Analysis of Geothermal Reservoir Stimulation using Geomechanics-Based Stochastic Analysis of Injection-Induced Seismicity

April, 2013

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EGS Component R&D › Stimulation Prediction Models

Relevance/Impact of Research

- Develop a model for seismicity-based reservoir characterization (SBRC) by combining rock mechanics, finite element modeling, and geo-statistical concepts to establish relationships between micro-seismicity, reservoir flow and geomechanical characteristics (3D modeling of MEQ distribution; EnKF algorithm)
  - By helping remove barriers to reservoir creation, the project will help increase reserves and lower costs
    - Permeable zones have to be created by stimulation, a process that involves fracture initiation and/or activation of discontinuities
    - Rock stimulation is often accompanied by multiple micro-seismic events. Micro-seismic events are used for detection of permeable zones, planning drilling
    - reservoir management; induced seismicity

Scientific/Technical Approach

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- Physical processes considered
  - Fully-coupled thermo-poroelastic constitutive equations
  - Rock damage & stress dependent permeability
  - Uncertainty in material parameters and the in-situ stress

    – Estimate hydraulic diffusivity and criticality distribution

    – Combine an initial probabilistic description with the information contained in micro-seismic measurements

    – Arrive at solutions (reservoir characteristics) that are conditioned on both field data and our prior knowledge

    – Uncertainty in material parameters and the in-situ stress

  – Calibration using lab and field data

- Thermo-poroelastic Constitutive Equations

$$\beta = \frac{\alpha - \varphi}{K_s} + \frac{\varphi}{K_f}$$

$$\dot{\sigma}_{ij} = 2G\dot{\varepsilon}_{ij} + \left(K - \frac{2G}{3}\right)\dot{\varepsilon}_{kk}\delta_{ij} + \alpha\,\dot{p}\delta_{ij} + \gamma_1\dot{T}\delta_{ij} \qquad \dot{\zeta} = -\alpha\dot{\varepsilon}_{ii} + \beta\dot{p} - \gamma_2\dot{T}$$

$$\gamma_1 = K\alpha_m$$

$$\gamma_2 = \alpha\,\alpha_m + \left(\alpha_f - \alpha_m\right)\phi$$

- Elastic Damage Mechanics

$$E = (1-d)E_0 \qquad d = 1 - \frac{f_{cr}}{E_0\varepsilon} \qquad (\varepsilon > \varepsilon_{cr})$$

$$d = 1 - \left[\left(\frac{f_{cr} - f_c}{\varepsilon_{cr} - \varepsilon_c}\right)(\varepsilon - \varepsilon_c) + f_c\right] \Big/ E_0\varepsilon \qquad (\varepsilon_c < \varepsilon < \varepsilon_{cr})$$

- Stress Dependent Permeability

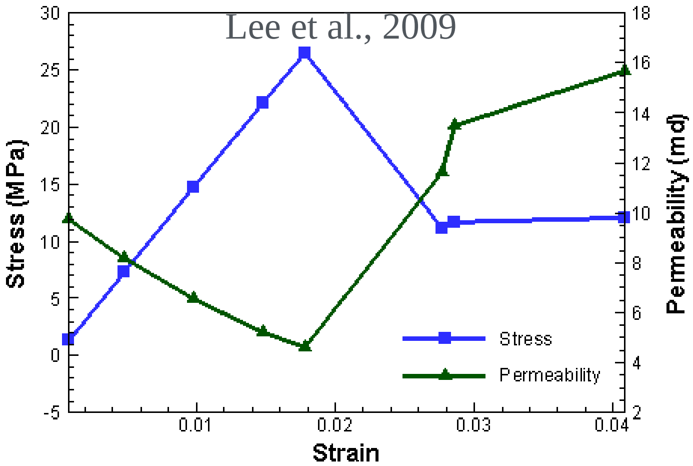
Elastic phase

$$k = k_0 e^{-\beta_d(\sigma_{ii}/3 - \alpha\,p)}$$

Damage phase

$$k = \zeta_d\, k_0 e^{-\beta_d(\sigma_{ii}/3 - \alpha\,p)}$$

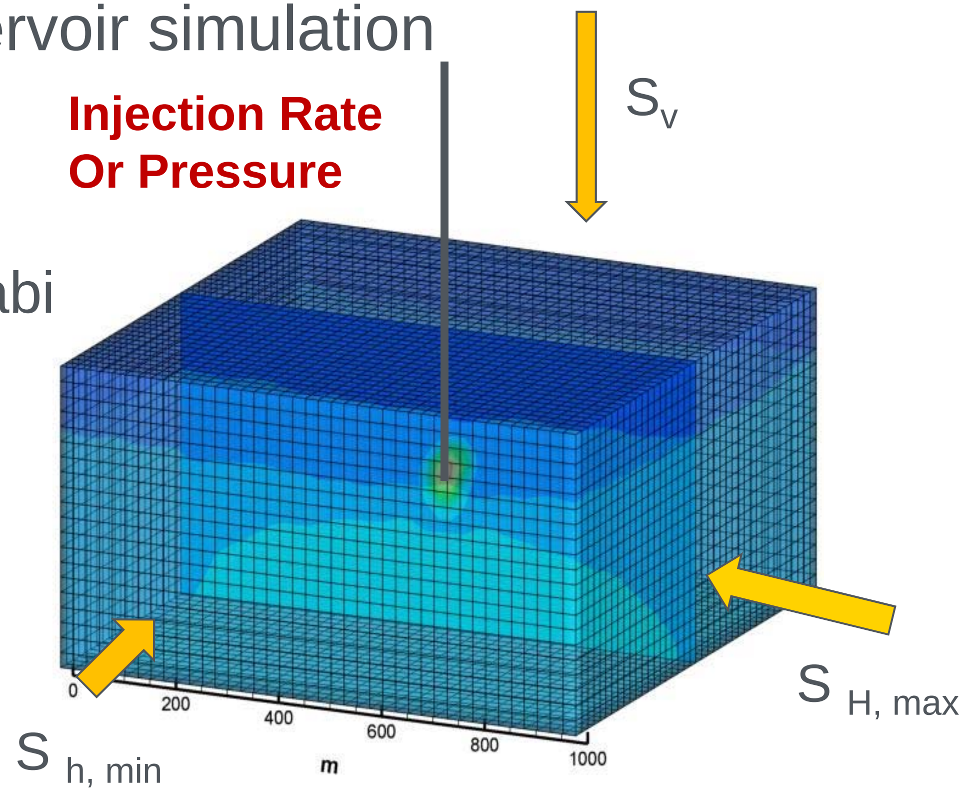
Tang et al., 2002



3D finite element model has been developed for thermo-poro-mechanical coupled reservoir simulation

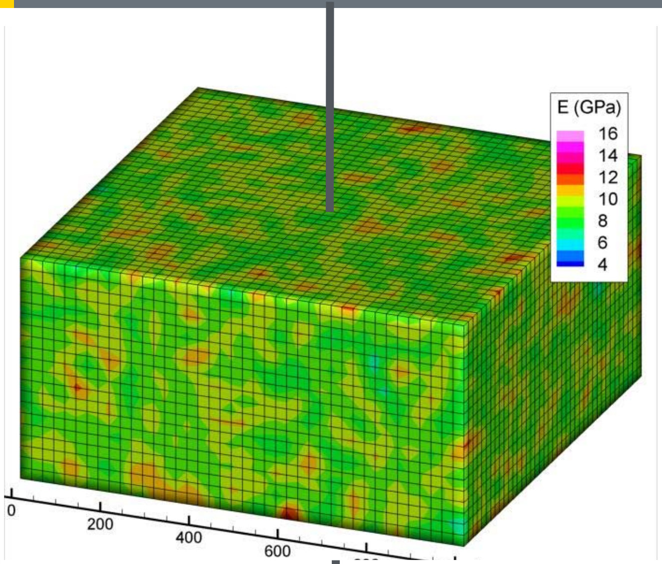
- Damage mechanics
- Stress dependent permeabi
- Convective heat transfer
- Rock heterogeneity
- Pressure & Injection rate

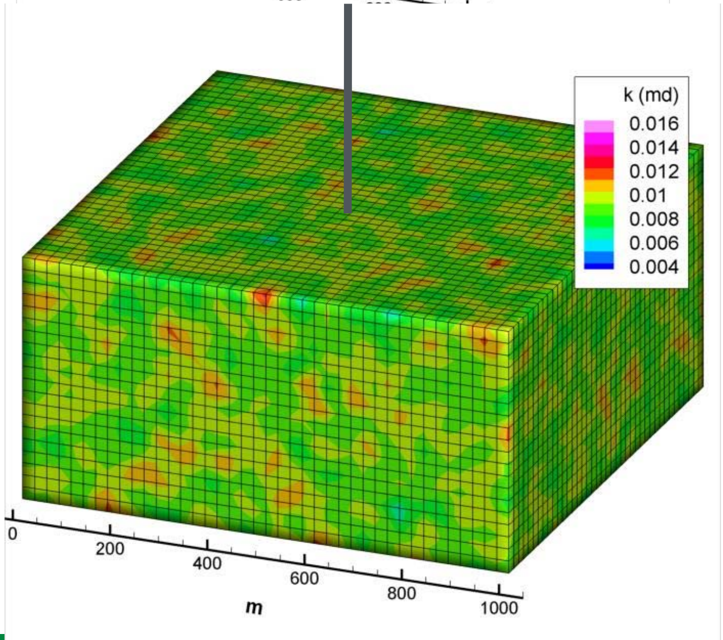
and pressure BC

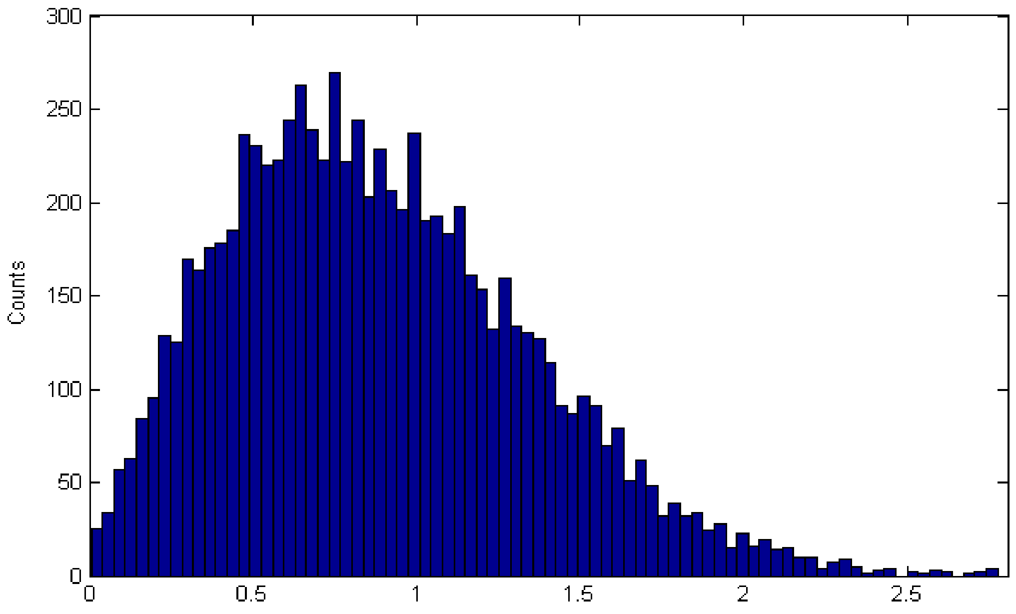


Simulation of Injection Experiment

- 3D rock body of dimensions x =1000, 1000, 500 m
- Water is injected into the granitic rock from a central interval of 25 m at 2.5 Km
- Temperature difference of 150 C, Distribution of shear stress, potential seismicity





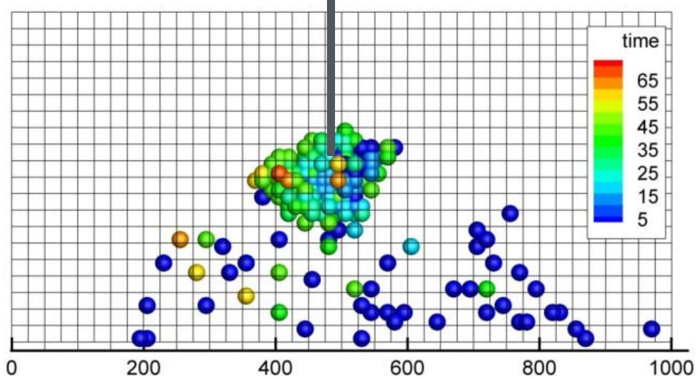


Point source injection cases

$S_{H,max}$= 48; $S_{h,min}$ =36; S_v= 60 MPa, p=10

Permeability
K_x =Ky= 1.e-2 md
K_x /Kv = 10

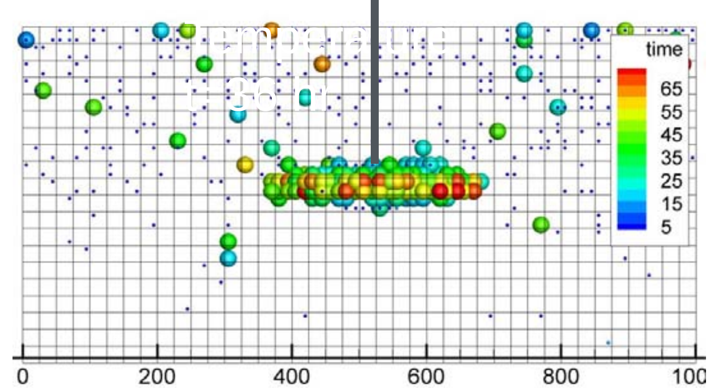
Normal



$S_{H,max}$= 95; $S_{h,min}$ =70; S_v= 60 MPa, p=10

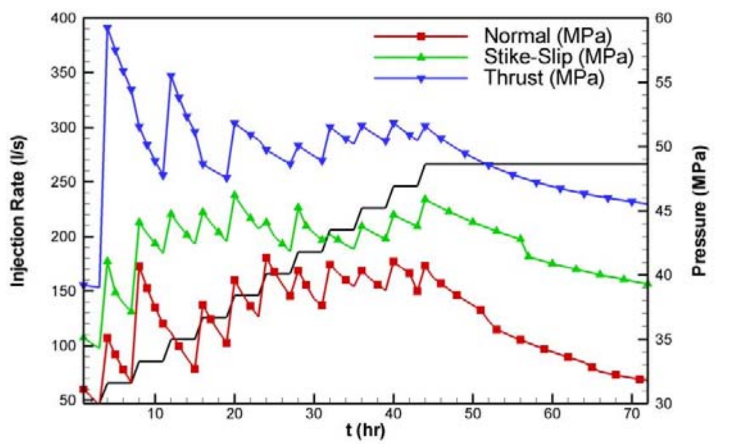
Permeability
K_x =Ky = 1.e-2 md
K_x /Kv = 10

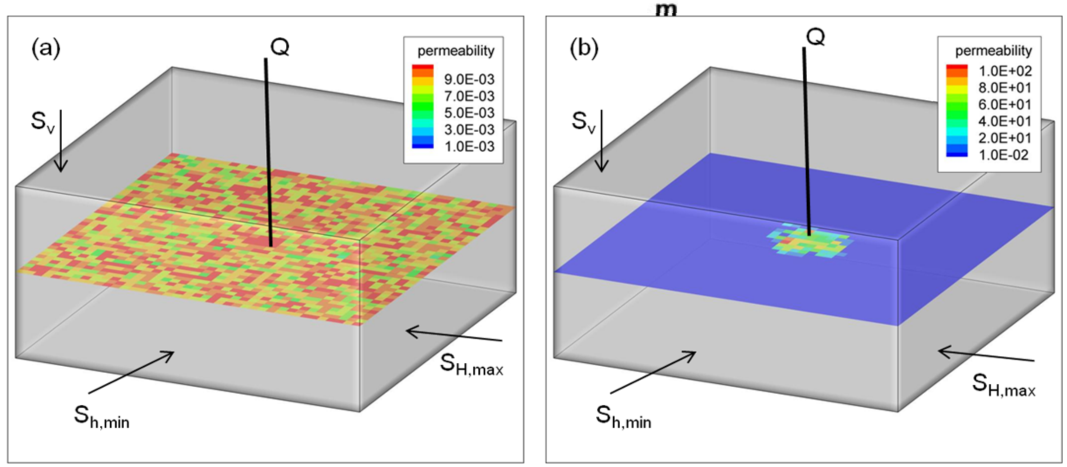
Thrust



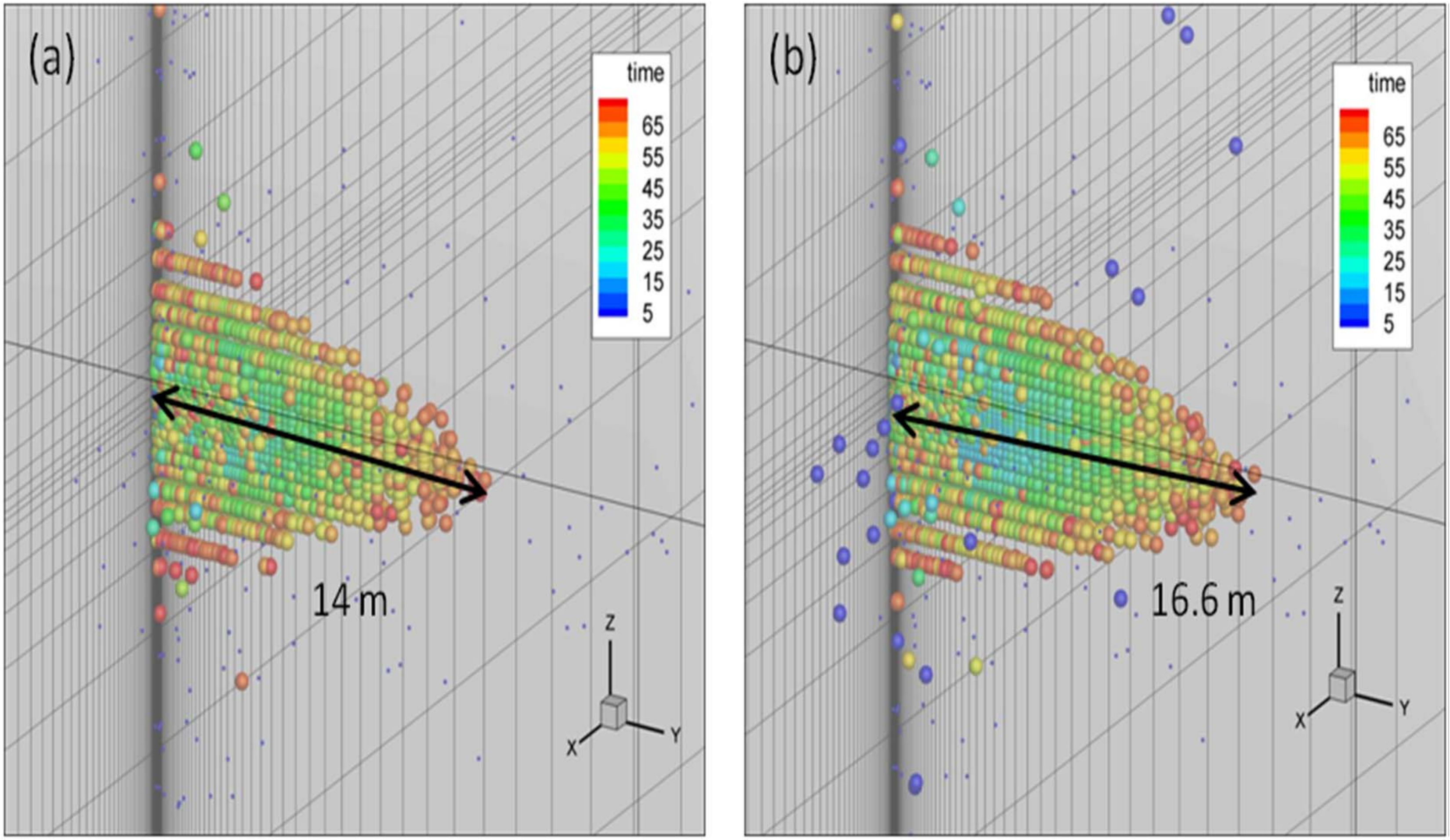
m

$S_{H, Max}$ ↔





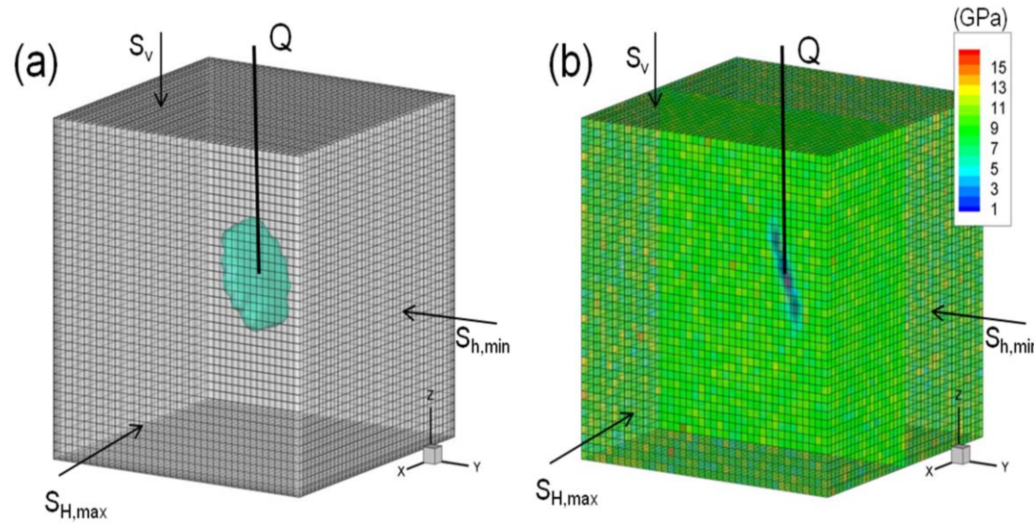
- **Role of thermal stress (wellbore simulation)**: MEQ events after 65 hrs of pumping: (a) isothermal and (b) cold water (50° C) injection into reservoir (200° C)-**See Supplements**

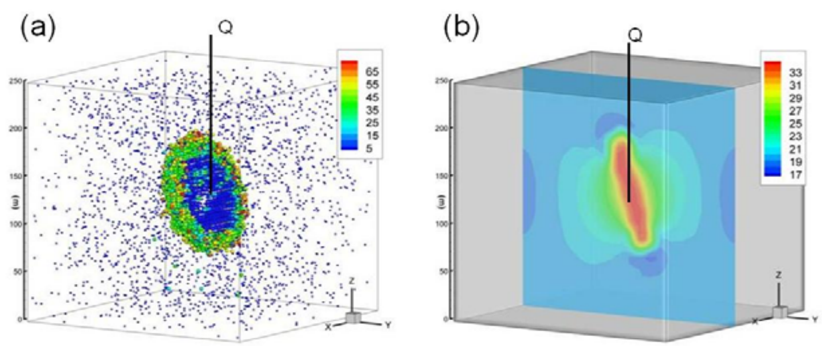


Injection-induced MEQ for GPK1 Soultz.; Natural fracture inclined 20° from vertical; 50 m radius NF modulus is (~0.1 MPa) with permeability of 1 darcy

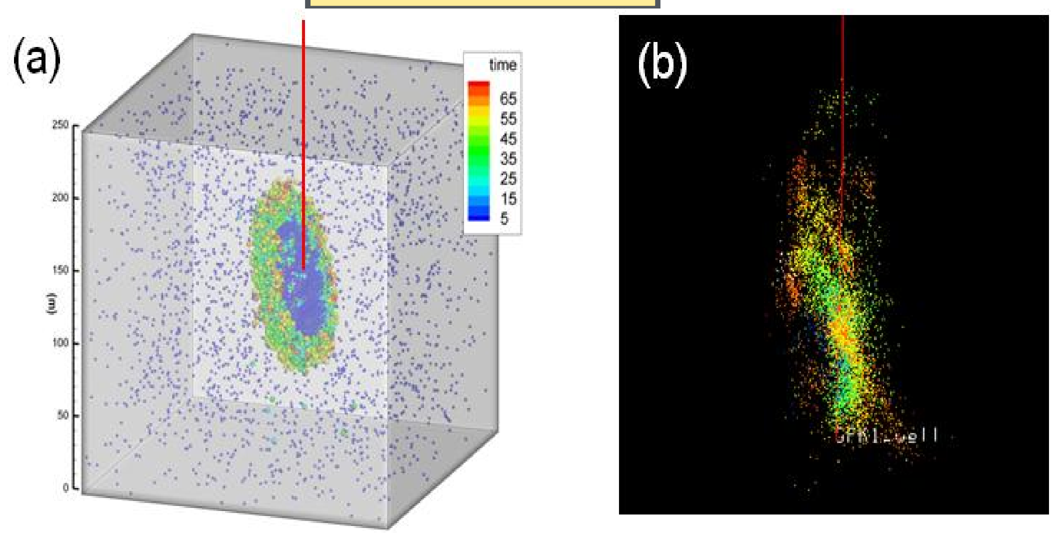
Normal stress regime:

$S_{H,max}$ = 50 MPa, $S_{h,min}$ = 30 MPa, Sv = 60 MPa





Injection Rate:
24 L/sec



Accomplishments & Progress: EnKF Procedure for 3D Application

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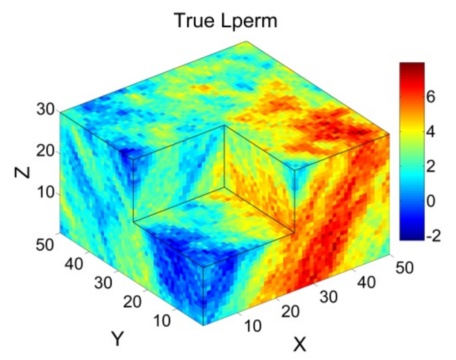
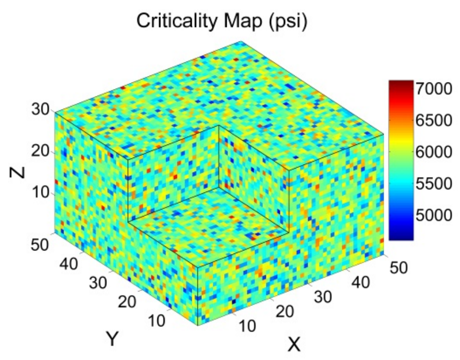
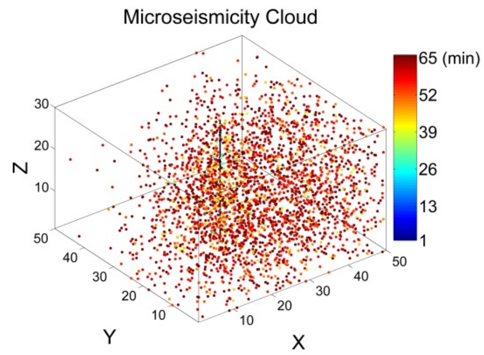


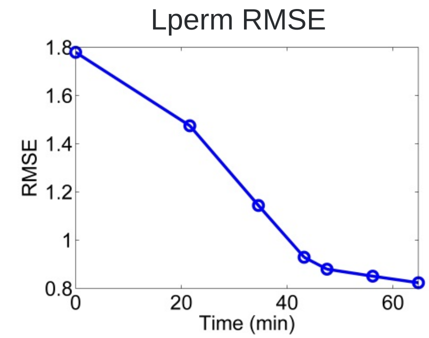
Assumed True permeability (Log-perm) distribution (the target parameter to be estimated)



Random criticality distribution (failure criterion)



Monitoring true MEQ data (resulted from true L_{perm}) is used to estimate L_{perm}



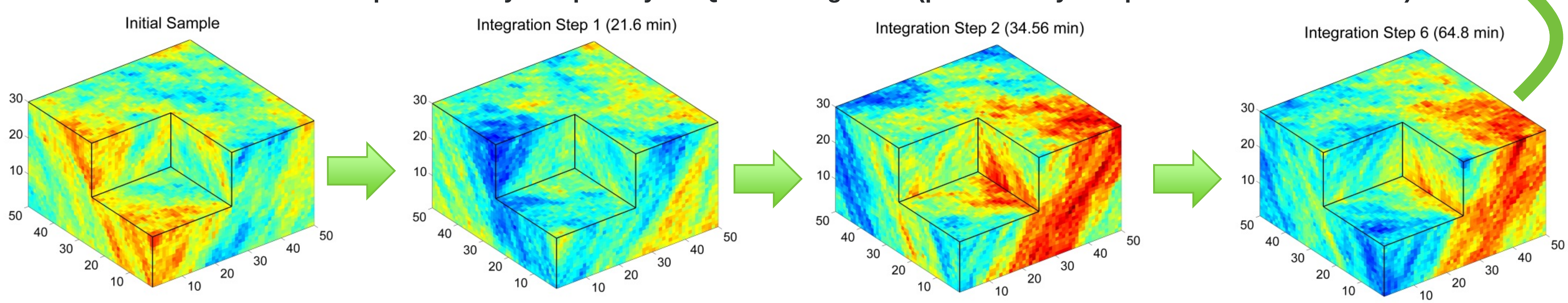
Log-perm estimation error (reduced by integrating true MEQ data through time)

Model specifications: a 3D pore-pressure-diffusion based model, one injection well (constant BHP) at center (perforated through entire thickness)

EnKF estimation procedure: estimating 3D permeability distribution from MEQ monitoring data

Final estimated L_{perm} which is very similar to true L_{perm} distribution

Evolution of one of the permeability samples by MEQ data integration (permeability sample estimation evolution)



confirms the suitability of EnKf for characterizing 3D permeability distribution using MEQ integration.

Accomplishments & Progress: EnKF Procedure for 3D Application

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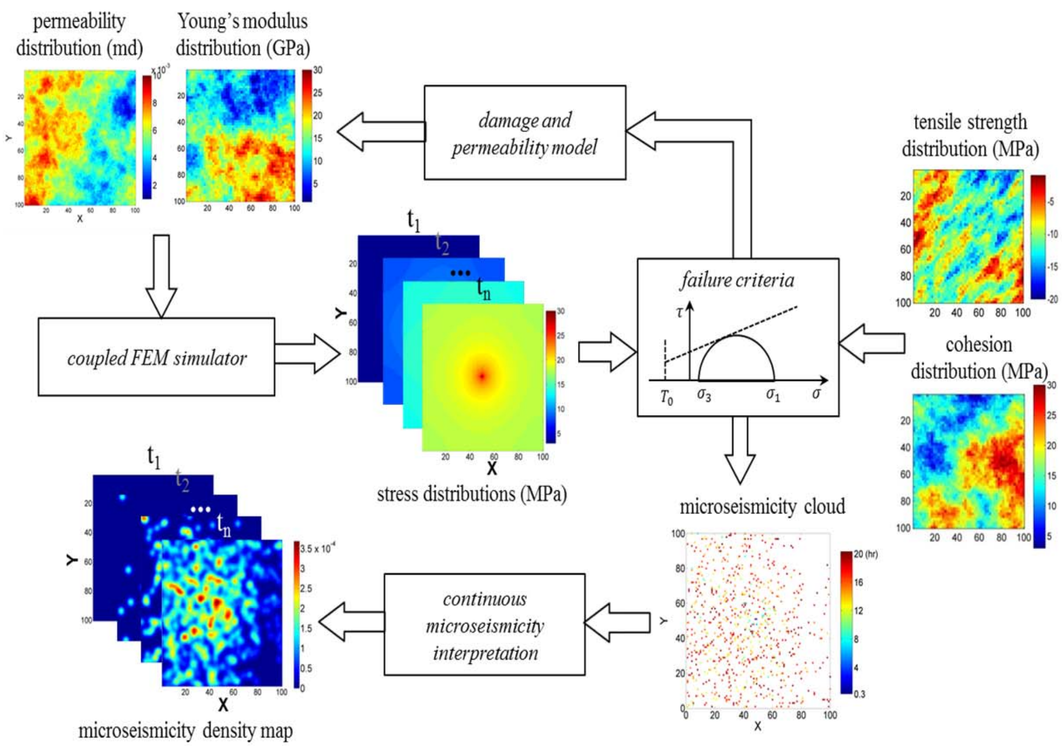
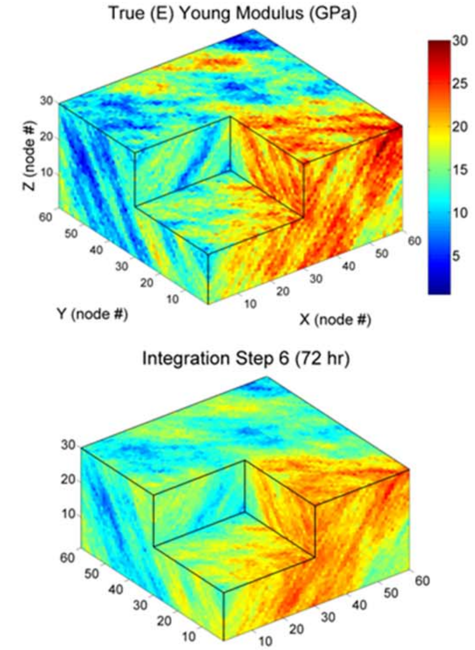
- Overall Procedure





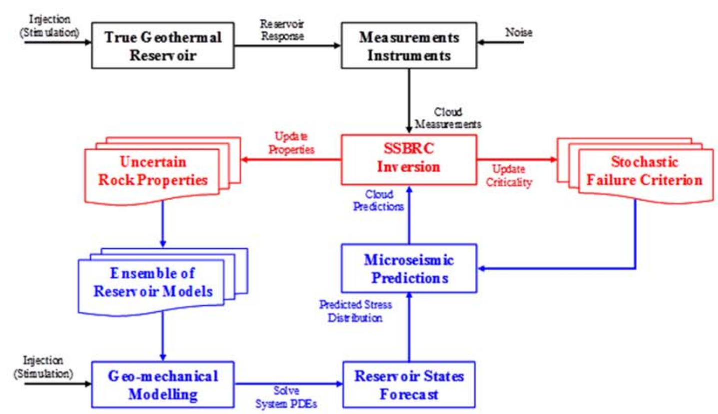


Figure 1. Proposed framework for stochastic seismicity-based reservoir characterization for enhanced geothermal systems.

Accomplishments, Expected Outcomes and Progress

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- Developed 2D and 3D coupled thermo-poroelastic reservoir geomechanics models
- Stress dependent permeability
- Rock heterogeneity and damage mechanics
- MEQ event location

- Implemented damage mechanics in the FEM and have shown its utility in simulation rock failure and stimulated volume for different stress regimes, rates, etc.

- Developed probabilistic approaches for integrating MEQ into EnKF inversion method, applied to 2D and 3D diffusion & geomechanics models

Accomplishments, Results and Progress

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
2D mode, a Preliminary 3D formulation	2D distribution of MEQ	10/2010
Full development of 3D geomechanics model, with damage and stress-dependent permeability	3D modeling of MEQ distribution	10/2011
Fine tuning of 3D geomechanics model, application to and analysis of different stress regimes, EnKF development	2D EnKF for geomechanics 3D EnKF with diffusion	6/2011
3D geomechanics stochastic modeling	3D geomechanics & EnKF	2012-13
Improve the FEM program to better define nature of damage zone and to treat larger scale problems, improve and implement stochastic algorithms in 3D model; Compare model with lab and field data	Will apply to some lab experiments, block experiment application ongoing	2013

Future Directions

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- The goal is to have a 3D geomechanical model to help analyze reservoir stimulation using MEQ
- The model will be applied to EGS experiments by AltaRock and others that have been done or are planned

- Future work includes
  - improve FEM program: consider introduce discrete fractures and fine tune damage interpretation, efficiency for large scale problems
  - Quantify MEQ events
  - Fully implement developed stochastic algorithms in 3D model and perform additional analysis
  - perform triaxial compression tests to determine rock mechanical properties and asses the model predictions for predicting shear and tensile failure

Summary Slide

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- **We have demonstrated**:
- Development of 2D and 3D reservoir characterization models based on geomechanics with relevant physical processes such as thermal and poroelasticity stress and rock heterogeneity
- Implemented damage mechanics in the FEM and have shown its utility in simulation rock failure and stimulated volume for different stress regimes, rates, etc.
- Developed probabilistic approaches for integrating MEQ into EnKF inversion method, applied to geomechanical modeling

Project Management

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Timeline:

Planned Start Date	Planned End Date	Actual Start Date	Actual /Est. End Date
1/1/2009	12/31/2011	9/15/2009	12/31/2013

Budget:

Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	Value of Work Completed to Date	Funding needed to Complete Work
$814,386	$203,598	$1,000,000	$1,010,000	$937,500	$75

- The project is slightly behind as we started late (funds not allocated); student recruitment and training required more time, and finally PI, co-PI and research team moved to another institution and some tasks are pending.