Fracture Characterization in Enhanced Geothermal Systems by Wellbore and Reservoir Analysis

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Reservoir Characterization

Project Overview

EGS is all about the fractures:

- **Where are they?**
- **What are their properties?**
- **How will they perform during energy extraction?**

1. **In-situ Multifunctional Nanosensors for Fractured Reservoir Characterization.**

2. **Characterization of Fracture Properties using Production Data.**

3. **Fracture Characterization by Resistivity Tomography.**

1. Nanosensors - Objectives

- Investigate a new tool (nanosensors) to measure:
  - Pressure and temperature anywhere in the formation.
  - Fracture aperture.
- Develop a method to estimate reservoir parameters and characterize fracture networks based on these measurements.

Study Phases

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NOW…

- Initial testing: *Investigate the feasibility of transporting various nanomaterials through porous media (rocks, long flow path).*

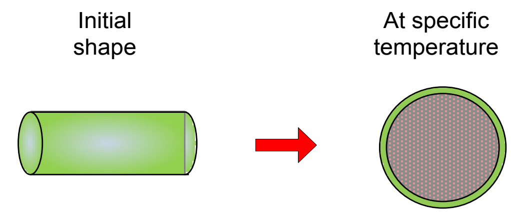
NEXT STEPS…

- Develop (fabricate) functional pressure- and temperature-sensitive nanoparticles.

Temperature-Sensitive Nanotracers

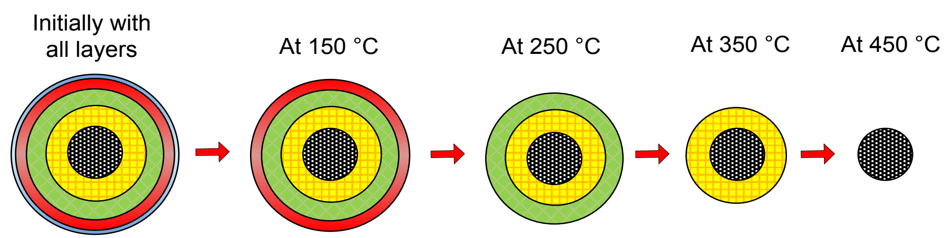
Now investigating various shapes/materials.

A. Cylindrical to spherical shape transforming nanoparticles.



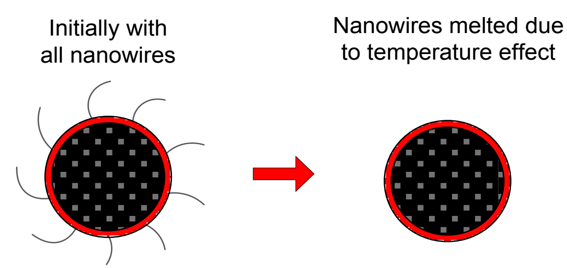
(A) Cylindrical to spherical shape transformation due to temperature change

B. Multilayer different coating thickness nanoparticles.



(B) Multi-layer nanoparticle with different coating thickness

C. Inert nanosphere with temperature sensitive nanowires.



(C) Spherical nanoparticle with nanowires attached to its outer surface

Preliminary Testing

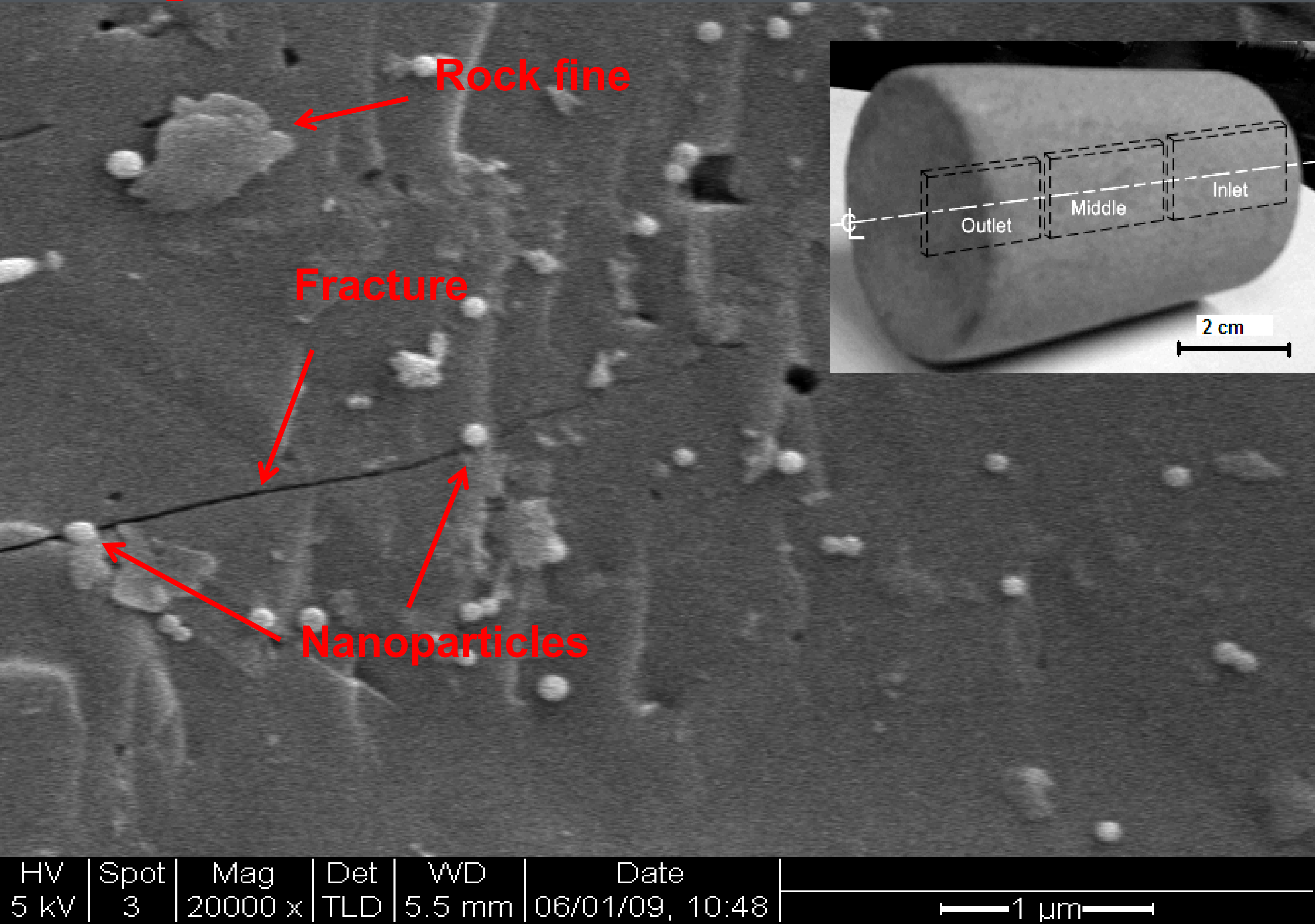
Can we pass solid particles through the pore spaces within a reservoir? What shape/material?

Spherical SiO_2
↓
Berea sandstone
↓
10 m sand-packed slim tube

Nonspherical silver nanowires
↓
Berea sandstone

Nonspherical Hematite nanorice
↓
Berea sandstone
↓
glass beads

SiO_2 nanoparticles within pore spaces – Berea-I



Berea - SiO_2 Milestone

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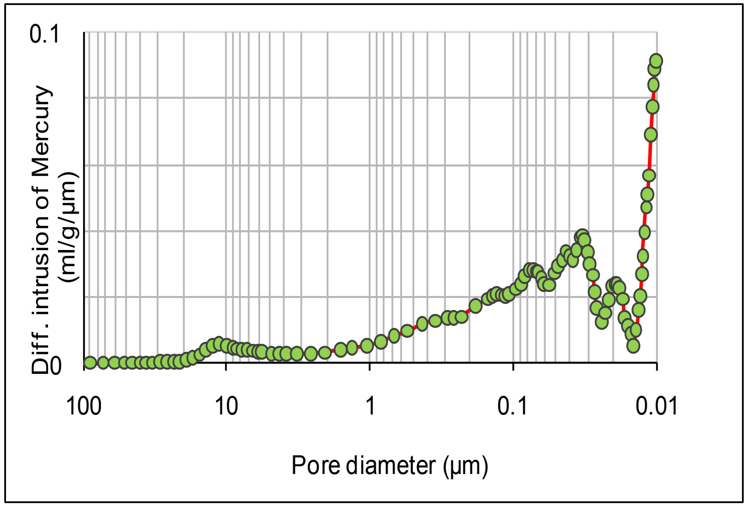
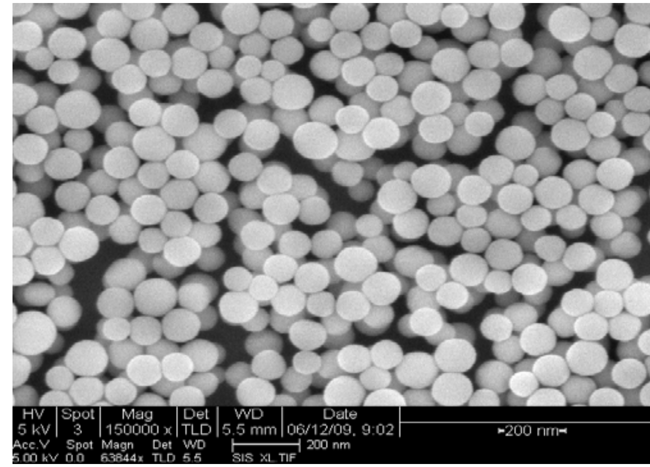
Pore size Distribution

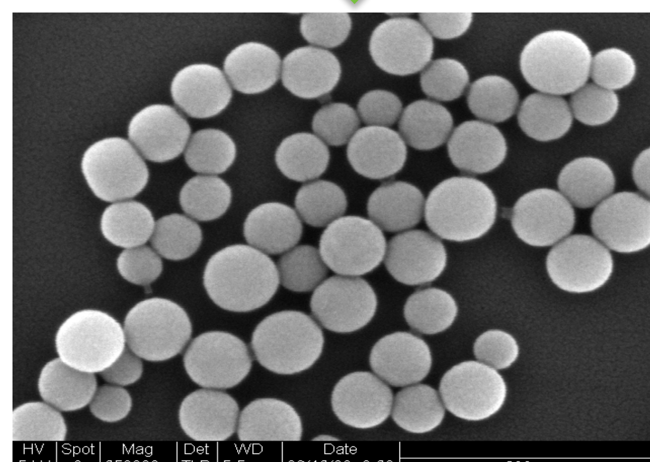


Particle size determination

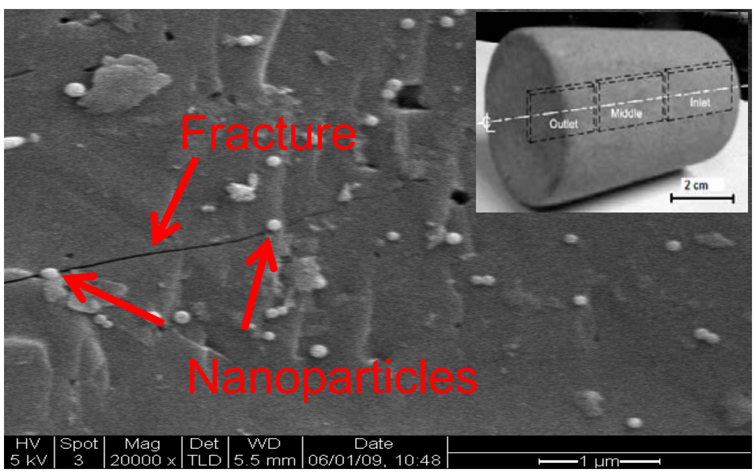
Influent



Effluent



Within pore spaces



***Scanning Electron Microscopy imaging SEM**

Berea - SiO_2 Milestone

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ABC News, June 2009

http://abclocal.go.com/kgo/video?id=6889459

Berea - SiO_2 Milestone

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Slim Tube - SiO_2 Milestone

Specific objective

- To study the transport and recovery of injected SiO_2 nanoparticles through a longer flow path.
- Imitates near-field interwell distance as in the conventional interwell tracer test.

Main result

- Nanoparticles were recovered.

Slim Tube - SiO_2 Milestone

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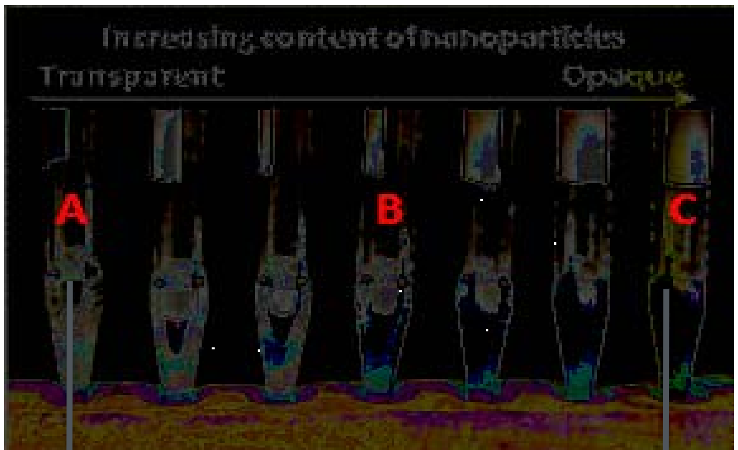
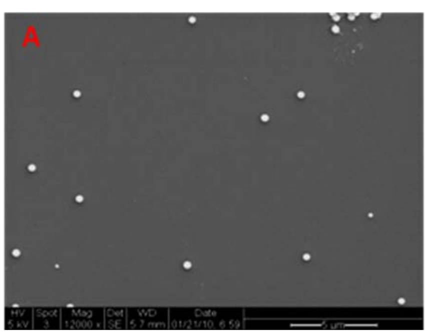
Investigate recovery through longer flow path (near-field interwell conditions)

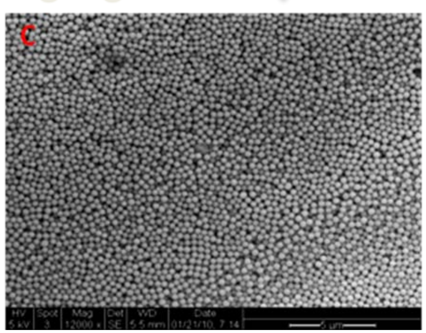
Effluent samples

Visual inspection



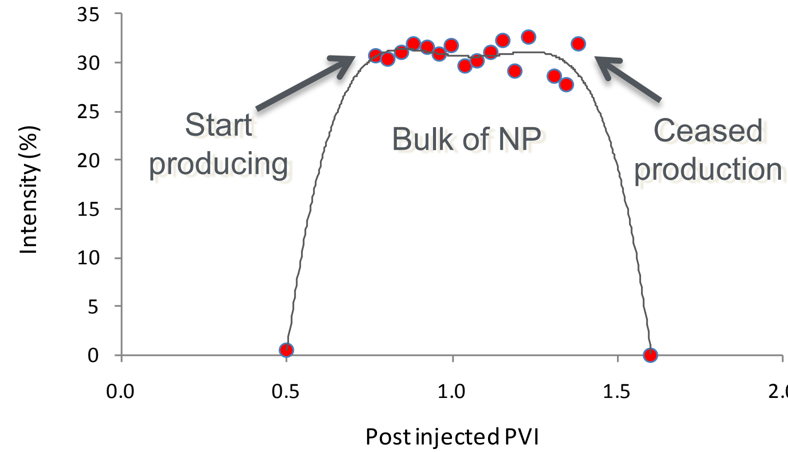
SEM imaging





Scale: 5 µm at 12,000x

Dynamic light scattering

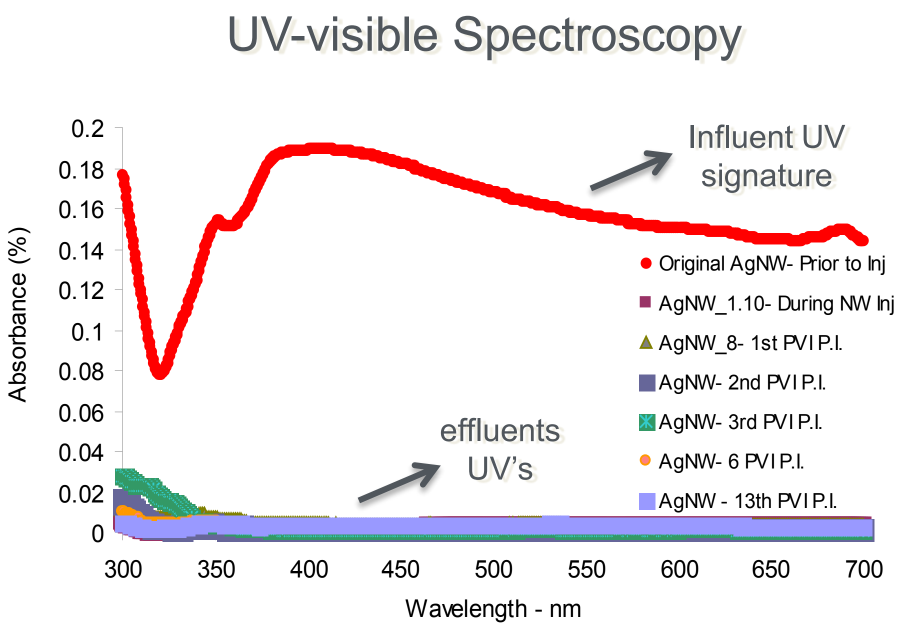


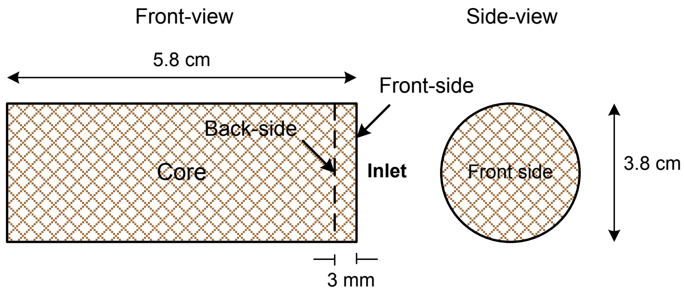
Bulk of Nanoparticle started and ceased production at half and 1.5 PVI, respectively.

Confirmed by SEM

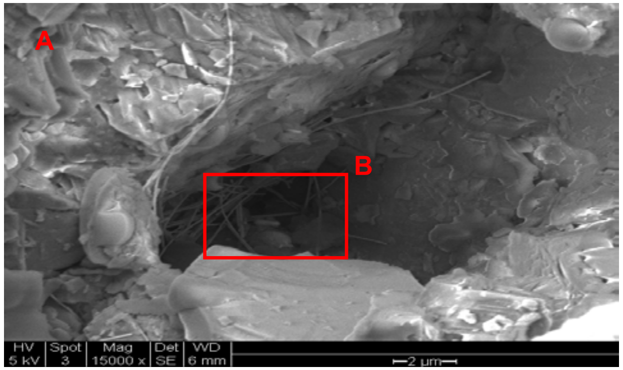
Berea - Silver Nanowires

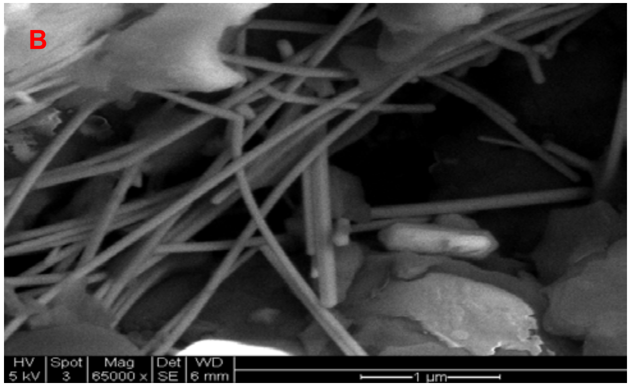
Investigate recovery of wire-like nanoparticles





SEM imaging of front face

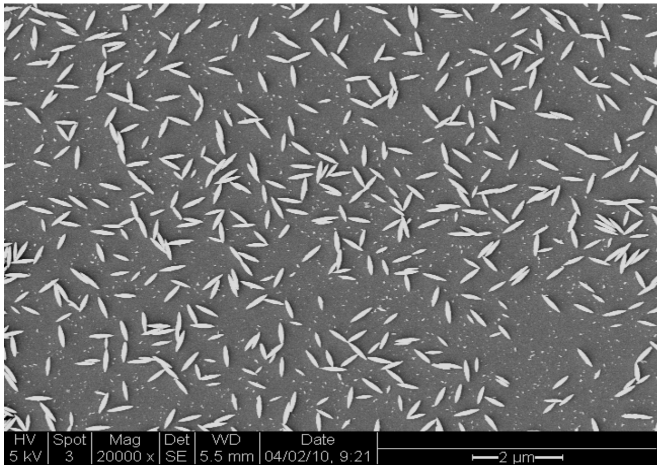




Note: The red curve is the right optical signature of silver nanowires. Effluent samples show pure water behaviour.

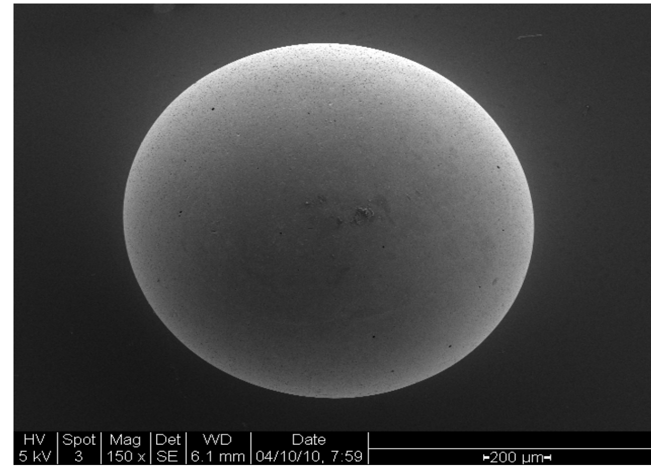
Glass Beads - Hematite

Hematite (nanorice) Influent

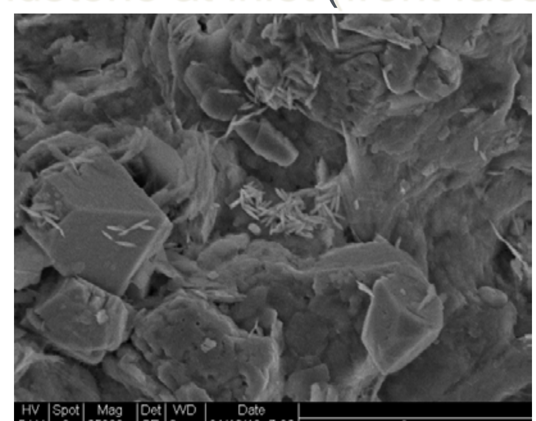


Injection into glass beads

A glass bead at the inlet side

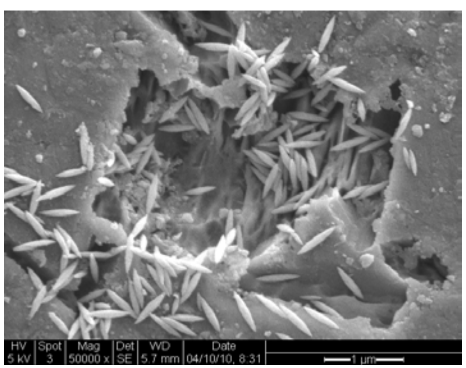


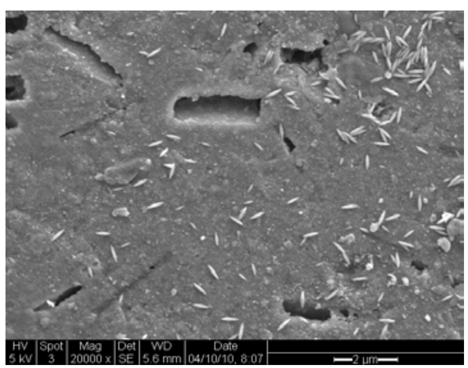
Sandstone at inlet (front face)



Is it core related issue (clay, etc…)?

On the surface of glass bead





Surface Interactions

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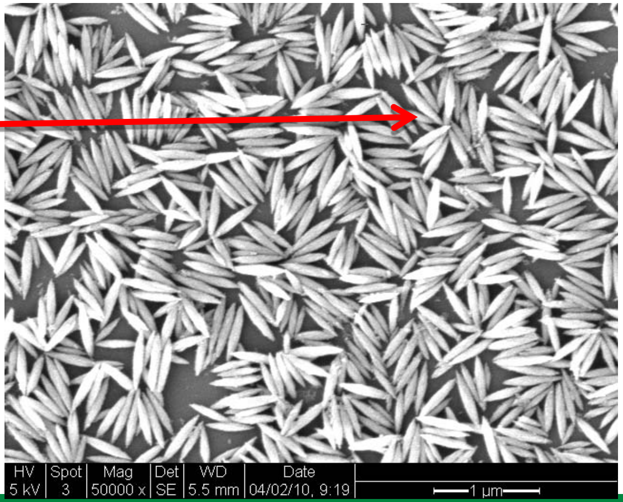
- Hypothesis
  - Transport of nanoparticles (especially nonspherical) is limited by interactions that reduce surface energy by effectively reducing surface area
    - Aggregation of particles, which leads to bridging of pores
    - "Sticking" to pore walls
  - Nonspherical particles are more prone to aggregation due to Gibbs-Thomson effect
  - Surface energy is inversely proportional to radius of curvature, leading to anisotropic surface energy for nonspherical particles
  - High surface energy causes aggregation to achieve lower free energy state
  - Test hypothesis by coating with surfactant

Aggregation



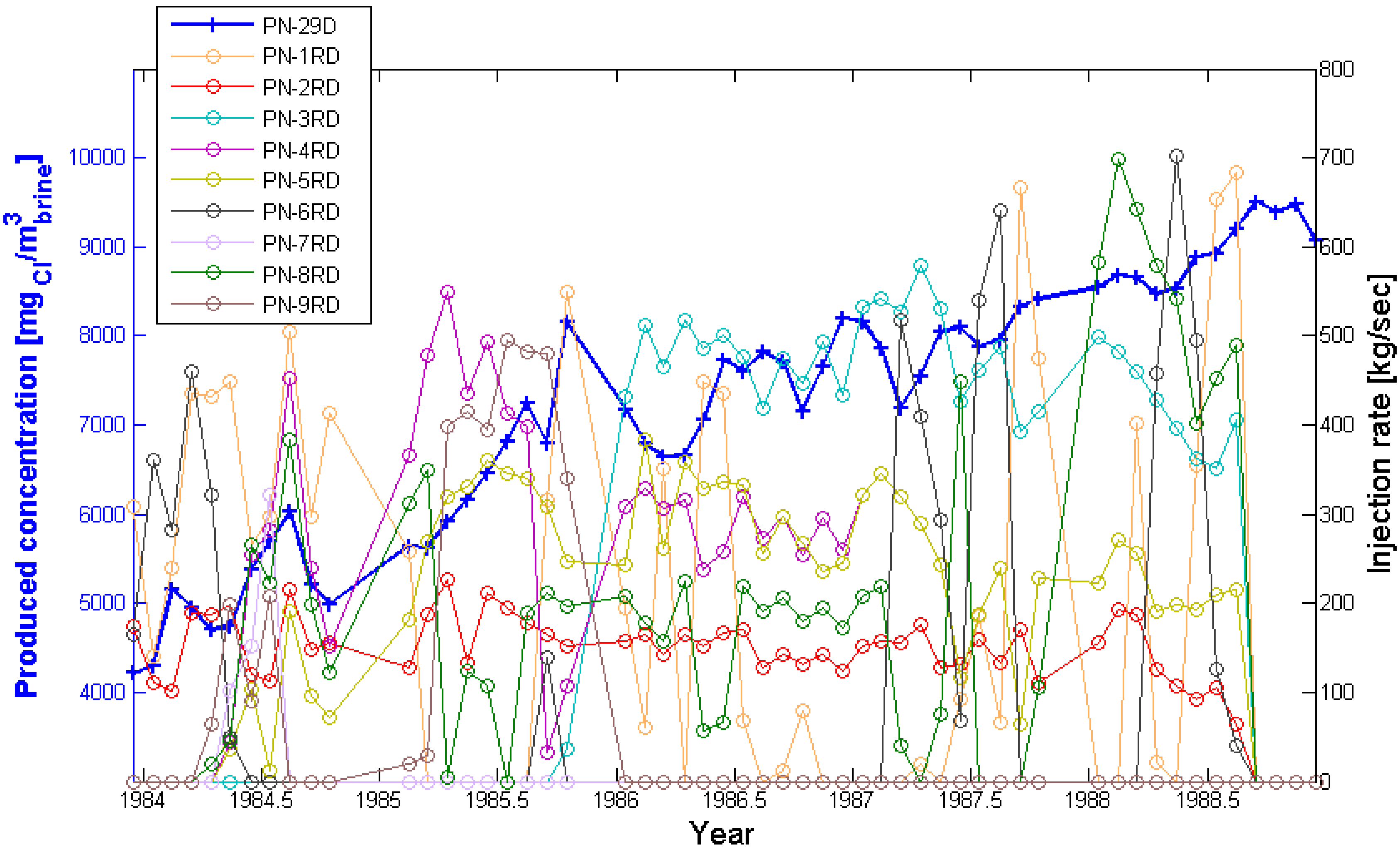
Next Steps

- Now fabricating prototype temperature-sensitive nanoparticles (target 150ºC).
- Test their temperature sensitivity.
- Test them in core flow.
- Test them in 10m and 20m slim tubes.

2. Characterization of Fracture Properties using Production Data

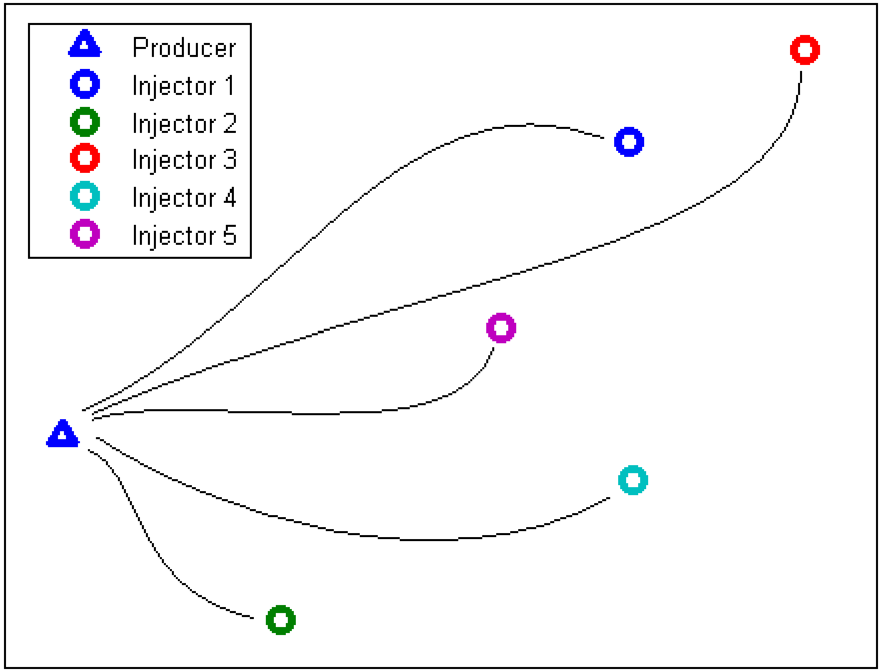
- Flow through EGS reservoirs is dominated by fractures
- Emphasis on understanding well-to-well relationships
- Focus on the correspondence between tracer and thermal transport

The Palinpinon Data



A Synthetic Example

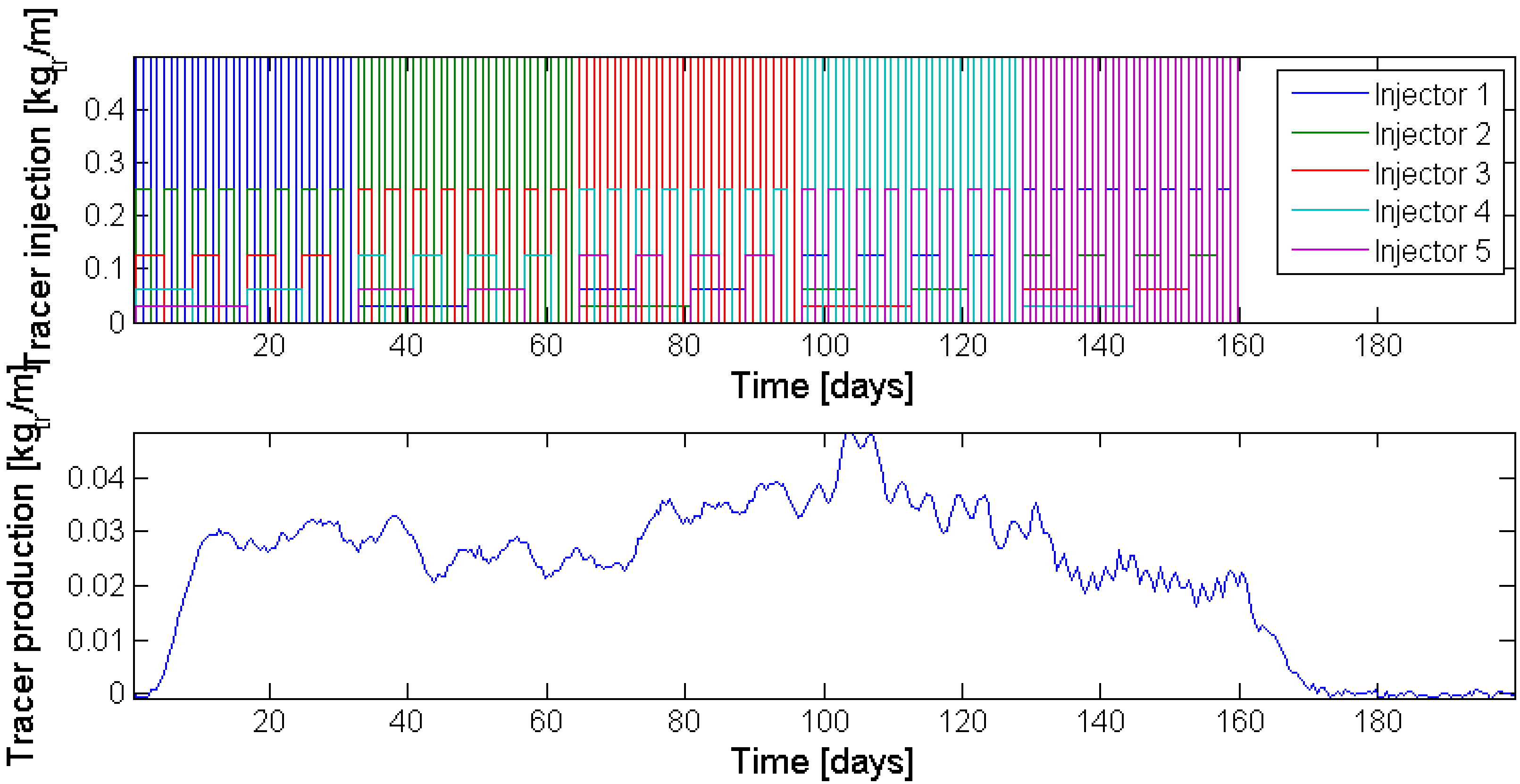
- How hard is it to solve an ideal synthetic example?



$$c_p(t) = \sum_{i=1}^{5} \int_0^t \frac{c_{r,i}(t-\tau)u_i}{\sqrt{4\pi D_i \tau}} \exp\left[-\frac{(L_i - u_i\tau)^2}{4D_i\tau}\right] d\tau$$

A Synthetic Example

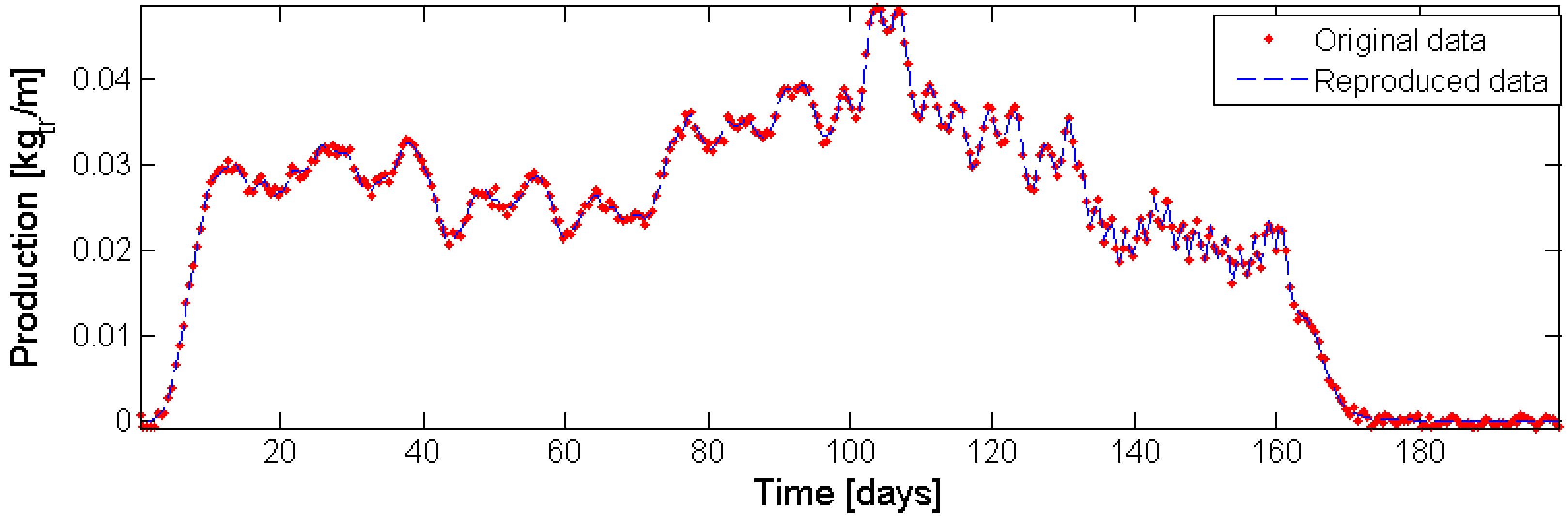
- Ideal synthetic data



A Synthetic Example

- Regularized blind deconvolution

$$F(\vec{\kappa}) = \underbrace{\frac{1}{2}(\vec{c}_p - H\vec{\kappa})^T(\vec{c}_p - H\vec{\kappa})}_{data \quad misfit} + \underbrace{\frac{1}{2}\vec{\kappa}^T R\vec{\kappa}}_{roughness \quad penalty}$$



A Synthetic Example

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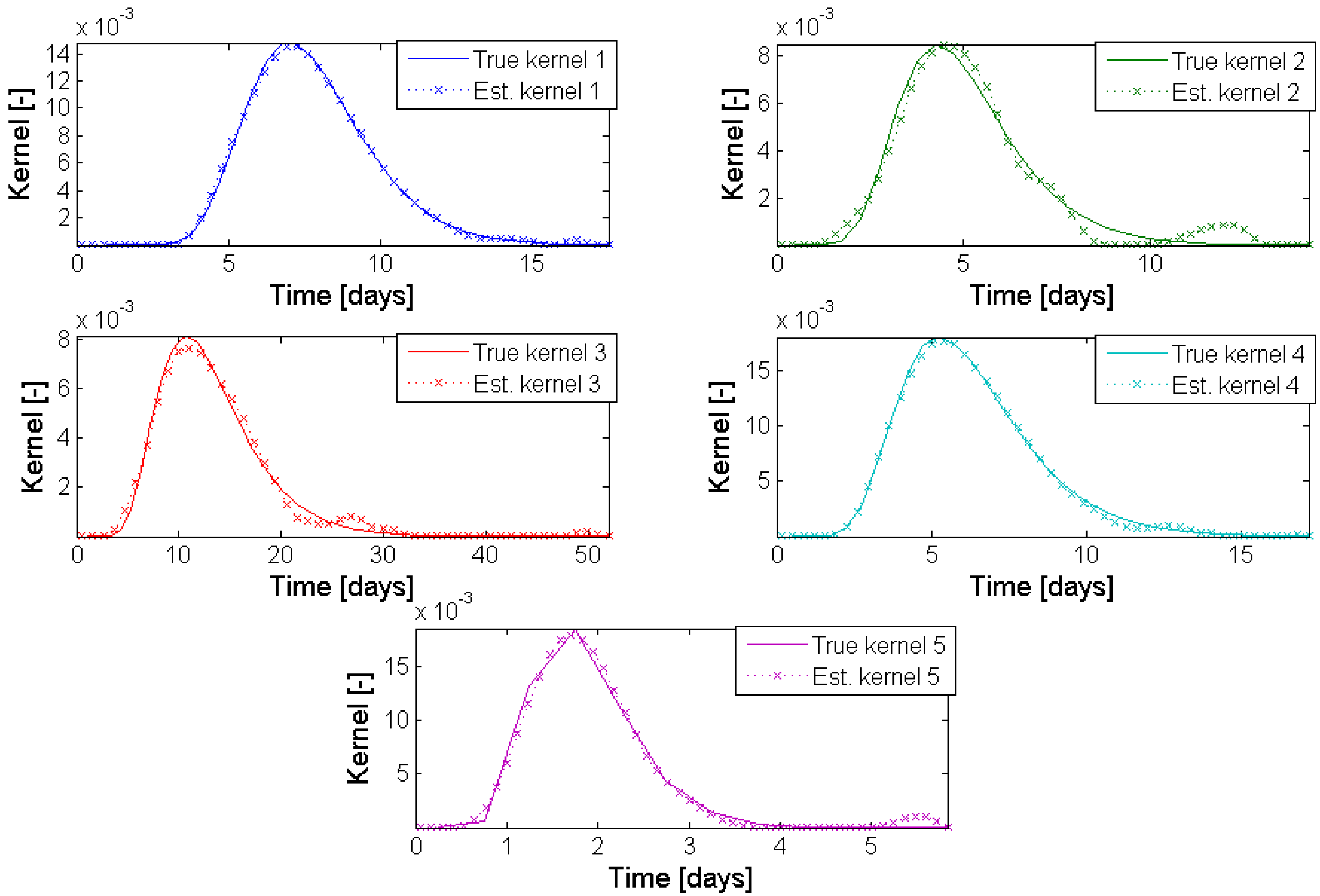
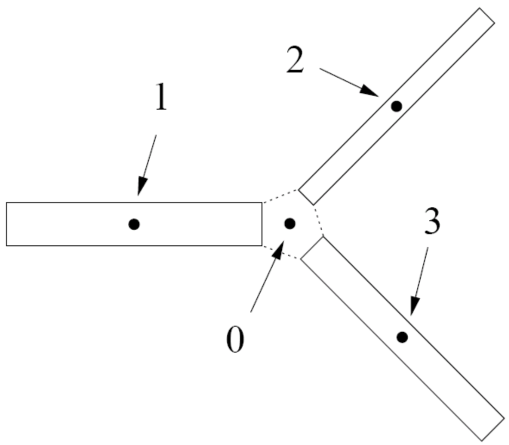
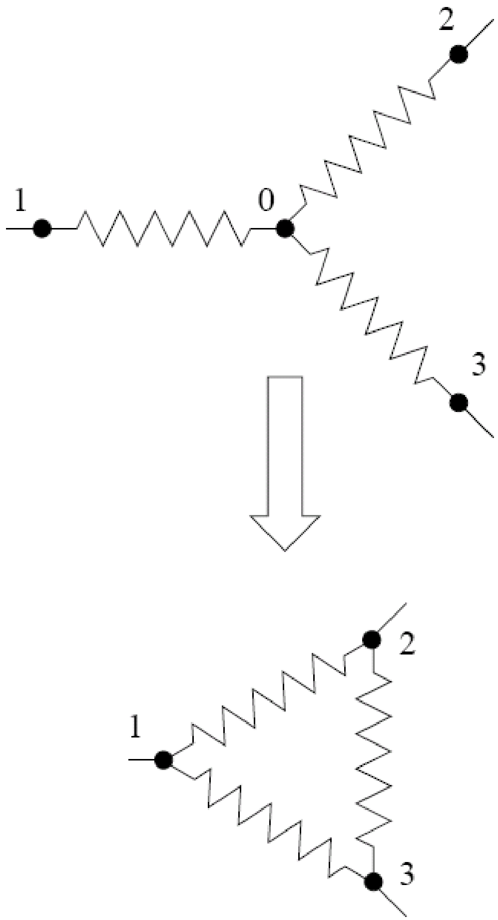
- Solving the ideal case is hard…



- Discrete fracture discretization method by Karimi-Fard et al.
- Implemented in TOUGH2 and GPRS





Discrete Fracture Simulation

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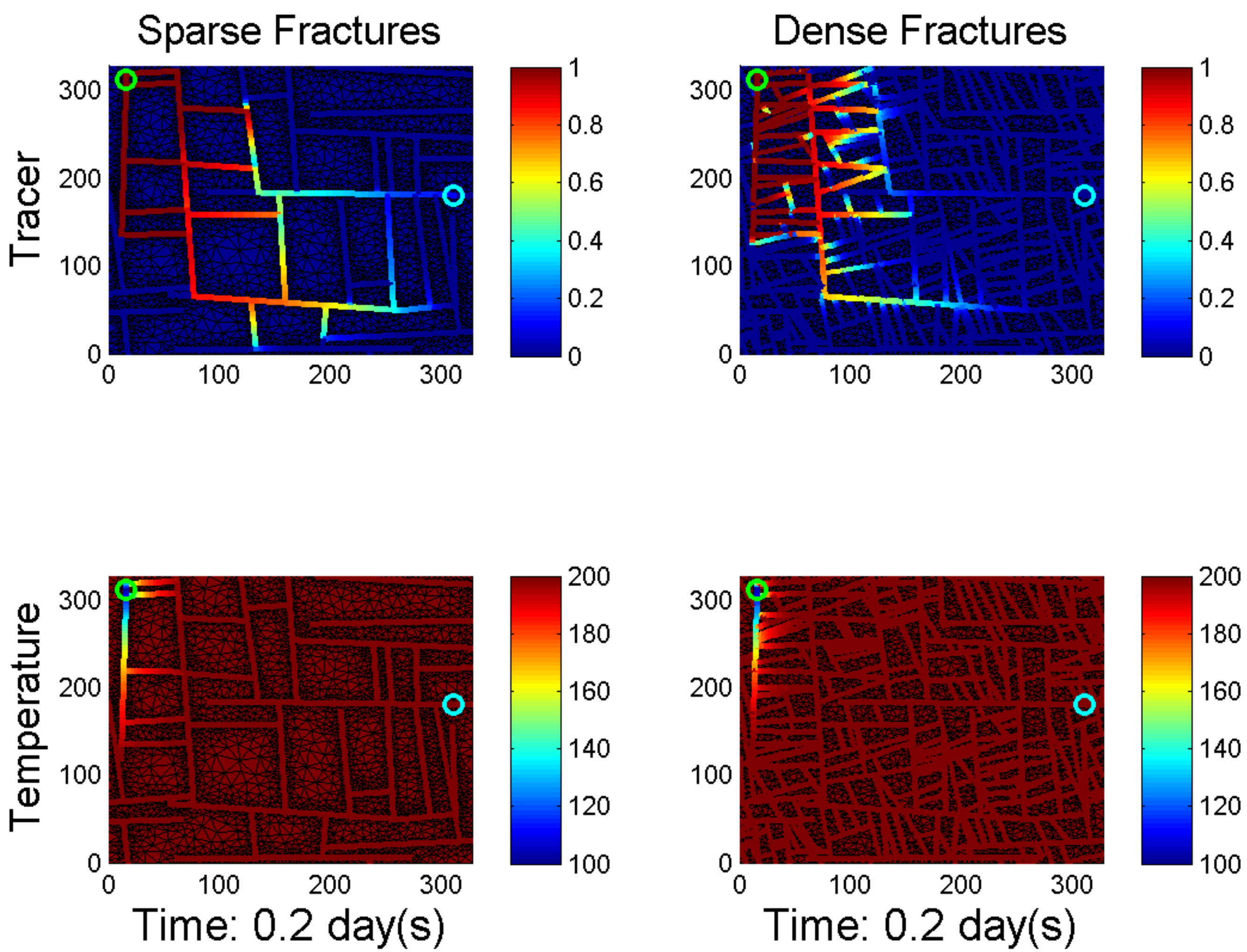

Discrete Fracture Simulation

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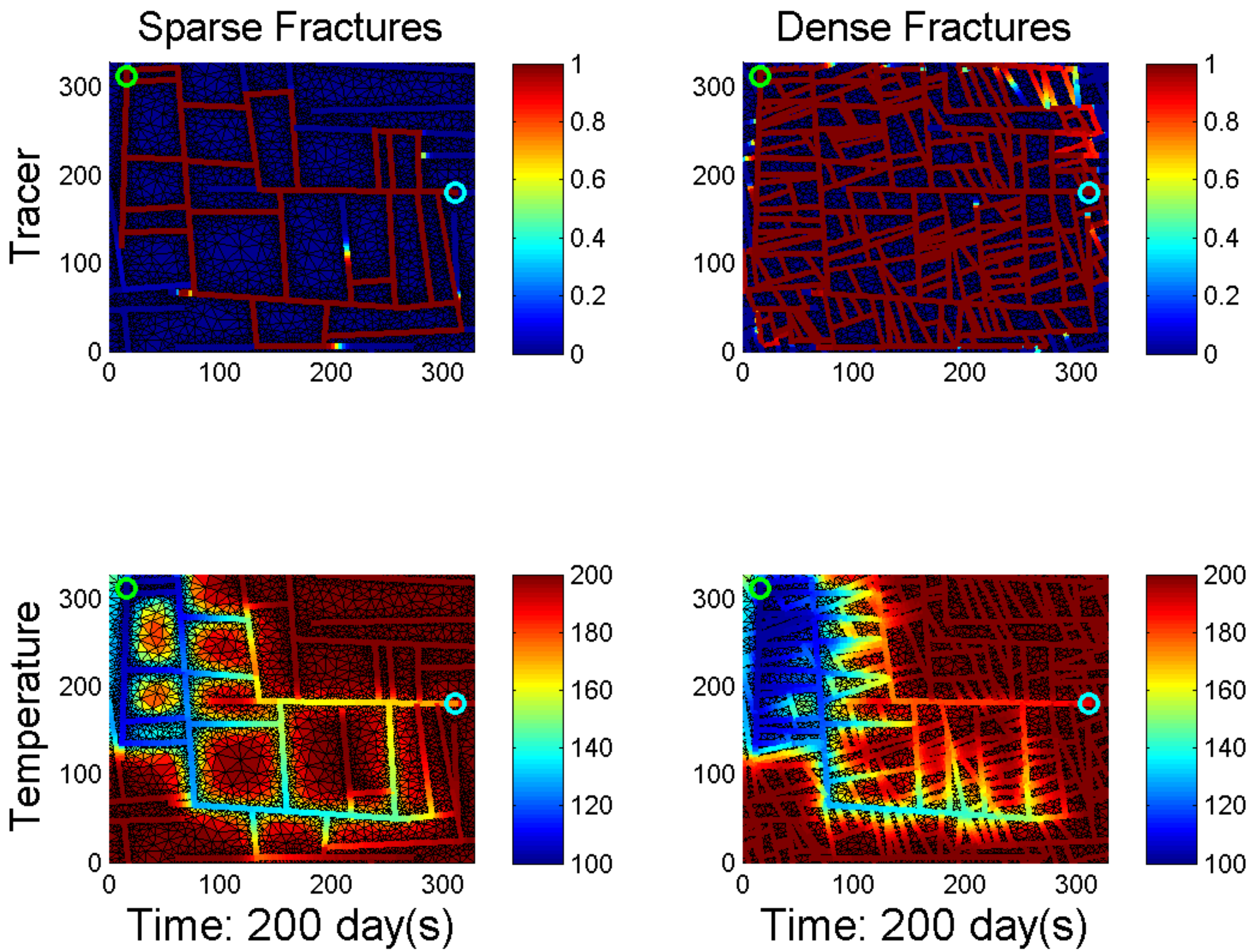
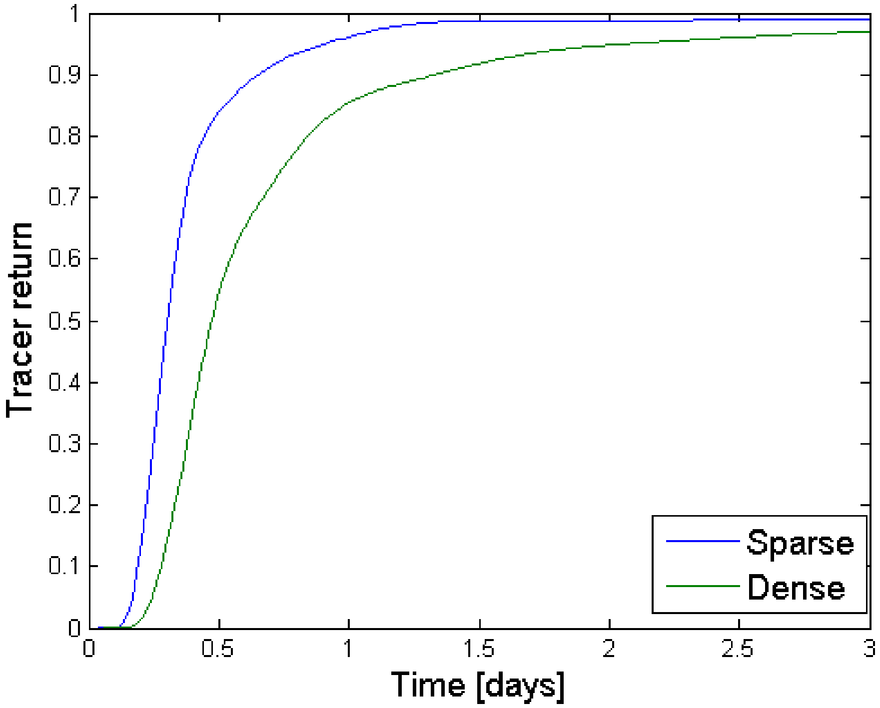
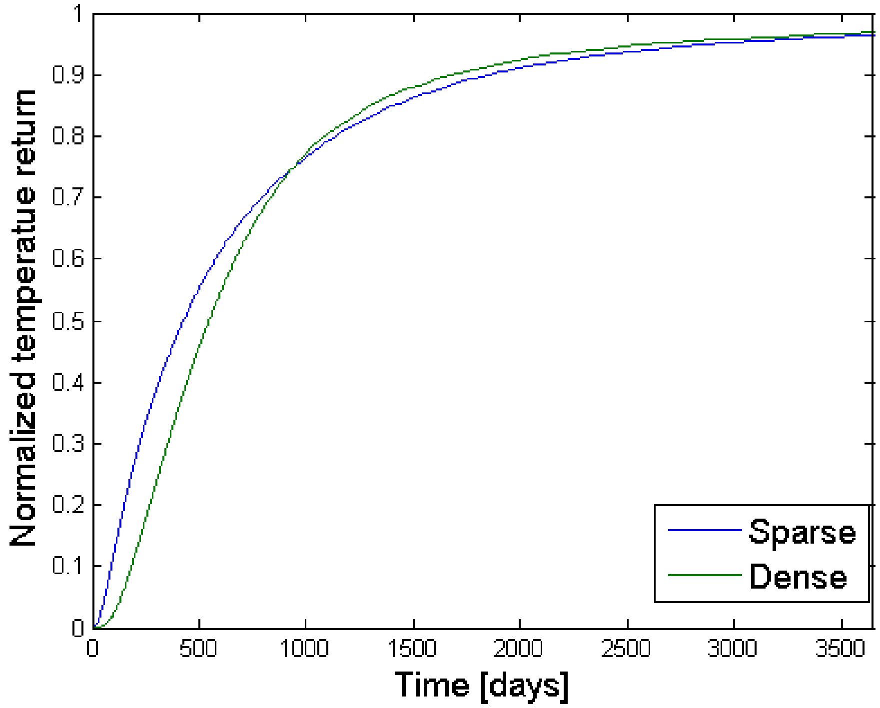


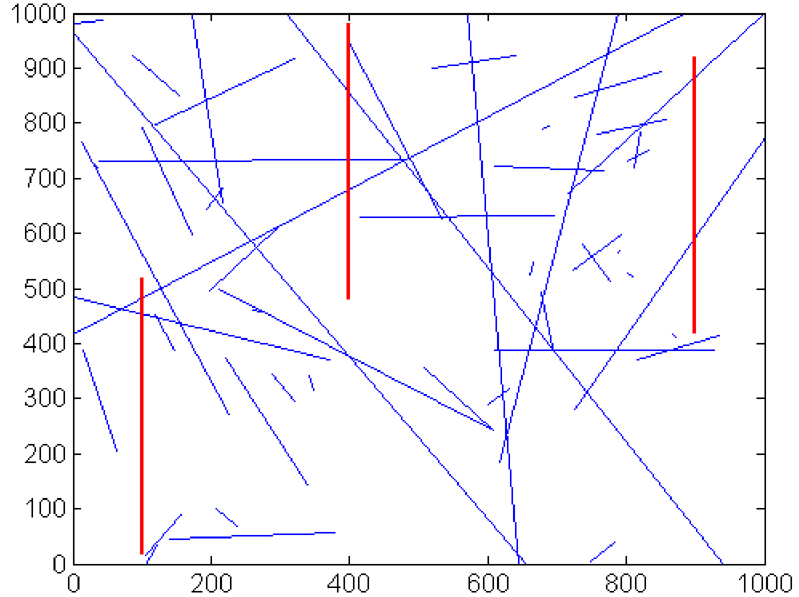
- Tracer and thermal returns for two fracture networks

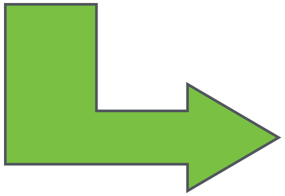


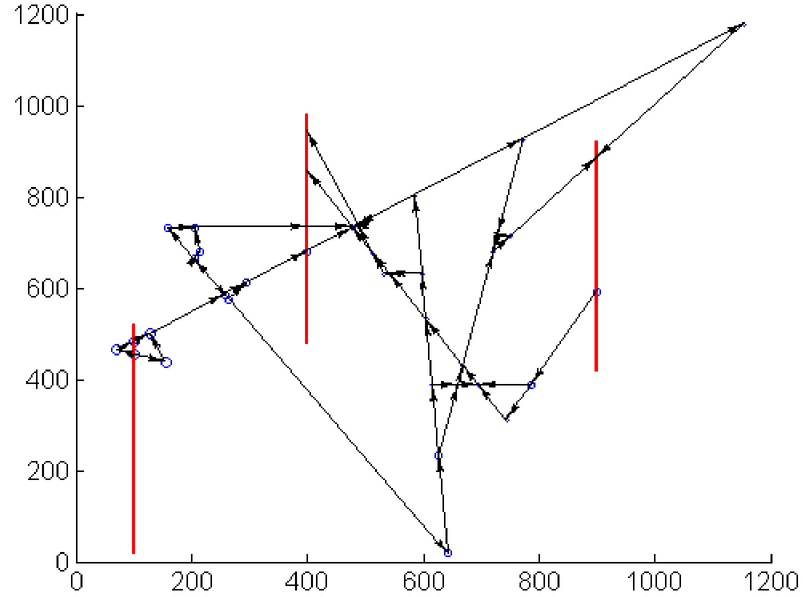


Simplified DFN Method

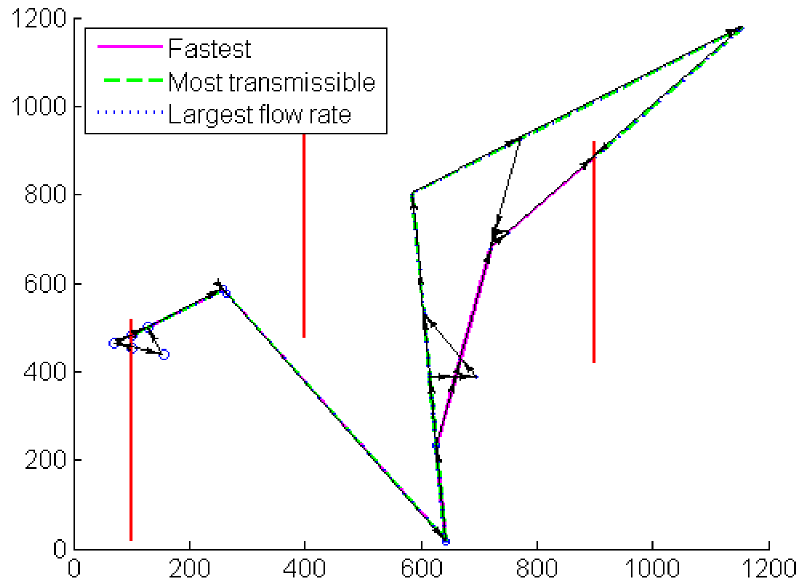
- View the fracture network as a directed graph

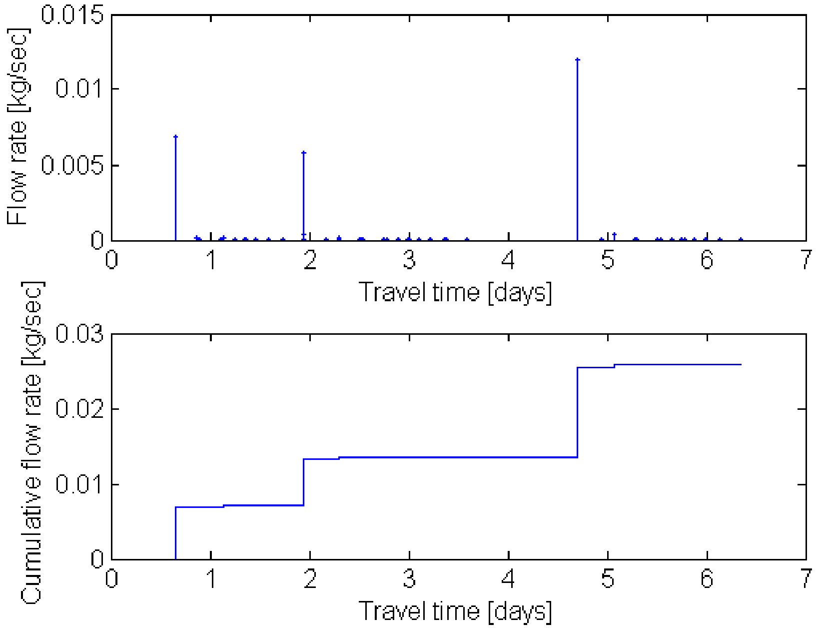






- Dispersion attributable to the fracture network





Next Steps

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- Characterize the fracture network in terms of its output responses (chemical and thermal)
- Seek “indicators” of network types
- Characterize the EGS in terms of its indicators, and hence forecast its performance

3. Resistivity Tomography

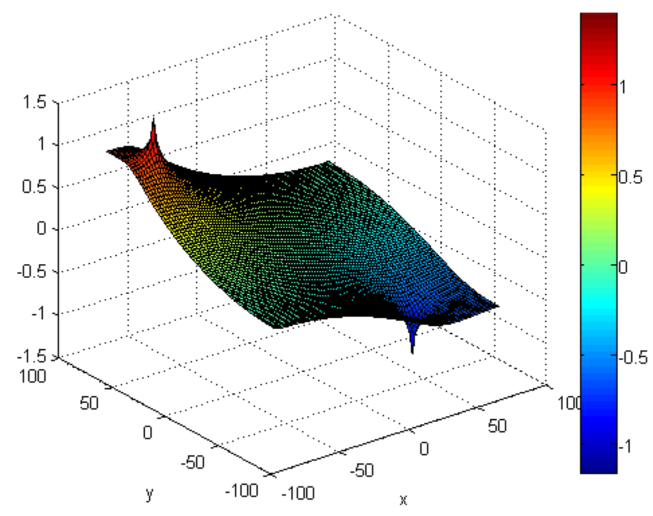
- Investigate ways use Electrical Resistivity Tomography (ERT) to characterize fractures
- Study resistivity anomalies between electrodes inside geothermal wells to infer fracture properties
- Investigate ways to enhance the contrast between fracture and rock resistivity
- Study the possibility of using conductive fluid
- Explore influences of temperatures and fluid stream and the effects of mineralization

Resistivity Modeling

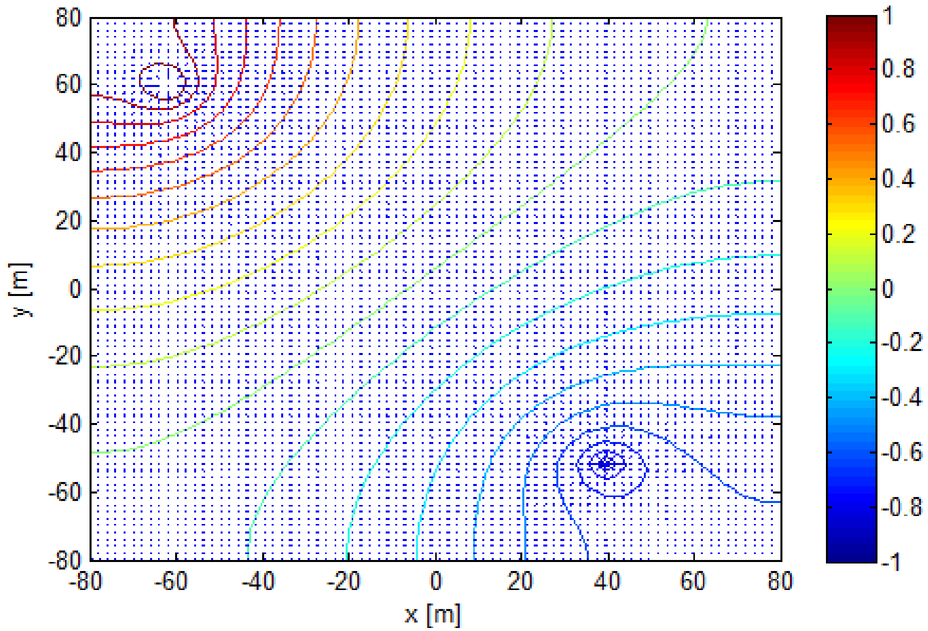
- Poisson's equation describes the potential distribution due to a point source of excitation:

$$\nabla\left[\sigma\nabla\phi\right] = -q(x,y,z)$$

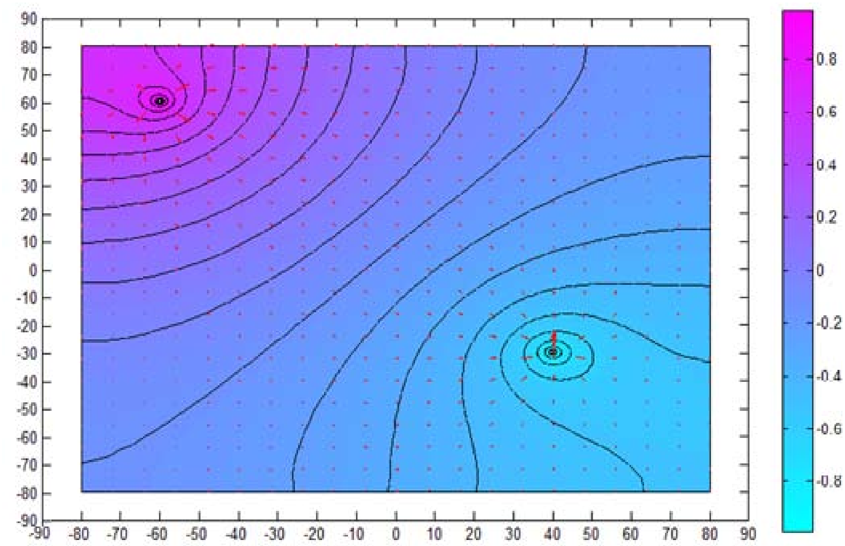
- Finite difference method used to approximate the solution
- Successive Over-Relaxation iteration method used to numerically solve the potential distribution



- Potential distribution for a homogeneous resistivity field
- The model gives similar results to the Partial Differential Equation (PDE) Toolbox in Matlab



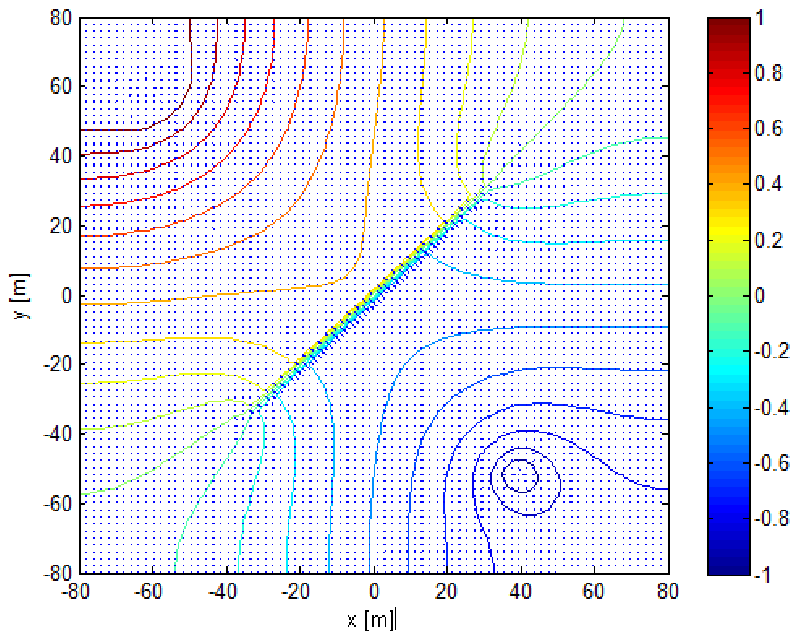
Resistivity Model



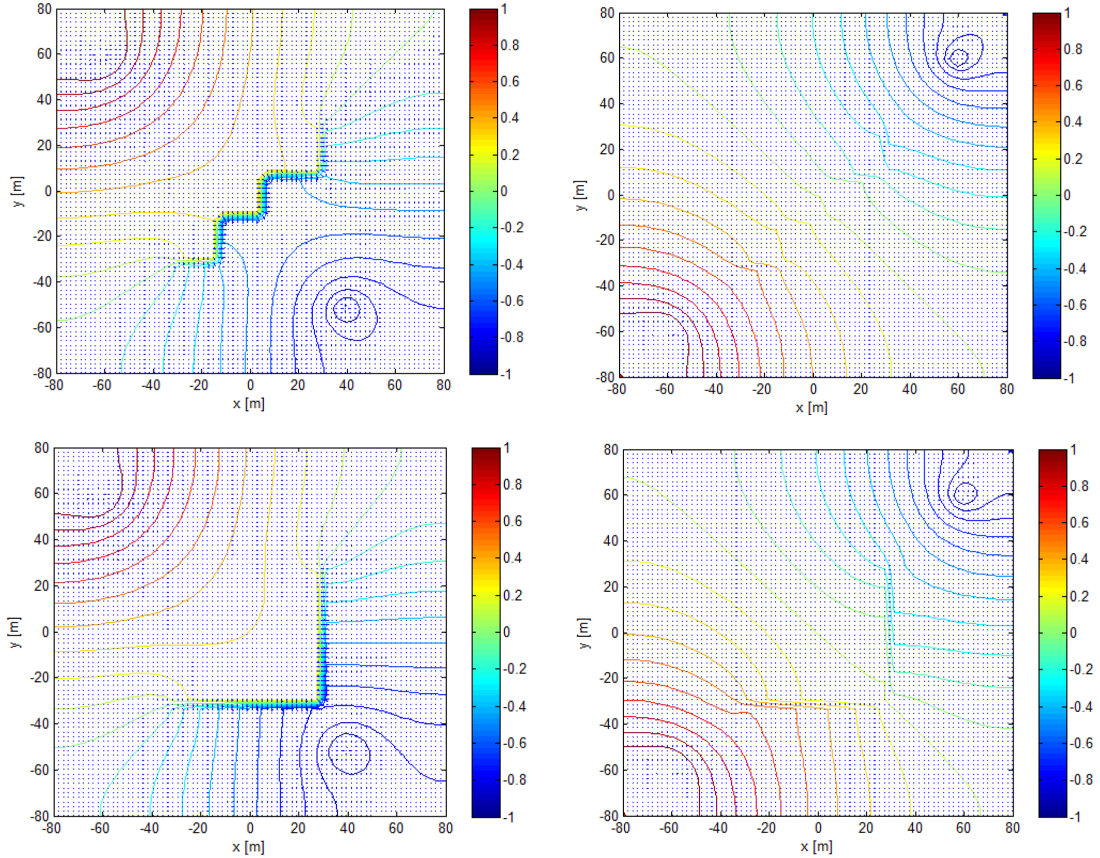
PDE Toolbox in Matlab

Resistivity Model

- PDE Toolbox in Matlab can not take into account heterogeneity
- Fractures modeled with different resistivity



- Potential field varies with the resistivity pattern and the location of current excitation



Fracture Characterization

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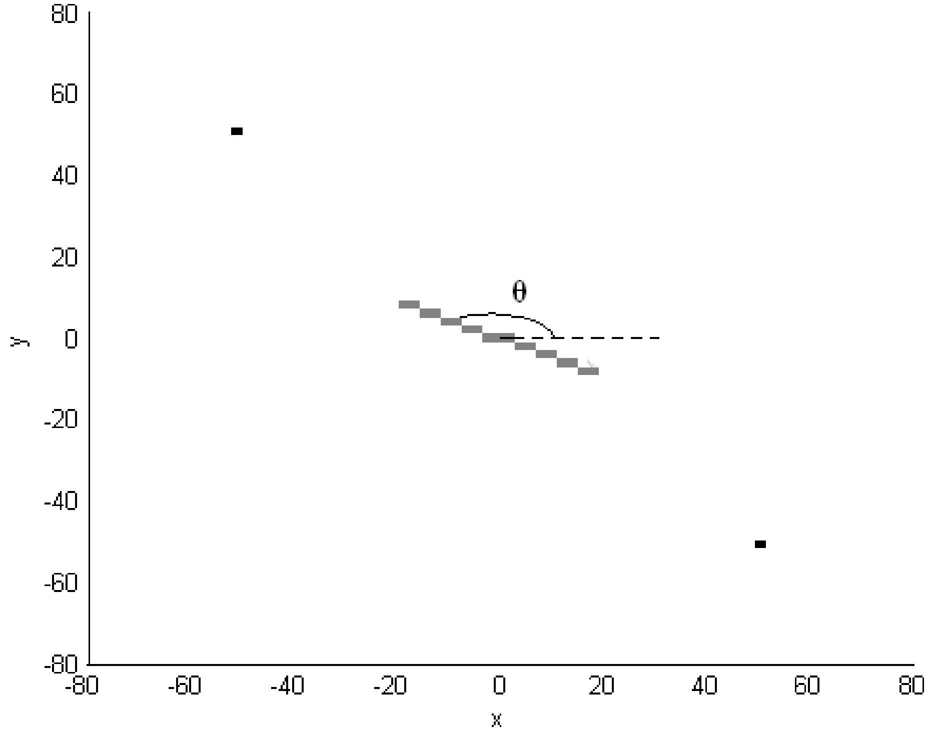
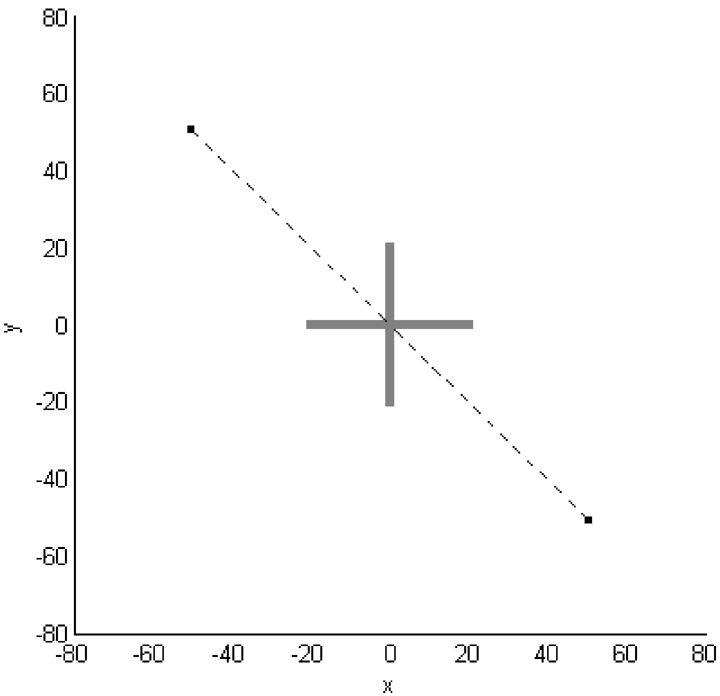
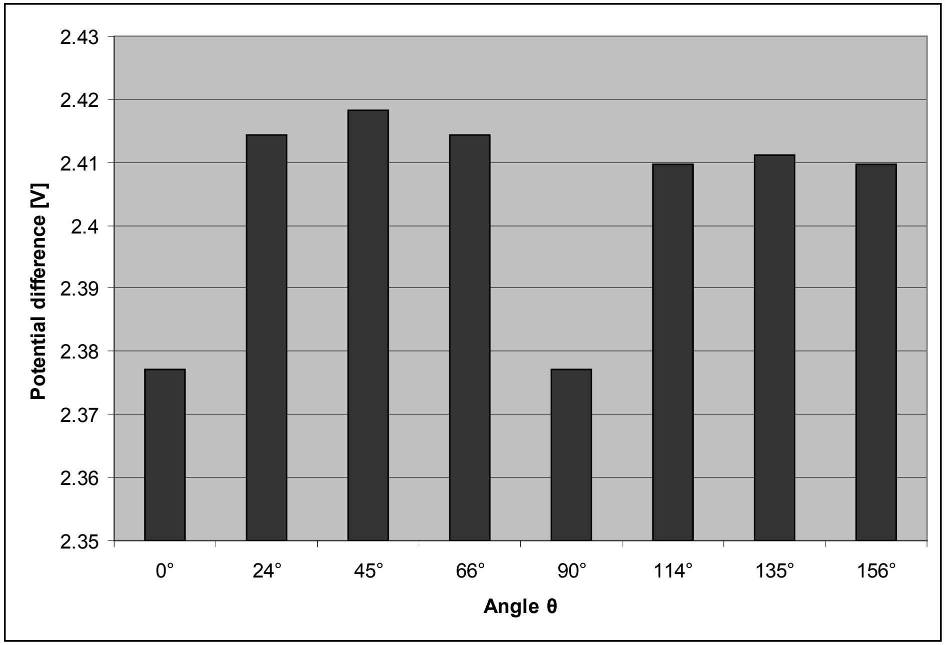
- Two points in a reservoir used to infer at what angle a straight fracture is placed
- Potential differences between the two points calculated for various angles



Fracture Characterization

- Different potential difference for most patterns but same difference for fractures that are symmetric to each other with respect to a straight line between the wells





Fracture Characterization

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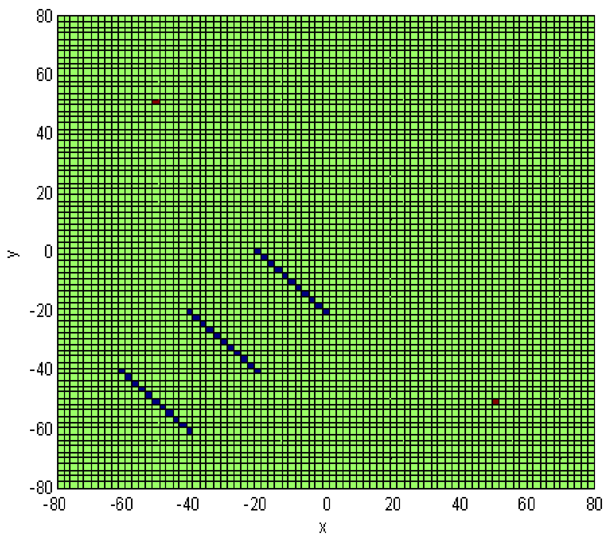
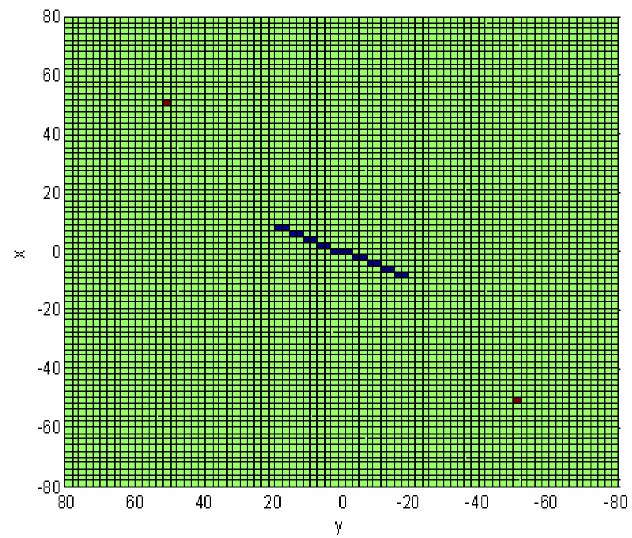
Conductive Fluid:

- Conductive fluid enhances the difference between fracture and rock resistivity
- Potential difference measured at various times, i.e. for different conductive fluid front locations
- Helps in recognizing some of the fracture patterns

Fracture Characterization

- Various fracture patterns modeled
- Same potential difference for some of the patterns
- Statistics of potential differences for various realistic fields could possibly be used to imply a fracture pattern





Next Steps

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- Investigate whether results for more realistic fracture patterns can be used to imply a pattern for a field where the potential difference is known
- Three measurement points instead of two points
- Conductive fluid
- Influences of temperature on resistivity
- Potential changes due to fluid streaming potential
- Mineralization