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

May 18, 2010

Principal Investigator:
Ahmad Ghassmi
Texas A&M University

EGS Component R&D › Stimulation Prediction Models

Overview

- **Timeline**
  - Project Established: September, 2009
  - Project End: December, 2011
  - Percent Completed: 25-30%

- **Budget**
  - Total project funding: $1,017,984
  - DOE share: $814,386,
  - Awardee share: $203,598
  - Funding received in FY 09: $275K, funding for FY10: $814K
- **Barriers**: Site/Well Characterization: Accurate Prediction of Reservoir's Response to Stimulation
- **Partners**: AltaRock Energy

Relevance/Impact of Research

- Develop a model for seismicity-based reservoir characterization (SBRC) by combining rock mechanics, finite element modeling, geo-statistical concepts to establish relationships between micro-seismicity, reservoir flow and geomechanical characteristics
- **First year targets**:
  - Develop a 3D Poro-thermoelastic FEM with damage & stress dependent permeability
  - Develop geostatistical algorithms for rock permeability and stochastic description of rock mass properties

Relevance/Impact of Research

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- **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

- Physical processes considered
  - Fully-coupled poro-thermoelastic 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 criticality solutions that are conditioned on both field data and our prior knowledge
- Calibration using lab and field data

Significance & Impact of Research

- Poro-thermoelastic 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

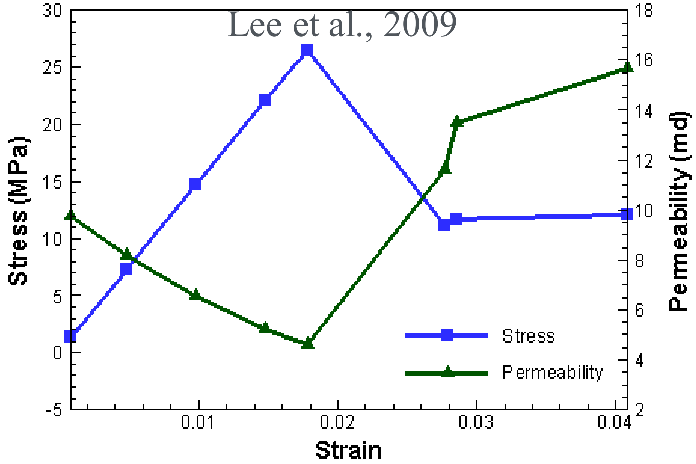
Elastic phase

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

Damage phase

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

Tang et al., 2002



Significance & Impact of Research

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- Uncertainty in material parameters and the in-situ stress
  - Estimate hydraulic diffusivity and criticality distribution
  - Combine an initial probabilistic description with the information from micro-seismic measurements
  - Arrive at criticality solutions that are conditioned on both field data and our prior knowledge.

Scientific/Technical Approach

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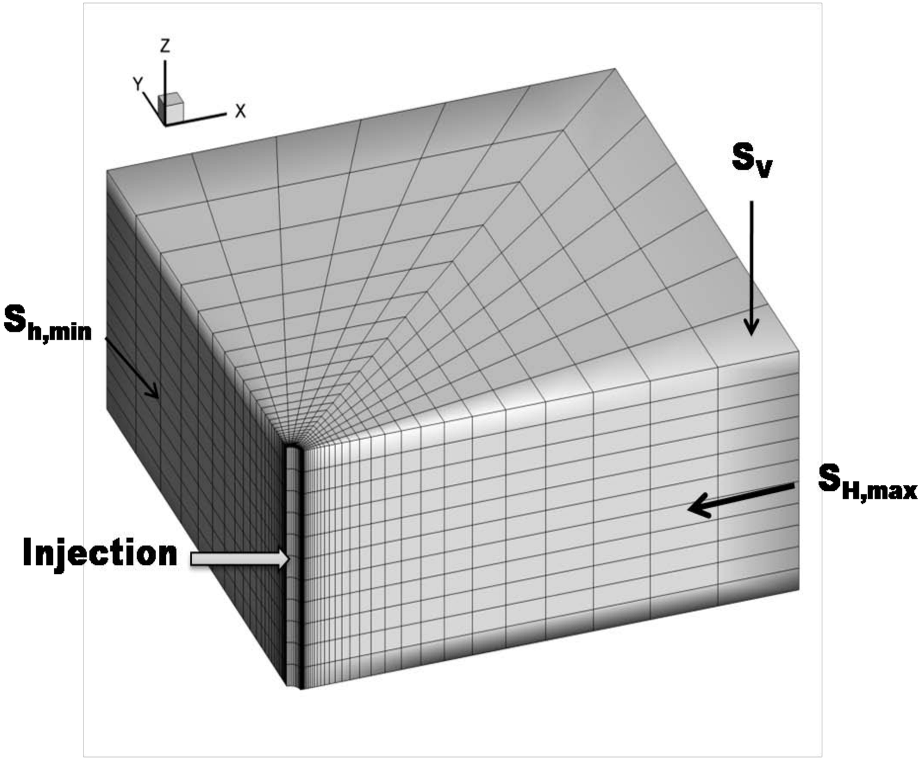
- Phase 1: Geomechanics model development
  - Develop and verify 3D Poro-thermoelastic FEM with damage mechanics & stress dependent permeability
  - Develop geostatistical algorithms for rock permeability and criticality, stochastic description of rock mass stress and strength and generation of an ensemble of prior models

- Future work
  - Improve the FEM program to treat large scale problems
  - Implement stochastic algorithms in the model
  - Conduct triaxial compression tests to determine rock mechanical properties and asses the model predictions for predicting shear and tensile failure
  - Compare full model with field data

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

- Damage mechanics
- Stress dependent permeability
- Convective heat transfer
- Rock heterogeneity
- Injection rate and pressure BC



Simulation of Injection Experiment

3D rock body of dimensions x =5 m, y =5 m, z = 2.2 m. Water is injected into the granitic rock from a central interval of 0.2 m. Temperature difference of 50 C.

Distribution of damage, permeability, pore pressure, temperature, effective tangential stress, axial stress, respectively (a-f) after 6 hrs of Pressurization (15-60 MPa).

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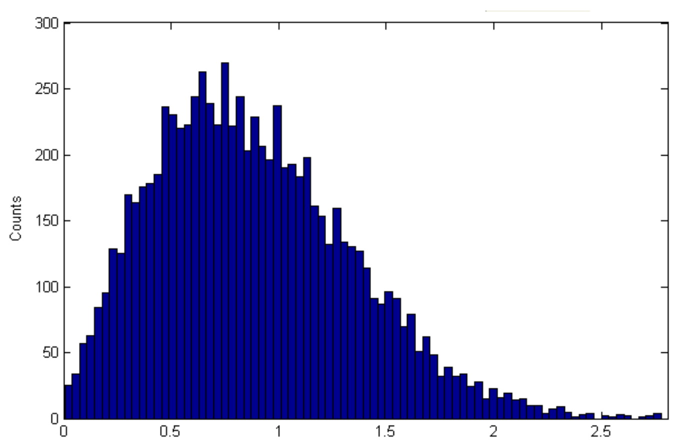

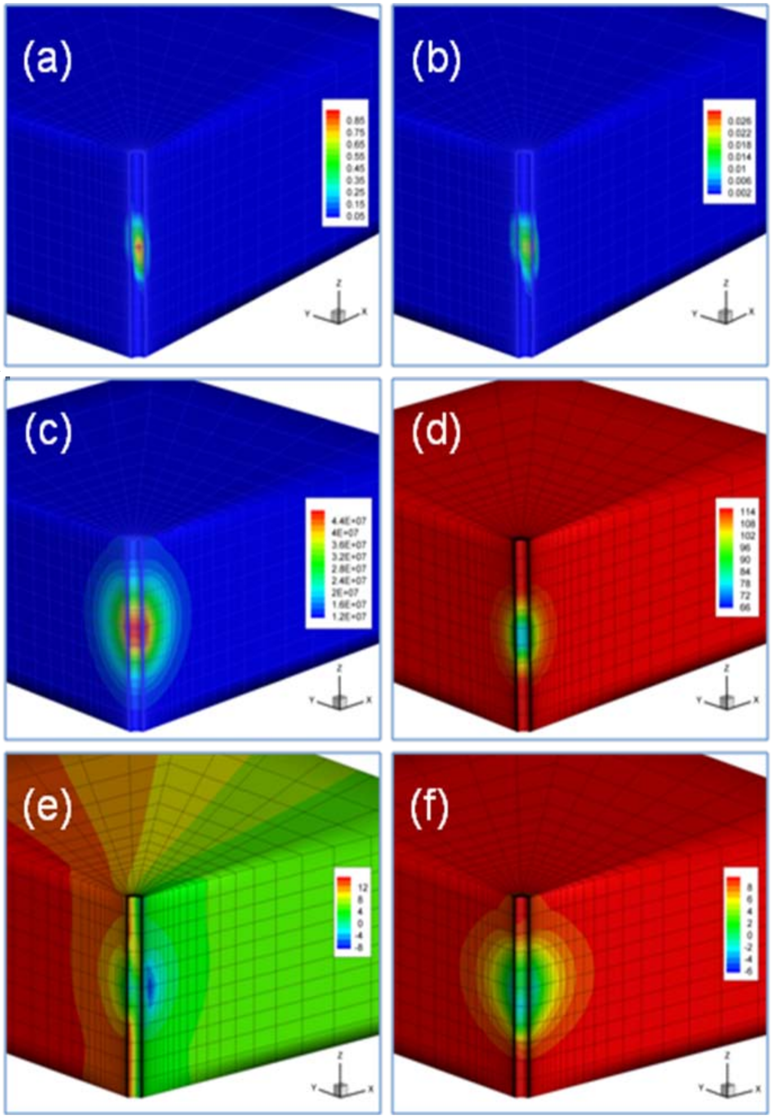

Accomplishments, Expected Outcomes and Progress

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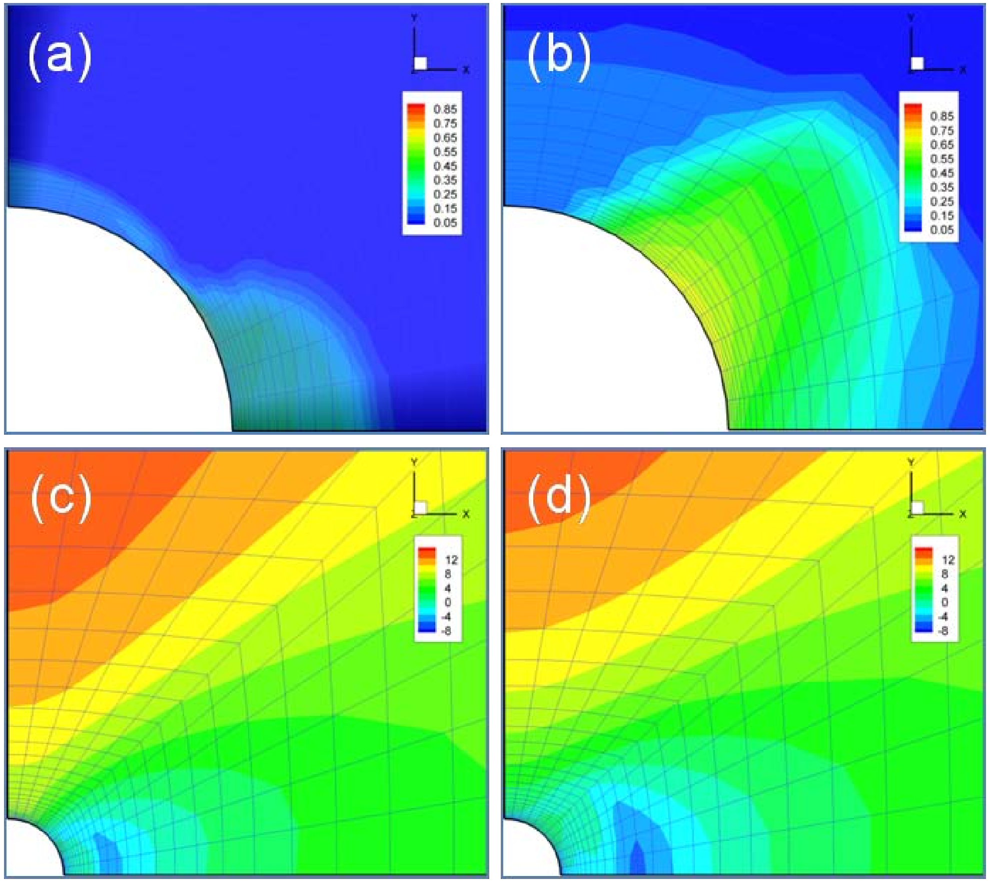
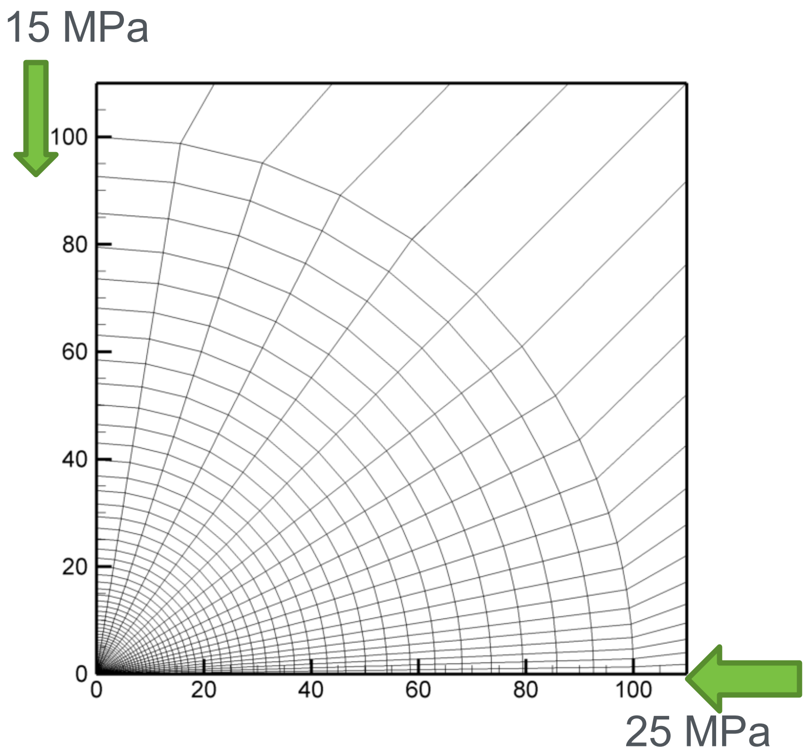
Comparison of damage and effective tangential stress distributions after 6 hrs:

(a) damage distribution for isothermal injection

(b) damage distribution for cooling case.

(c) Differences of effective tangential stresses for isothermal & cooling



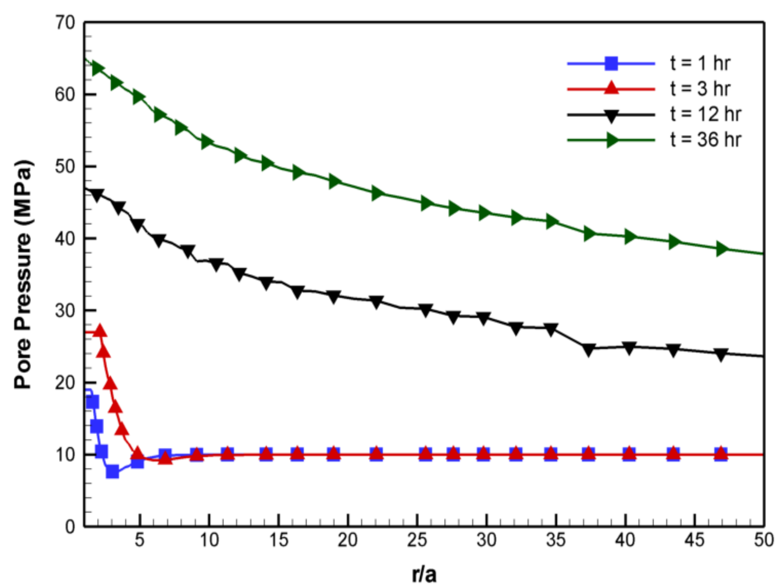


Mesh: a domain of 110 m x 110 m; 6303 nodes & 2020 elements

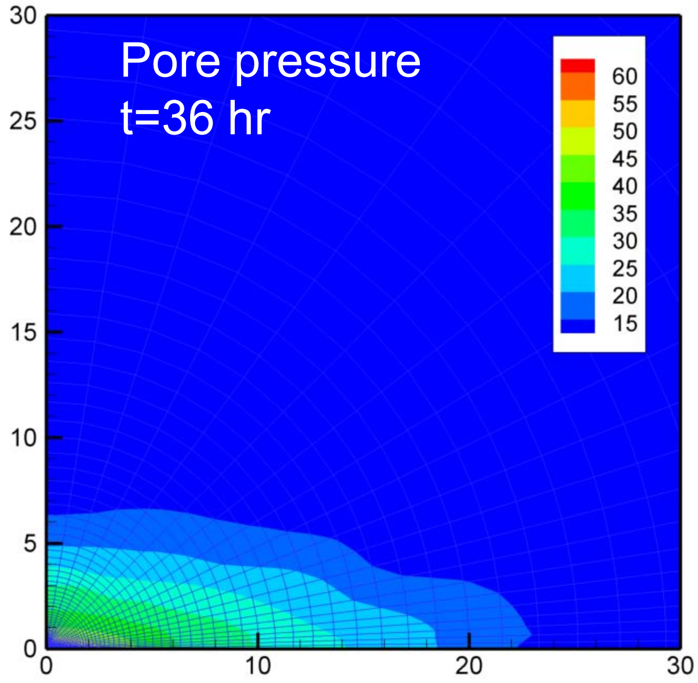
- . 8 nodes for displacements & 4 nodes for pressure &temp.

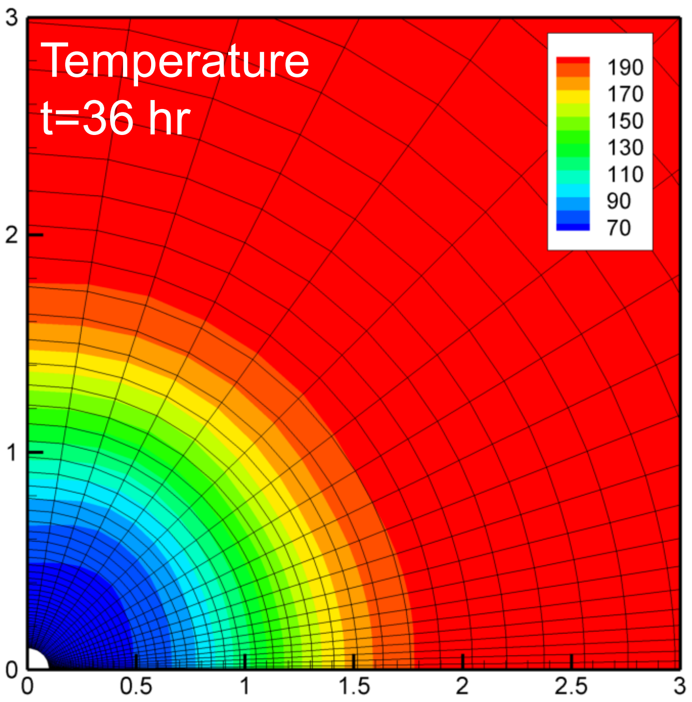
Granitic Reservoir

- E ~ 39.9 GPa (Weibull Distributions, n=2)
- Initial Avg Permeability of $k=10^{-2}$ md (Weibull Distributions, n=2)
- $P_{reservoir}$ = 10 MPa
- $T_{reservoir}$ = 200° C
- $T_{injection}$ = 65 ° C

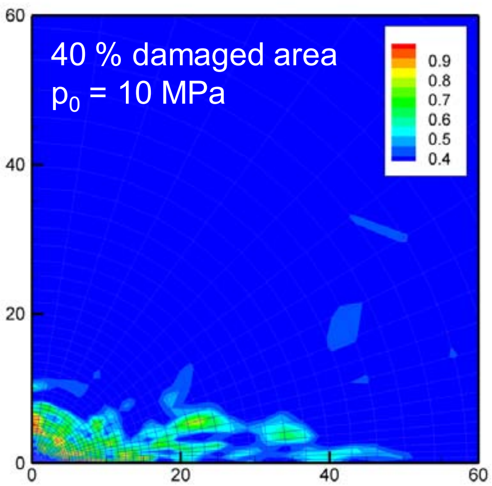


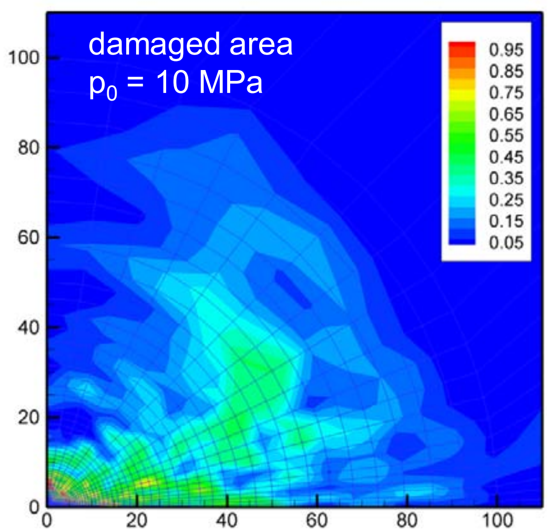
Pressure & Temperature Distributions

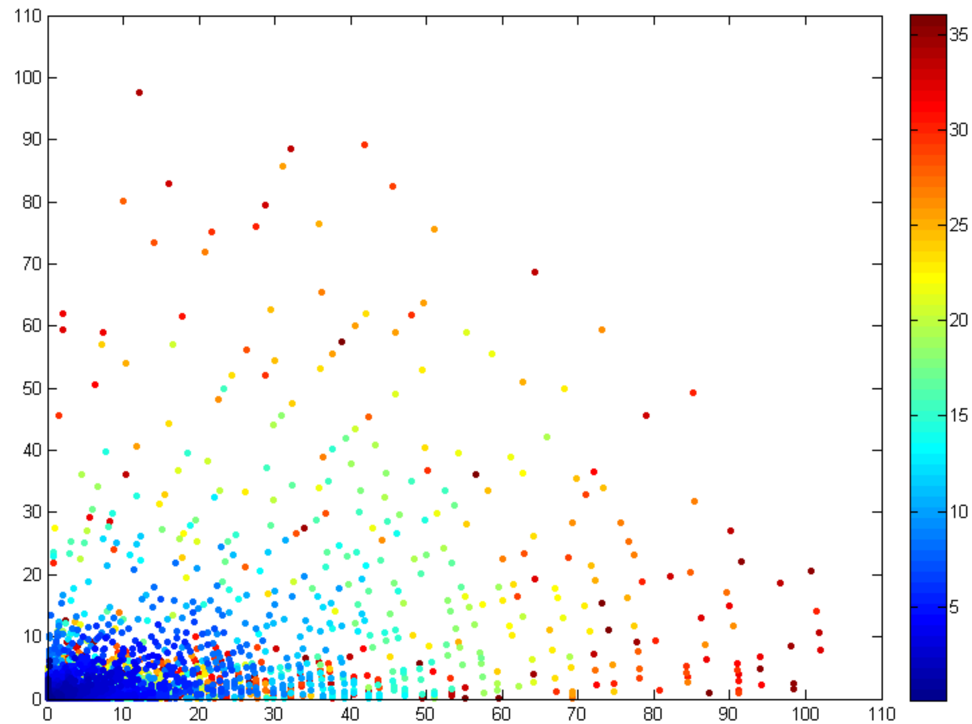




Rock Damage & Potential for Induced Seismicity

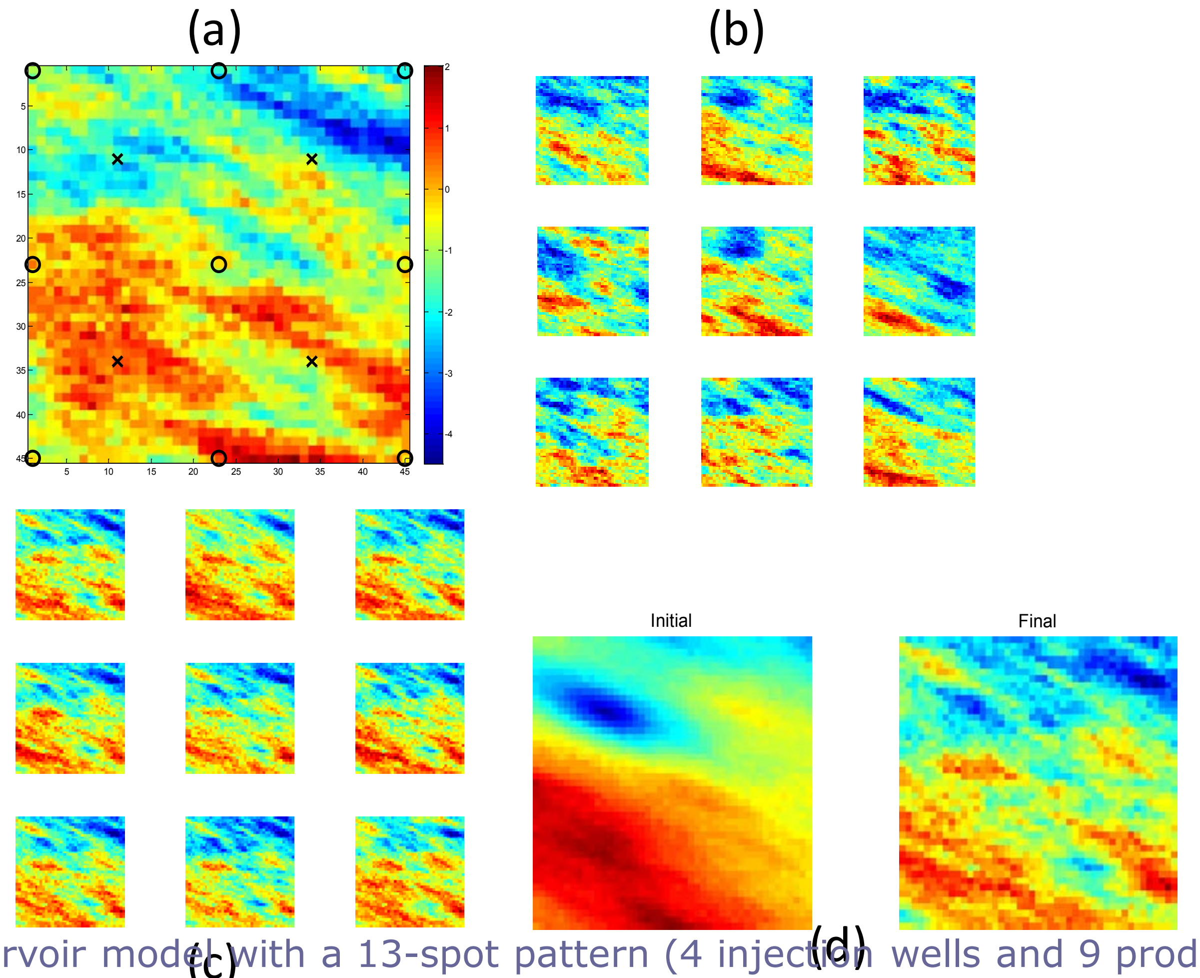






Failure events at different times (scale in hrs)

EnKF Procedure development



45x45x1 reservoir model with a 13-spot pattern (4 injection wells and 9 production wells); True permeability field (b) Nine samples from initial ensemble (generated by *sgsim*) (c) Updated (final) nine realization at the end of EnKF procedure (d) Mean of initial ensemble and mean of final ensemble.

Project Management/Coordination

- Work will continue on schedule
- Bulk of work done by graduate students
- Anticipate addition of a Post-Doc to group
- Will likely attract funds from petroleum industry- Crisman Institute
- Will meet with partners this summer (possibly in June) to coordinate future testing and input data needs, planned injection experiments; stress regimes, rates,

- This project integrated with other projects through workshops; demonstration projects

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 planned EGS experiments by AltaRock
- We plan to use results from European and Australian EGS experiments as well
- Future work includes
  - improve FEM program and solvers to enable treatment of large scale problems; fine tune damage interpretation (fracture)
  - develop and implement contact algorithms
  - perform analysis using various geo-mechanical variables
  - implement developed stochastic algorithms in the model
  - perform triaxial compression tests to determine rock mechanical properties and asses the model predictions for predicting shear and tensile failure

Mandatory Summary Slide

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- **We have demonstrated**:
- Development of a SBRC tool based on geomechanics with relevant physical processes such as pressure diffusion and cooling, and heterogeneity
- Implemented damage mechanics in the FEM and shown that the approach promises to be an effective tool for simulation rock failure in response to coupled processes
- We have developed EnKF procedure for use in the model

Related Publications

- Lee, S. H. and Ghassemi, A., 2010. "Themo-poroelastic analysis of injection-induced rock deformation and damage evolution." Proc., 35th Workshop on Geothermal Reservoir Engineering. Stanford University, CA, February 1-3, 2010.

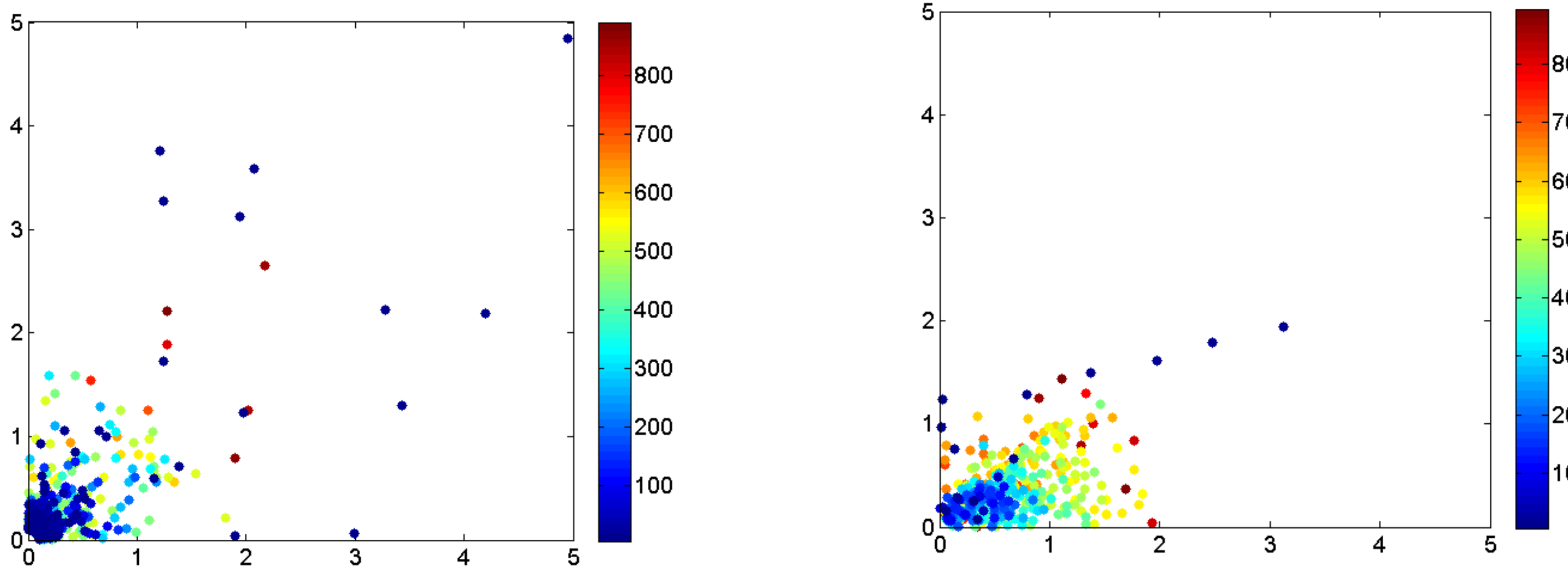
- Lee, S. H. and Ghassemi, A. 2010. "A Three-Dimensional Thermo-Poro-Mechanical Finite Element Analysis of a Wellbore on Damage Evolution." 44th US Rock Mechanics Symposium and 5th U.S.-Canada Rock Mechanics Symposium, held in Salt Lake City, UT June 27–30, 2010.

- Lee S. H. and Ghassemi, A., 2009. "Thermo-poroelastic Finite Element Analysis of Rock Deformation and Damage." 43rd US Rock Mech. Symp., Asheville, NC June 28th – July 1, 2009.

- Akbarnejad-Nesheli, B., and Ghassemi, A. 2009. "Undrained Poroelastic Response of Berea Sandstone and Indiana Limestone to Confining and Deviatoric Stress Change." 43rd US Rock Mech. Symp., Asheville, NC June 28th – July 1, 2009.

- Jafarpour B., Tarrahi M. 2010. (in revision): "Assessing the Performance of the Ensemble Kalman Filter for Subsurface Flow." Water Resources Research.

Comparison with pore pressure approach



Simulation results showing potential locations of micro-seismicity. (a); pore pressure criticality, Shapiro et al., (b) rock failure criticality (this study).