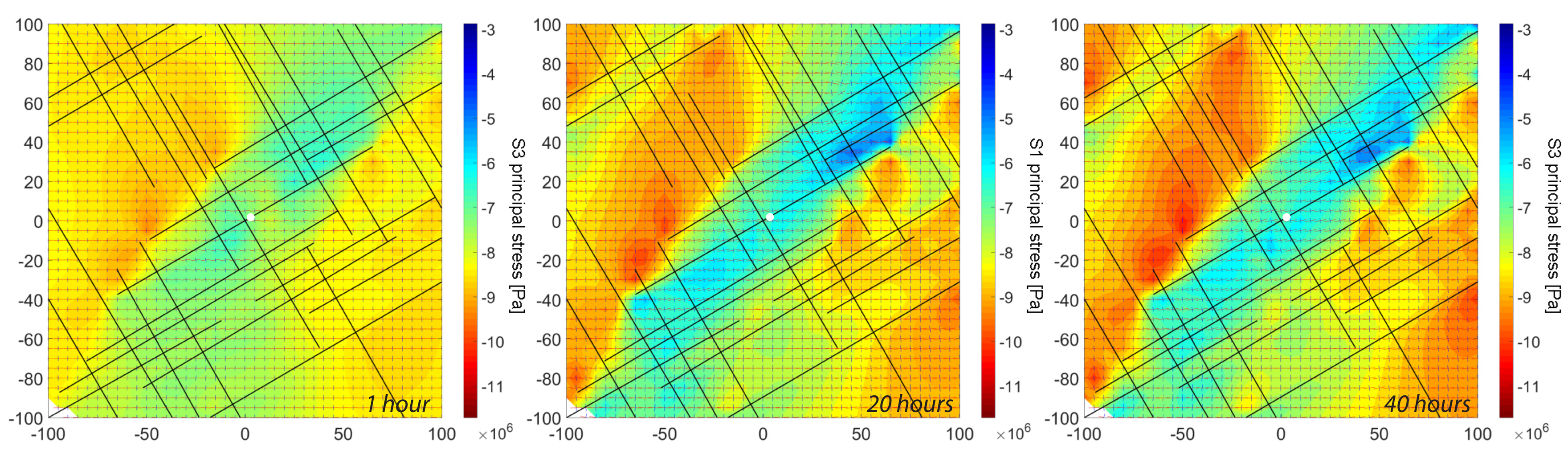
Fracture normal displacement (aperture) @ 1, 20, and 40 hours



Fracture shear displacement @ 1, 20, and 40 hours



Maximum principal stress and stress rotation @ 1, 20, and 40 hours



Minimum principal stress and stress rotation @ 1, 20, and 40 hours

Two fracture sets with the orientation of 30 and 120 degrees (sets #1 and #2) with a power law length distribution are considered under a constant pressure injection (p_{inj} = 8 MPa) in the middle of a 200 by 200 m^2 model. Anisotropic in-situ stress (σ_{xx}=15 MPa, σ_{yy}=8 MPa) is applied. The dominant flow paths are along the set #1 fractures which were undergone shear failure and presents more than two orders of magnitude permeability enhancement.

References

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