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Three-dimensional Modeling of Fracture Clusters in Geothermal Reservoirs

May , 2015

Principal Investigator:
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The University of Oklahoma

EGS Component R&D › Stimulation Prediction Models

Relevance/Impact of Research

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- The objective is to develop a 3-D numerical model propagation of multiple fractures to help predict geothermal reservoir stimulation using VMIB
- Able to simulating mode I, II, and III (tensile, shear, and tearing)
- Consider thermal and poroelastic effects; alleviate the need for explicit propagation criterion
- Help remove barriers to reservoir design, the project will help increase reserves and lower costs
  - Contribute to securing the future with Enhanced Geothermal Systems
  - Permeable zones have to be created by stimulation, a process that involves fracture initiation and propagation in the presence of natural fractures
  - Fracture can propagate in modes other than tensile
  - Reservoir creation and control

Scientific/Technical Approach

- Physical processes considered
    - 3D fracture propagation driven by hydraulic pressure and thermal stress
        - Pressurization and cooling
        - Pore pressure effects
        - Fracture interactions
    - Non-linear rock deformation
    - Rock heterogeneity
    - Modes I, II, III
- Calibration using lab and field data such as stress-strain behavior and pressure-time record

- Thermo-poroelastic Constitutive Equations

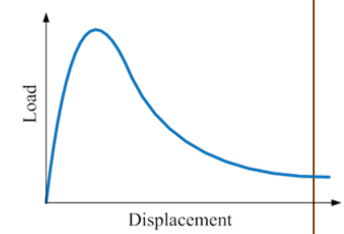
$$\dot{\sigma}_{ij} = 2G\dot{\varepsilon}_{ij} + \left(K - \frac{2G}{3}\right)\dot{\varepsilon}_{kk}\delta_{ij} + \alpha\,\dot{p}\delta_{ij} + \gamma_1\dot{T}\delta_{ij}$$

$$\gamma_1 = K\alpha_m \qquad \beta = \frac{\alpha - \varphi}{K_s} + \frac{\varphi}{K_f}$$

$$\dot{\zeta} = -\alpha\dot{\varepsilon}_{ii} + \beta\,\dot{p} - \gamma_2\dot{T}$$

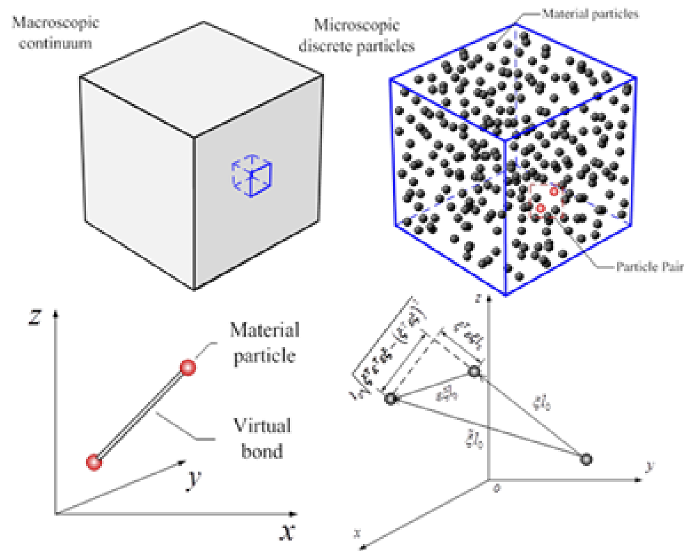
$$\gamma_2 = \alpha\,\alpha_m + \left(\alpha_f - \alpha_m\right)\phi$$

- Virtual Internal Bond (VIB) & Damage



-Material consists of particles Interacting (at the micro scale) through a network of virtual internal bonds (Kline, Gao, 98)

-The macro constitutive relation is derived directly from the cohesive law between material particles



Scientific/Technical Approach

- Virtual Multiple Internal Bond (VIB)

Fracture criterion is implicitly incorporated into the constitutive relation by cohesive law. It is not necessary to employ a separate fracture criterion

Shear effect is considered in the interaction of material particles

By developing a suitable bond evolution functions, the VMIB successfully simulates fracture initiation and propagation.

Bond density function

$$\Phi = \int_0^{2\pi}\int_0^{\pi} U_L D(\theta,\phi)\sin(\theta)\,d\theta d\phi + \int_0^{2\pi}\int_0^{\pi}\left(U_{R1}+U_{R2}+U_{R3}\right)D(\theta,\phi)\sin(\theta)\,d\theta d\phi$$

Contributed by Normal stiffness

Contributed by Shear stiffness

Scientific/Technical Approach

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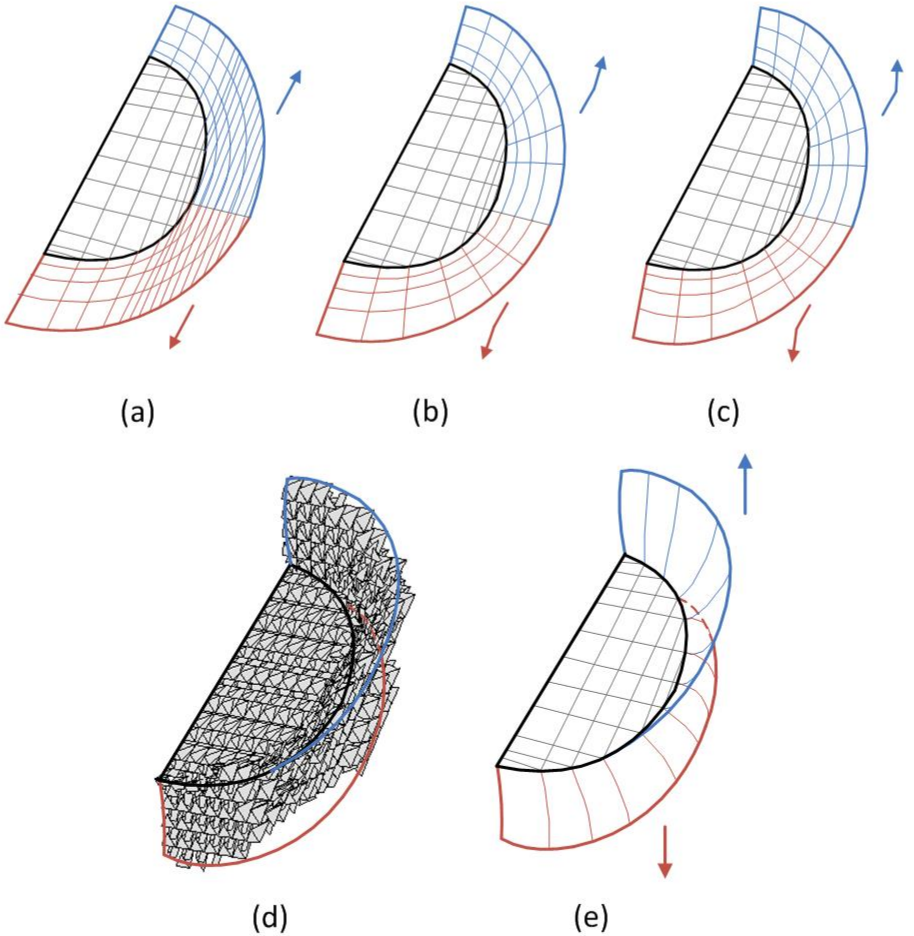
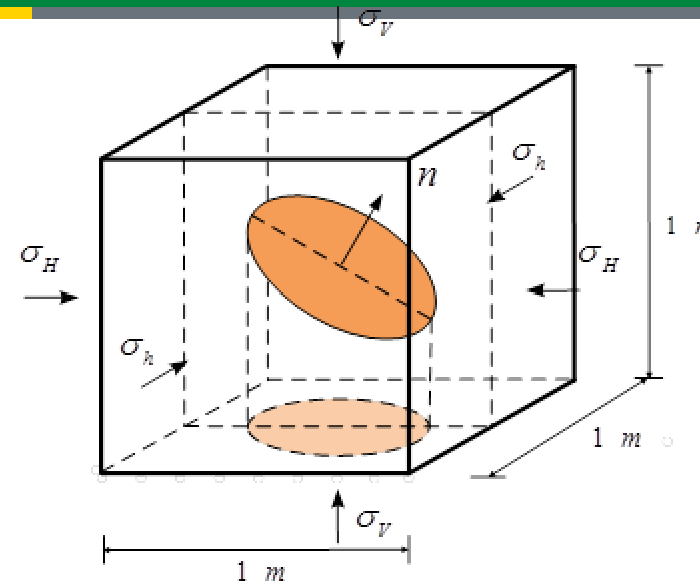
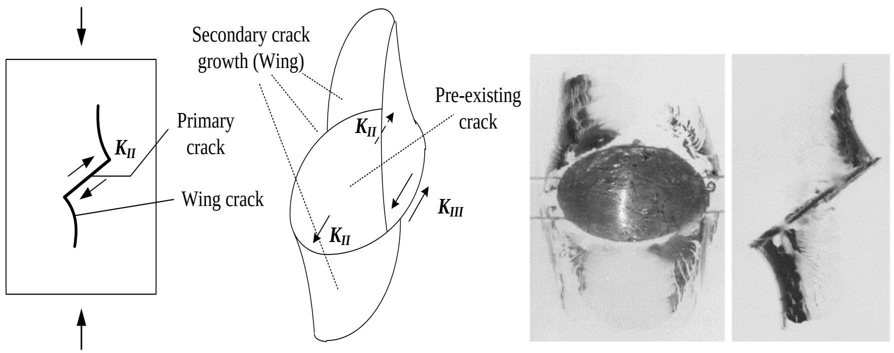
- Model 3D fracture propagation in multiple modes
  - Consider rock heterogeneity; 3D stress state; pore pressure and thermal stress
  - Multiple cracks, no explicit fracture criterion
  - Mixed mode (tensile, shear, and tearing) to aid in geothermal reservoir stimulation design
  - Develop special algorithms to improve accuracy and to enable fracture-natural fracture interaction in 3D
  - Compare with experiments, field data

Accomplishments, Results and Progress
Natural Fracture propagation in Mixed-Mode







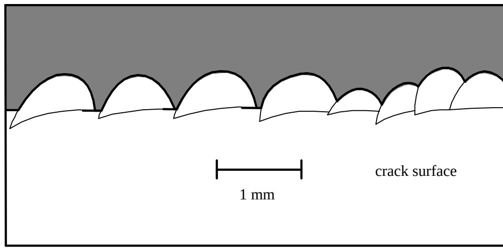
Case I: $\sigma_V = 0.8$, $\sigma_h = 0.8$, $\sigma_H = 0.8$, $p_0 = 1.6$ MPa

Case II: $\sigma_V = 1.6, \sigma_h = 0.8, \sigma_H = 0.8$, $p_0 = 2.4$ MPa

Case III: $\sigma_V = 2.0, \sigma_h = 0.8, \sigma_H = 0.8$, $p_0 = 2.8$ MPa

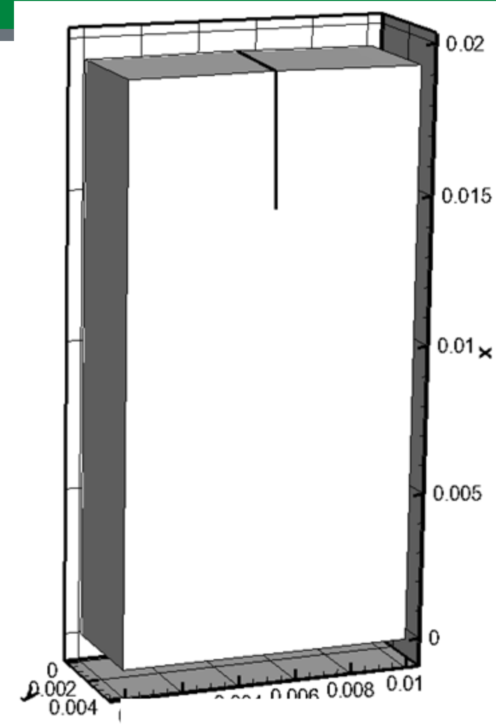
Case IV: $\sigma_V = 2.4, \sigma_h = 0.8, \sigma_H = 0.8$, $p_0 = 3.2$ MPa

Fragment of a resin sample with a single wing crack. (two horizontal lines are threads holding the inclusion) from experimental results of Dyskin et al (2003). Two-D wing crack growth (**K_{II}**) and 3D wing crack growth (Mixed mode of **K_{II}** &**K_{III}**).

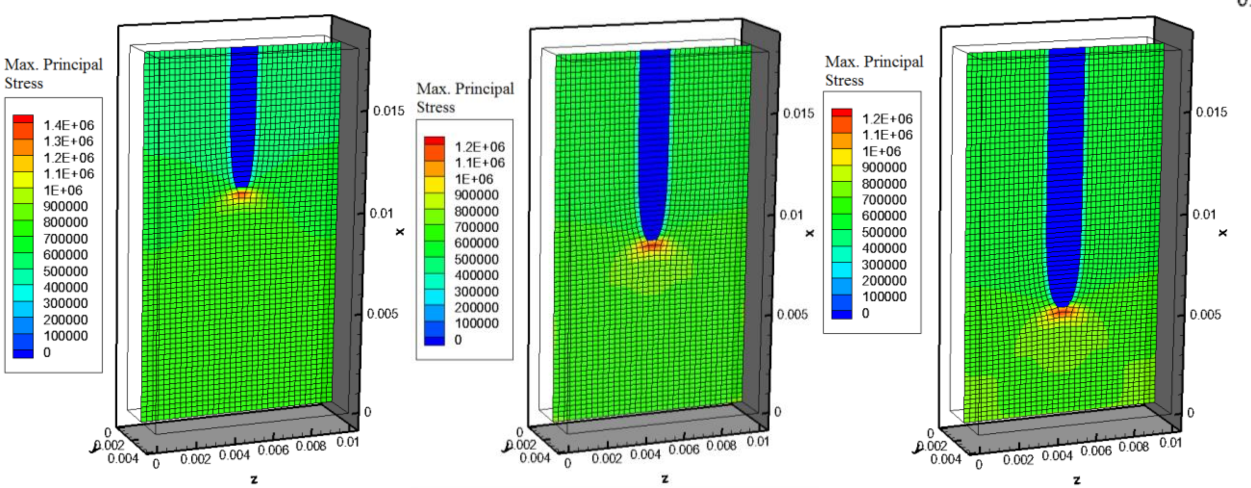


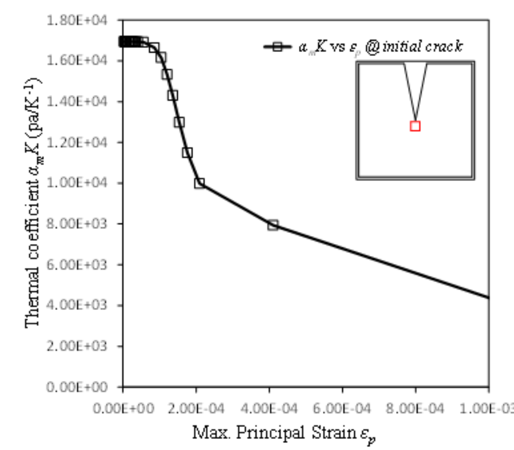
3D VMIB Model for Thermal fracturing

A cubic of granitic rock having a fracture as shown is simulated. Uniform cooling is assumed to test the mechanical response. The normal displacement of all rock surfaces except the top one are confined.



The middle slice of maximum principal stress contour with deformed mesh configuration (amplified 1200 times) when the rock is cooled by: (a)-3 ;(b)-6 ;(c)-9 ;(d)-12 ;(e)-15 ;(f)-18 .



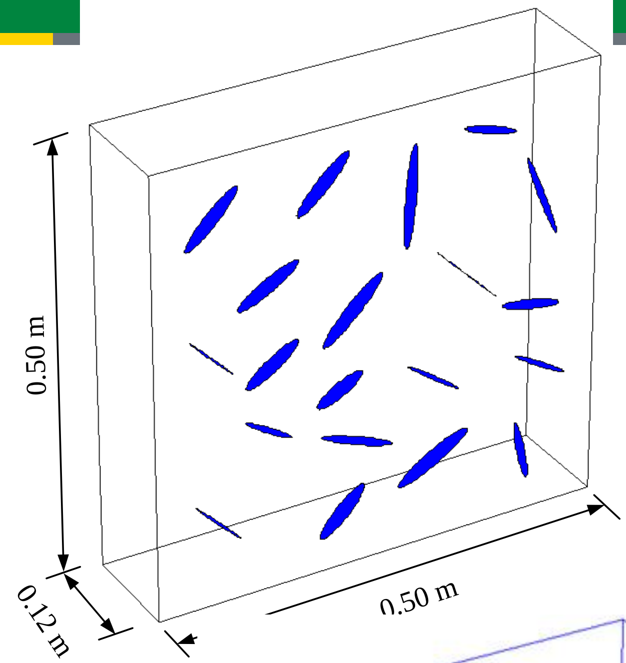


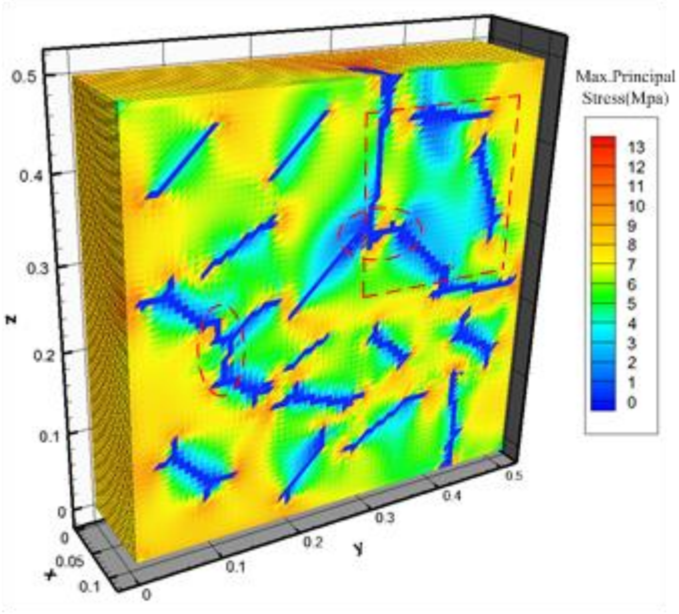
3D VMIB Model for Thermal fracturing

Randomly Distributed Multiple Fractures

Thermal fracture propagation and interaction. Multiple fractures are simulated with a structured mesh without re-meshing

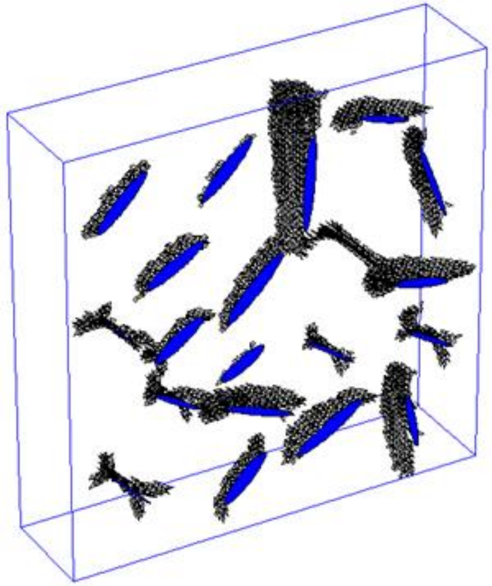
A cubic specimen of granitic rock with 20 randomly distributed small fractures is considered





Left: maximum principal stress contour when the rock was cooled by:-38 C.

Right: Propagation of thermal fracture when the rock was cooled by: -38 C.



3D VMIB Model for Thermal fracturing

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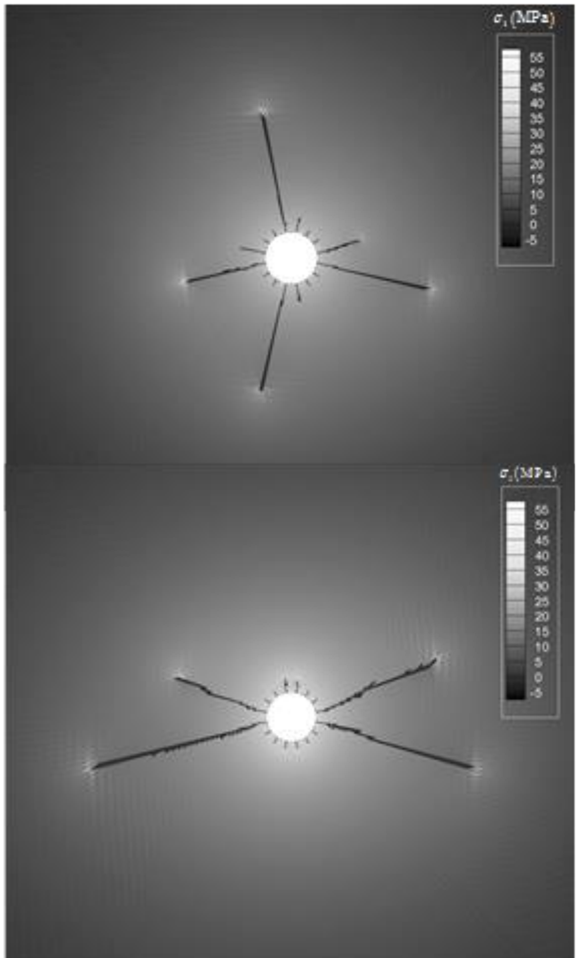
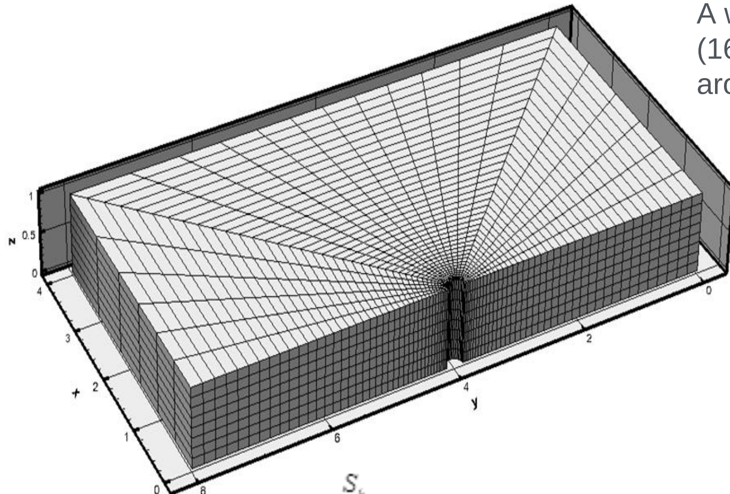
Randomly Distributed Multiple Fractures:

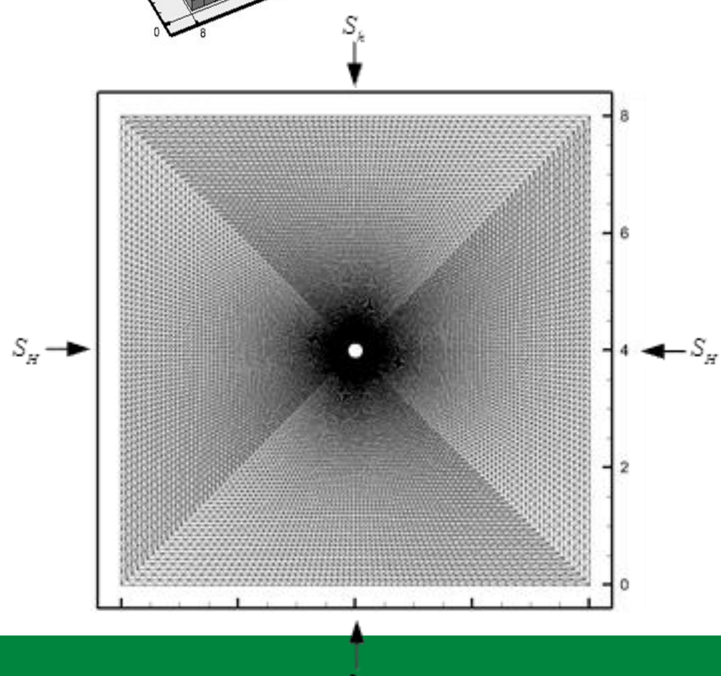
Left (top) isotropic stress state; (bottom) anisotropic stress

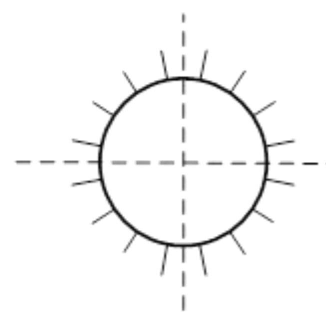




A wellbore with multiple pre-existing cracks (16) of 3.33-4 cm long are equally spaced around the well

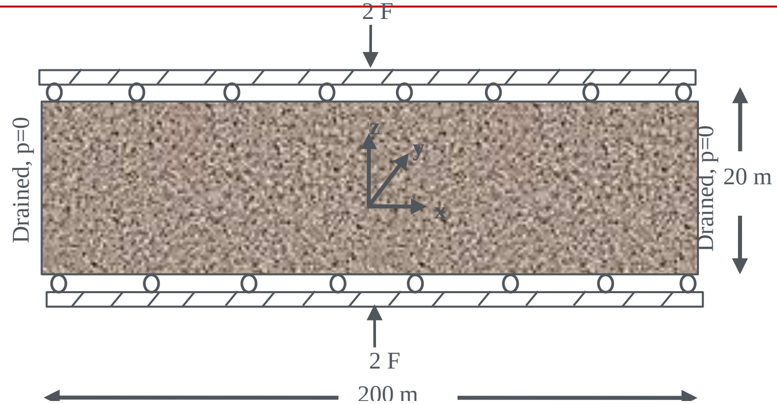
The initial temperature in the matrix is 200 C and 40 C on the surface of wellbore

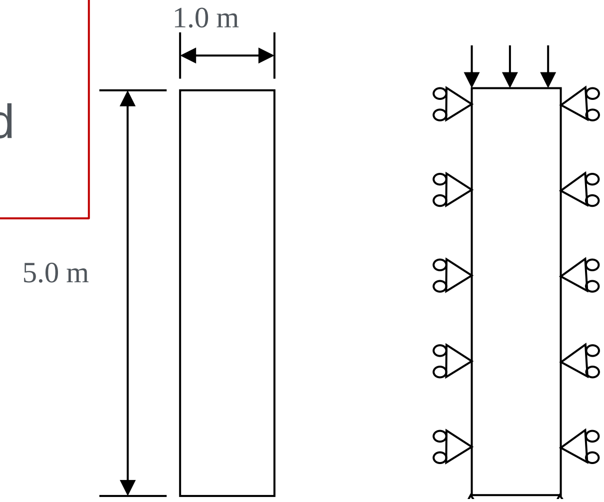


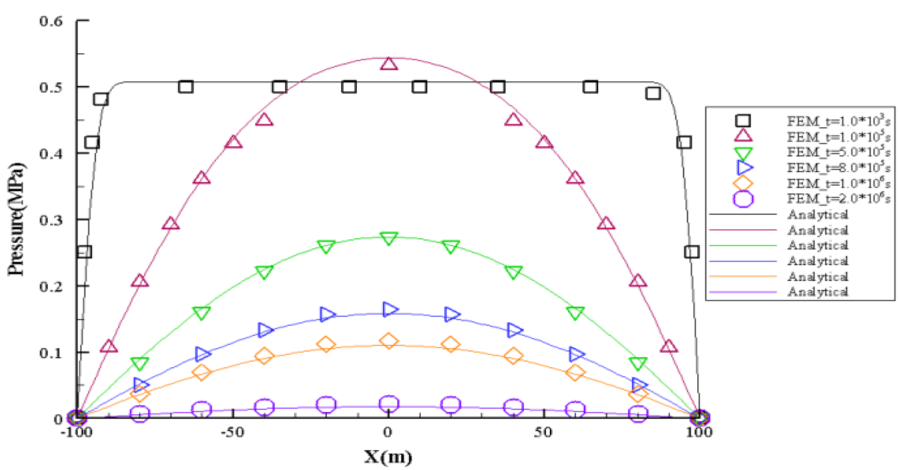


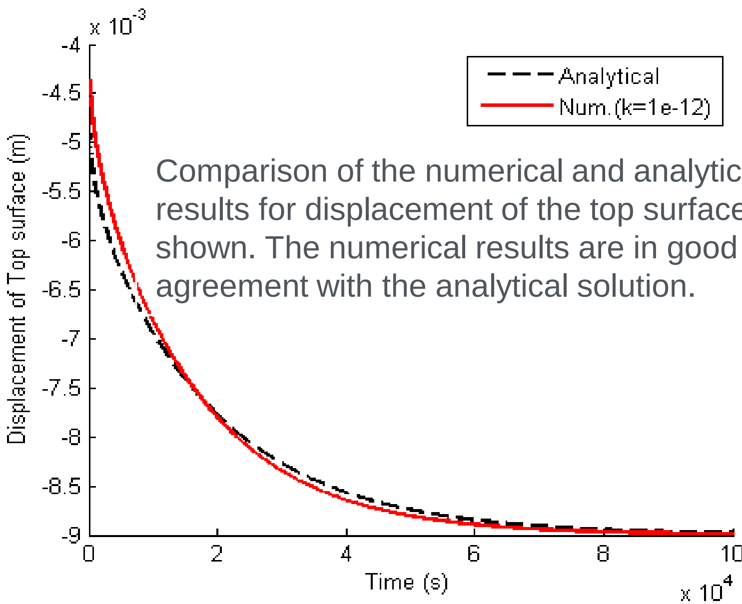
Poroelastic VMIB Model

3) Test problem for poroelastic VMIB:
One-D consolidation and Mandel's Problem:
Compression of a poroelastic column, layer of rock and ensuing displacements and pore pressure









Comparison of the numerical and analytical results for displacement of the top surface is shown. The numerical results are in good agreement with the analytical solution.

Accomplishments, Results and Progress
Poroelastic VMIB Model

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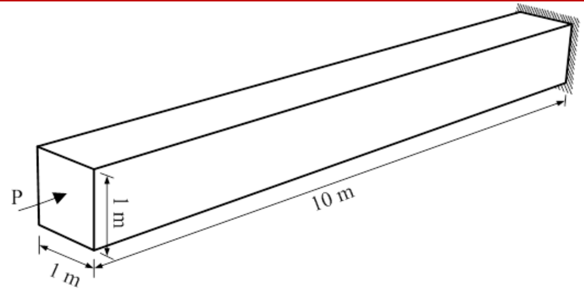
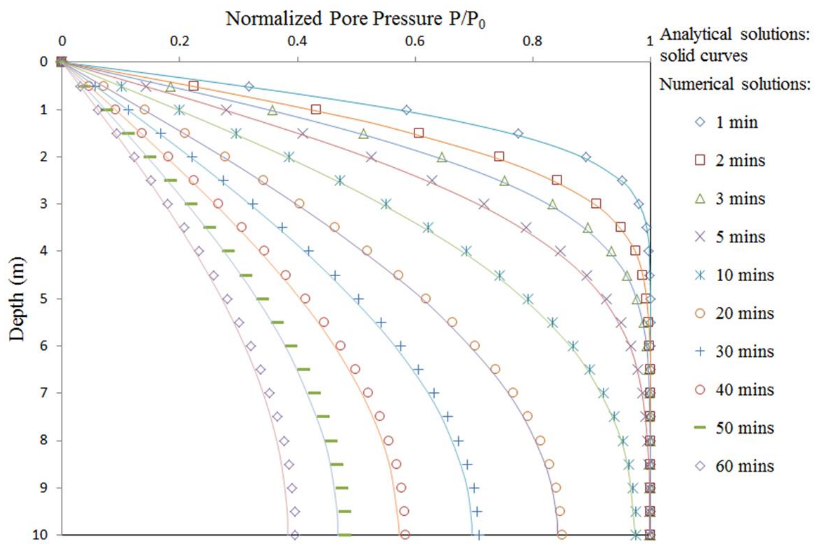
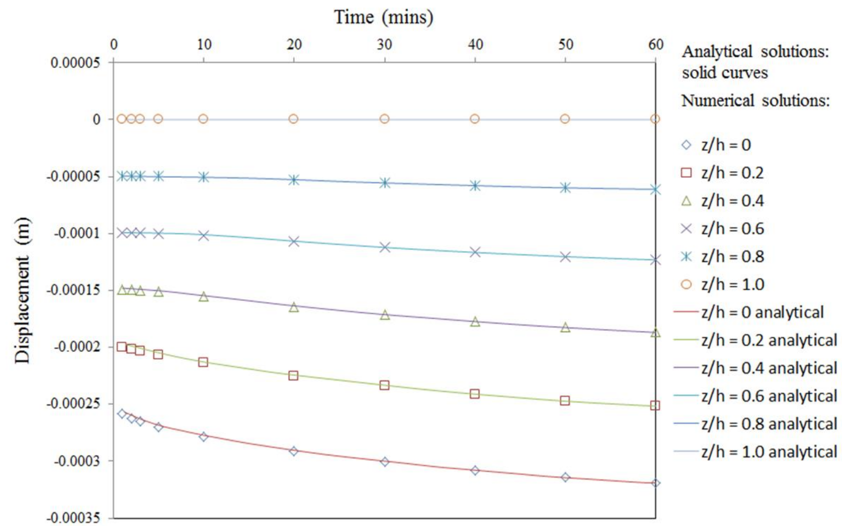
3) Test problem for poroelastic VMIB, damage:
One-D consolidation compression of a poroelastic column

Input Parameters for Terzaghi 1D Consolidation	
Shear modulus,	12.0 GPa
Poisson's ratio,	0.15
Undrained Poisson's ratio,	0.29
Biot's coefficient,	1.0
Permeability,	0.5 md
Fluid viscosity,	
Load,	







Comparison of the numerical and analytical results for pore pressure with depth and displacement of the top surface is shown. The numerical results are in good agreement with the analytical solution.

Modeling 3D Poroelastic Hydraulic Fracture Propagation

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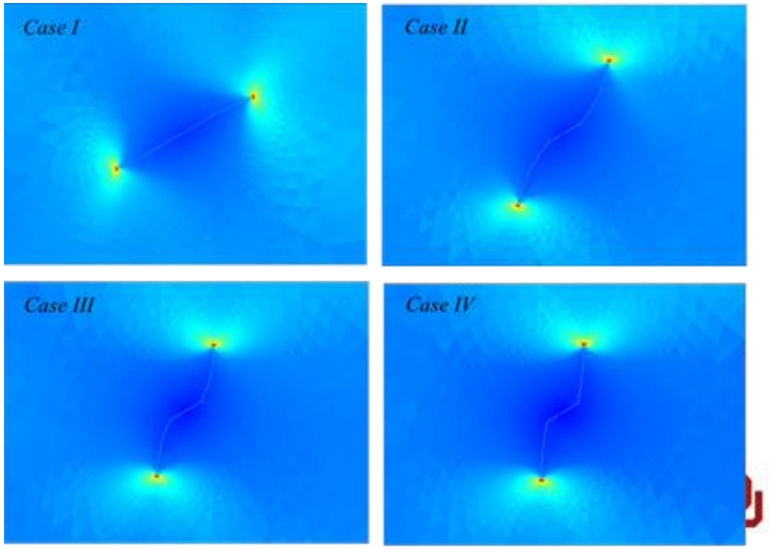
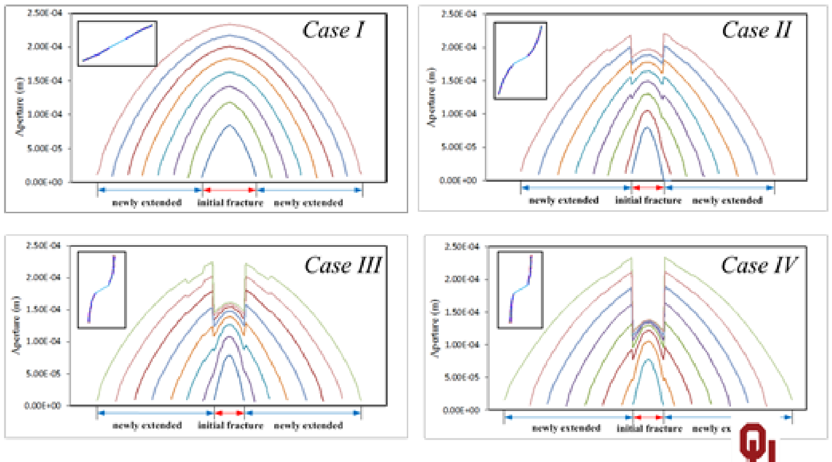
A hydraulic fracturing example for different in-situ stress states using the nonlocal damage version of the model. The present model is built in three-dimension, but the following examples are only use a single layer of volumetric element considering the computational volume

case I: $S_H = 1.0\text{MPa}; S_h = 1.0\text{MPa}$; case II: $S_H = 2.0\text{MPa}; S_h = 1.0\text{MPa}$
case III: $S_H = 3.0\text{MPa}; S_h = 1.0\text{MPa}$; case IV: $S_H = 4.0\text{MPa}; S_h = 1.0\text{MPa}$

The Young's modulus=20 GPa; Poisson's ratio=0.2;
Damage Parameters: $\varepsilon_0 = 1.2\times10^{-4}$ $\varepsilon_f = 6\times10^{-4}$

5 mm element is used in the mesh-refined area. The nonlocal interaction radius=2.5mm
viscosity =0.01 Pa.sec, Q=0.01 m^2/sec





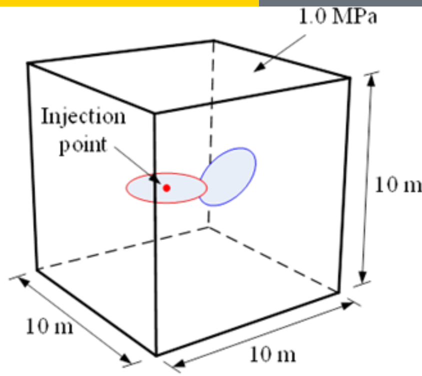
The principal stress contour during the fracture propagation for each in-situ stress: (a) case I;(b) case II; (c) case III; (d) case IV. Aperture and pressure profiles for each in-situ stress case on the left. Note the shear induced aperture on the wings.

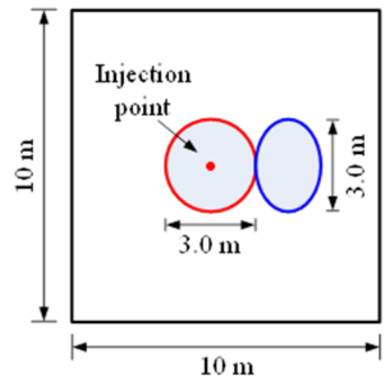
Hydraulic fracture and natural fracture interaction (3D)

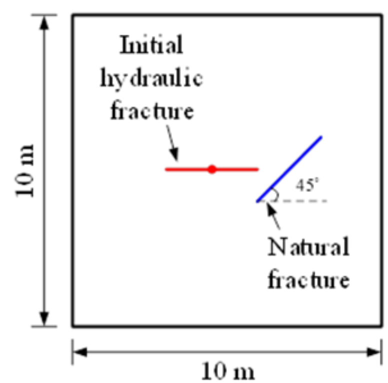
The red dot indicates the injection point
A natural fracture is located nearby initial hydraulic fracture
The diameters for hydraulic and natural fractures are both 3 meters. Natural fracture is inclined 45 degree to the horizontal plane
After hydraulic and connects with the natural fracture, the latter becomes part of the hydraulic fracture with complex curved surface

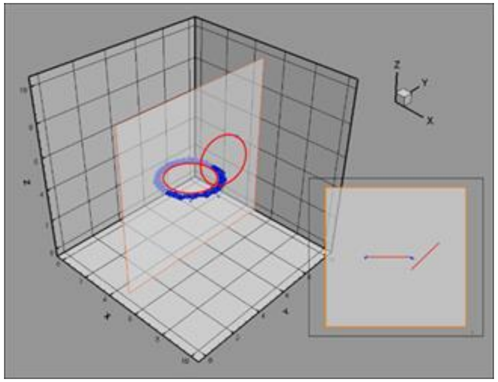
The pattern of fracture propagation displayed by damaged element with continued injection

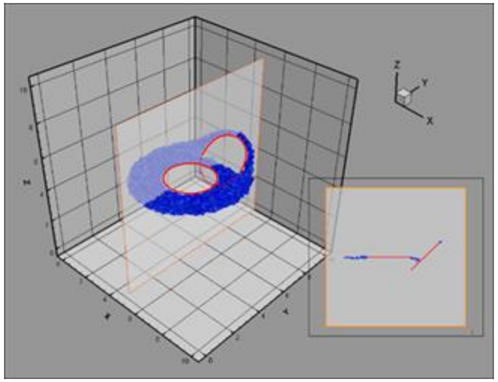
The Young's modulus=28 Gpa; Poisson's ratio=0.15;
Damage Parameters: $\varepsilon_0 = 0.3\times10^{-3}$ $\varepsilon_f = 4.0\varepsilon_0$
5 mm element is used in the mesh-refined area. The nonlocal interaction radius=2.5mm
viscosity =0.03×10^{-03} Pa.sec, Q=0.002 m_3/sec

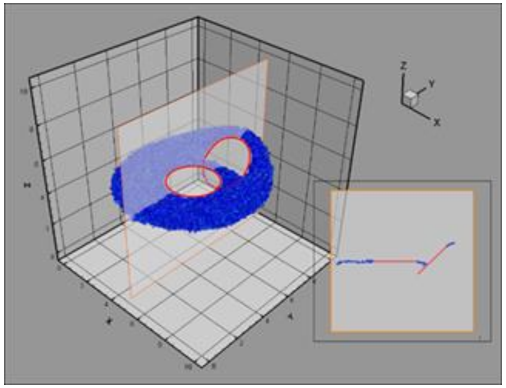












Accomplishments, Expected Outcomes and Progress

3D fracture propagation model using the finite element method with VMIB has been developed

- VMIB has been also been combined with pore pressure, thermal stress & poroelastic effects
- Multiple fractures and propagation modes can be considered
- Results show good agreement with lab data
- Nonlinearity and rock heterogeneity can be considered
- Also implemented non-local damage mechanics
- State of the art

Accomplishments, Results and Progress

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Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Elaborate the three-dimensional multiple internal bond method	3D VMID successfully developed	10/2010
Implement VMIB in 3D FEM and compare model with lab results; verify simulations and add hydraulic fracture routines	VMIB implemented; results compare well with available lab data (literature); pressurization routines developed & tested	10/2011
Implement in a 3D FEM, Hydraulic fracture routine in the VMIB-FEM; Include joint elements; Hydraulic pressurization; Included thermal effects	Thermal effects and pressurization successfully implemented in 3D, joint elements implemented	6/2012
Study and verify thermal and poro effects on fracturing	Thermal effects in 3D, poroelastic effects in 3D (ongoing); mesh optimization solutions	2015
Application to lab and/or field fracturing experiments	Applied to some lab experiments, block experiment application ongoing	2015

Future Directions

- key activities for the rest of FY and to project completion (Dec. 2015)
  - Continue to develop the 3-D VMIB numerical model for propagation of multiple fractures in mixed mode (tensile, shear, and tearing) coupled with fluid flow
  - Develop special algorithms to improve accuracy and to enable fracture-natural fracture interaction in 3D, additional poroelastic and thermoelastic analyses
  - The model will be applied to interpretation laboratory large block hydraulic fracture experiment published and planned as part of another project

Summary Slide

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- We have developed the VMIB method for 3D fracture propagation in rock
- Numerical algorithms have been developed to allow element partitioning, application of hydraulic pressure, and consideration of heterogeneity in 3D
- A 3D poro- and thermoelastic fracture propagation model has been developed and verified against experimental results
- The model has successfully predicted mode I and mode III fracture growth in compression
- Thermoelastic fracture propagation in 3D has been successfully modeled

Project Management

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Timeline:

Planned Start Date	Planned End Date	Actual Start Date	Actual /Est. End Date
01/1/2009	12/31/2011	6/15/2009	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
$685,141	$171,285	$856,000	$780,000	$756,000	$130,000

- The project is behind as we started late (funds not allocated).
- PI and research team moved to OU but significant project delays have resulted from difficulties in transferring the contract between the DOE and Texas A&M to the University of Oklahoma. This has prevented availability of funds necessary to continue the research, resulting in a gap in research activities.
- Although slowed down, work has been ongoing.

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

May, 2015

Principal Investigator:
Ahmad Ghassemi
The University of Oklahoma

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

- 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

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

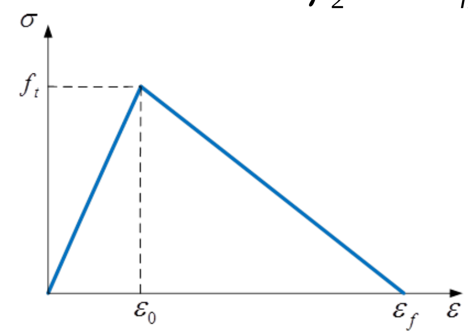
$$\dot{\sigma}_{ij} = 2G\dot{\varepsilon}_{ij} + \left(K - \frac{2G}{3}\right)\dot{\varepsilon}_{kk}\delta_{ij} + \alpha\,\dot{p}\delta_{ij} + \gamma_1\dot{T}\delta_{ij} \qquad \dot{\zeta} = -\alpha\dot{\varepsilon}_{ii} + \beta\,\dot{p} - \gamma_2\dot{T}$$

$$\gamma_1 = K\alpha_m$$

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

- Elastic Damage Mechanics

$$\varphi(\kappa) = \begin{cases} 0 & \text{if } \kappa \le \varepsilon_0 \\ \dfrac{\varepsilon_f}{\varepsilon_f - \varepsilon_0}\left(1 - \dfrac{\varepsilon_0}{\kappa}\right) & \text{if } \varepsilon_0 \le \kappa \le \varepsilon_f \\ 1 & \text{if } \varepsilon_f \le \kappa \end{cases}$$



Lee et al., 2009

- Stress Dependent Permeability

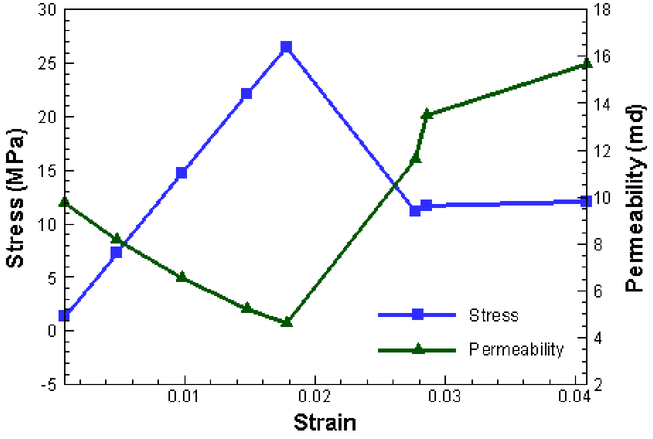
Elastic phase

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

Damage phase

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

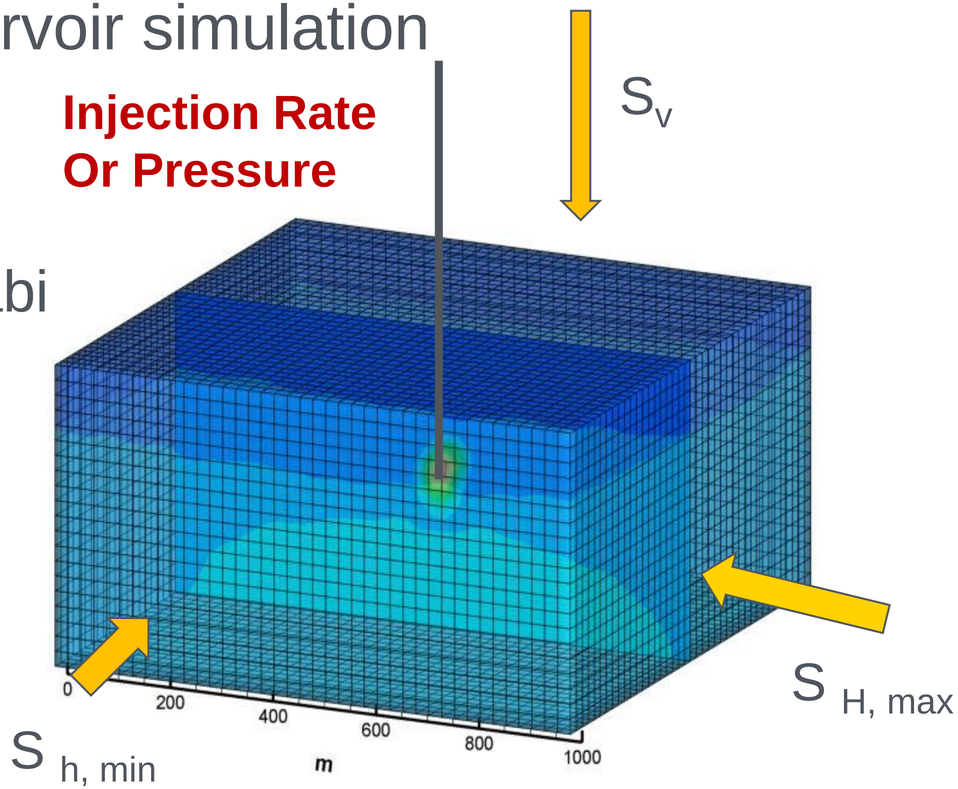
Tang et al., 2002



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

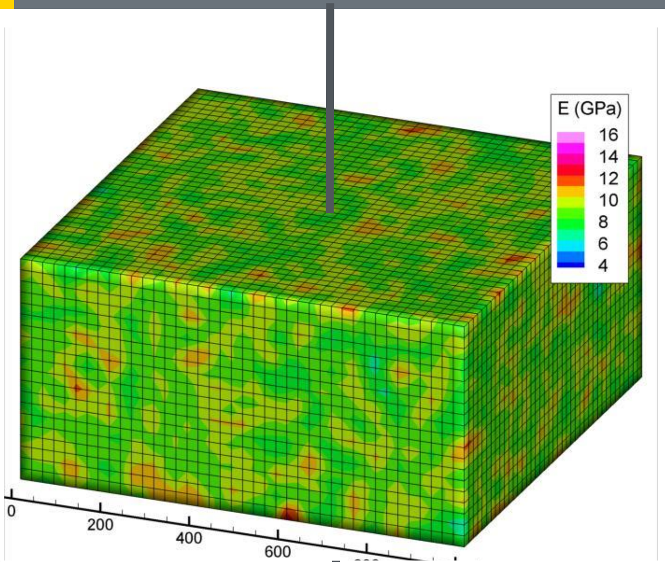
- Damage mechanics
- Stress dependent permeabi
- Convective heat transfer
- Rock heterogeneity
- Pressure & Injection rate

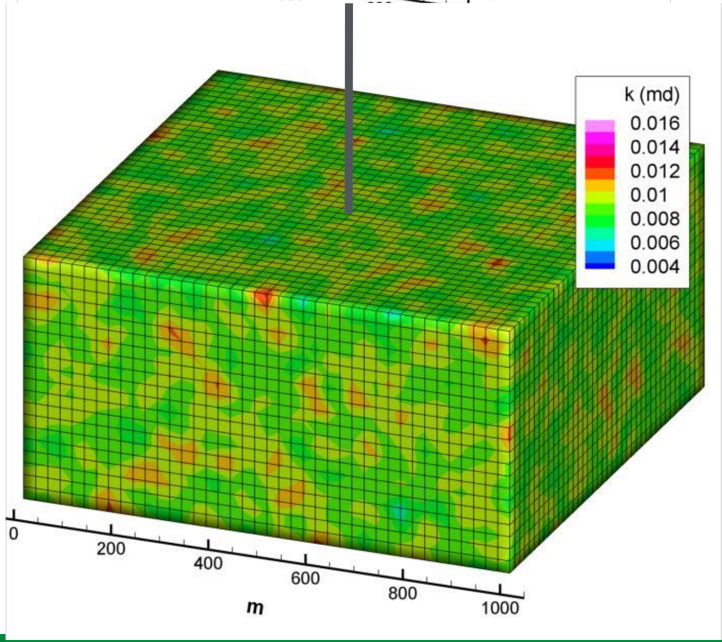
and pressure BC

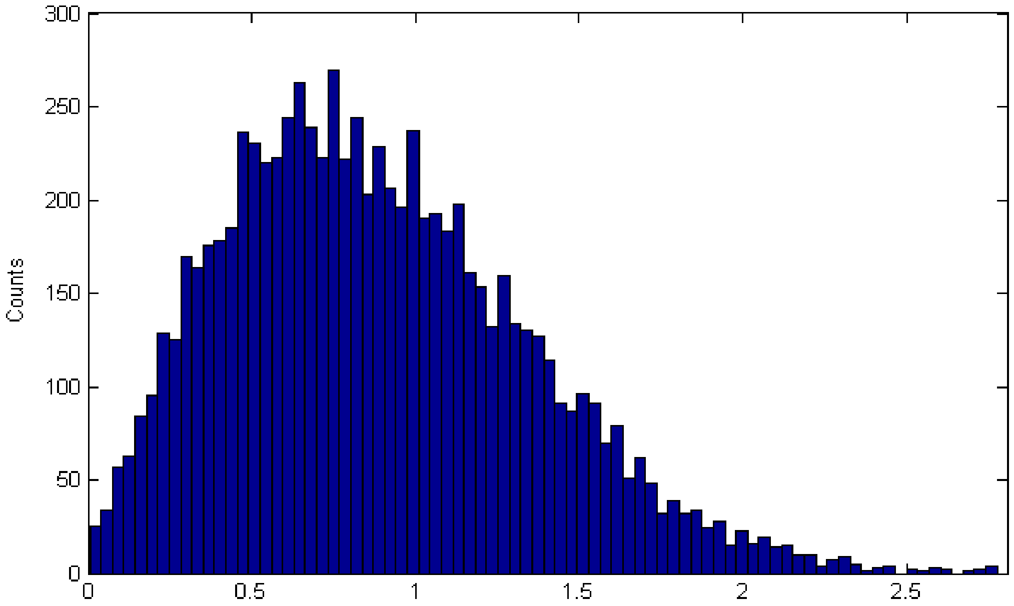


Simulation of Injection Experiment

- 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







Accomplishments, Expected Outcomes and Progress

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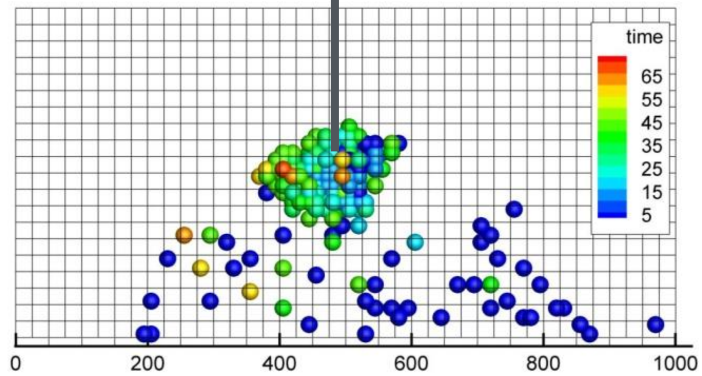
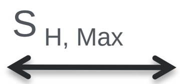
$S_{H,max}$= 48; $S_{h,min}$ =36; S_v= 60 MPa, p=10

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

Normal



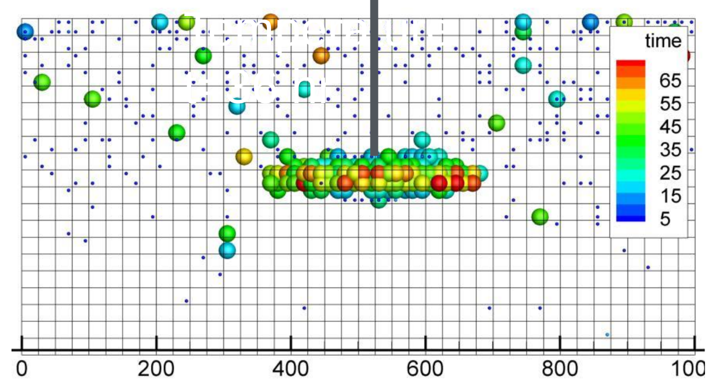
Point source injection cases

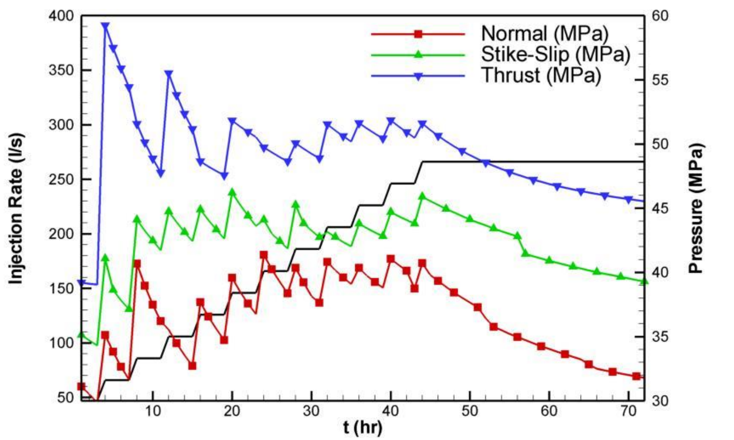


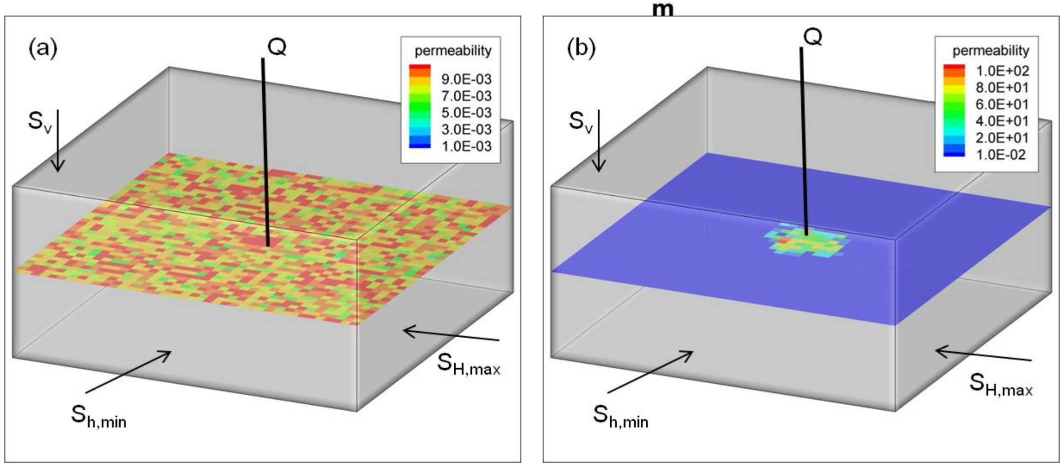
$S_{H,max}$= 95; $S_{h,min}$ =70; S_v= 60 MPa, p=10

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

Thrust







Accomplishments, Expected Outcomes and Progress

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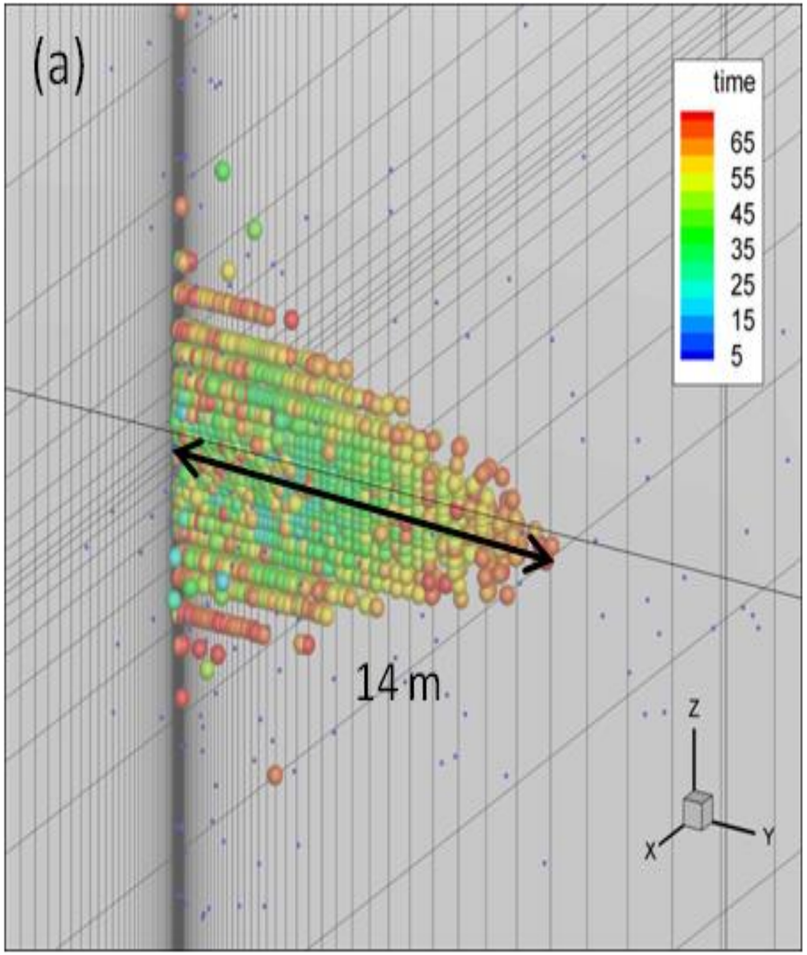
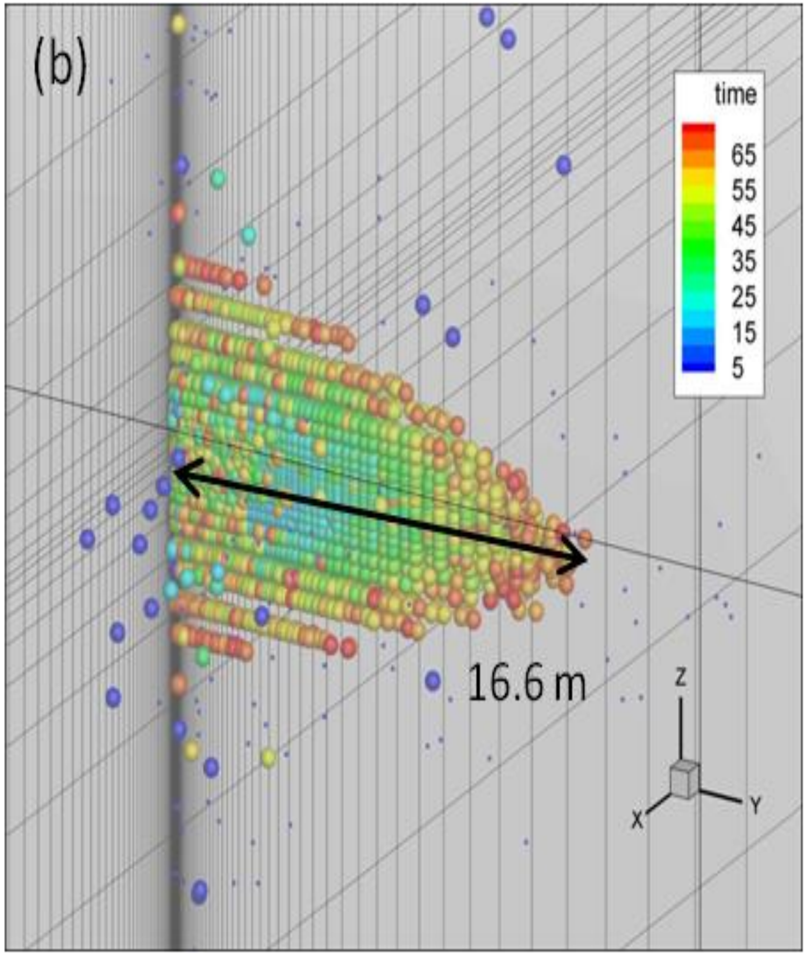
- **Role of thermal stress (wellbore simulation)**: MEQ events after 65 hrs of pumping: (a) isothermal and (b) cold water (50° C) injection into reservoir (200° C)-**See Supplements**



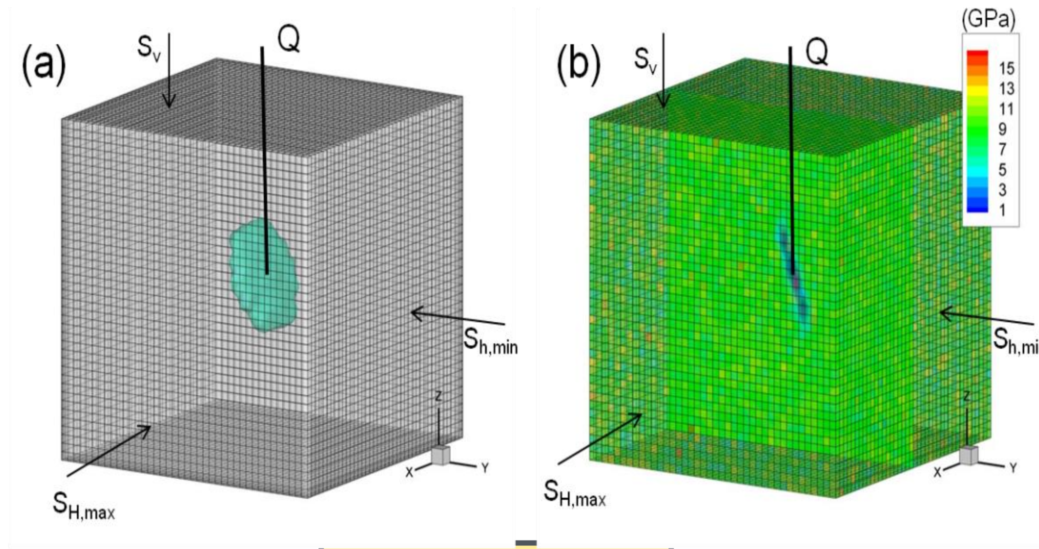


Accomplishments, Expected Outcomes and Progress

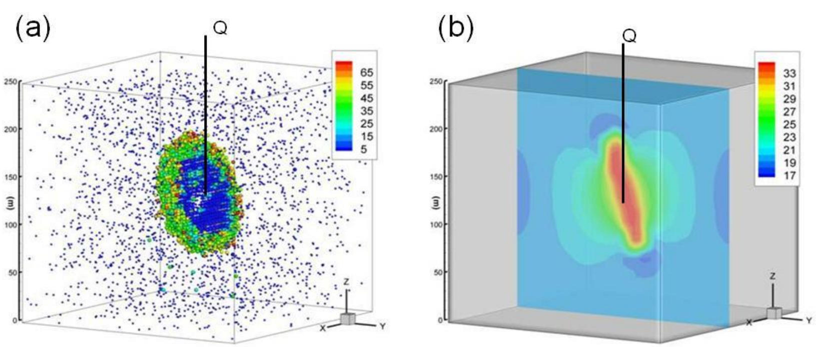
Injection-induced MEQ for GPK1 Soultz.; Natural fracture inclined 20° from vertical; 50 m radius NF modulus is (~0.1 MPa) with permeability of 1 darcy

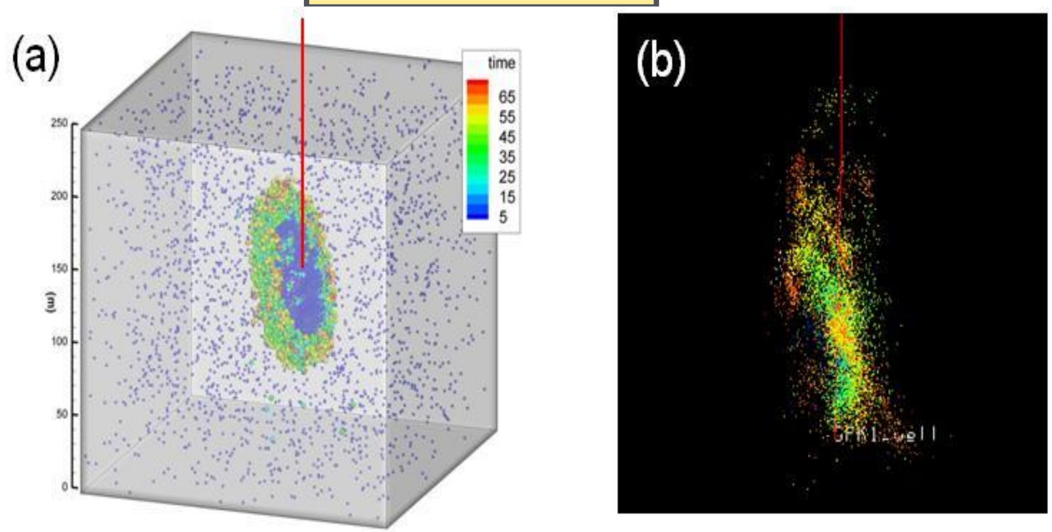
Normal stress regime:

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



Injection Rate:
24 L/sec





Accomplishments & Progress: Simulation of Phase I of Newberry Stimulation

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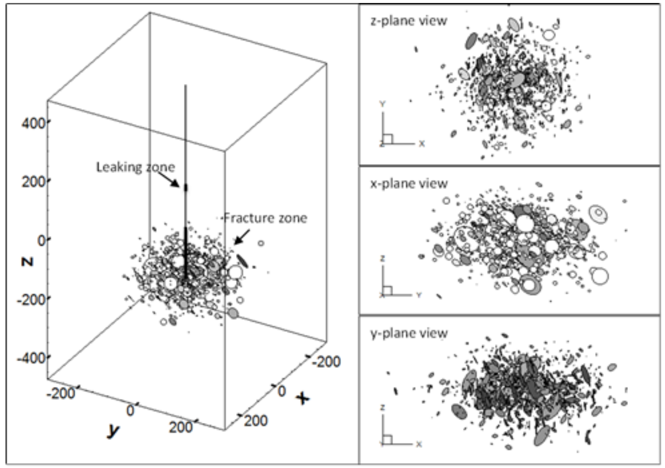
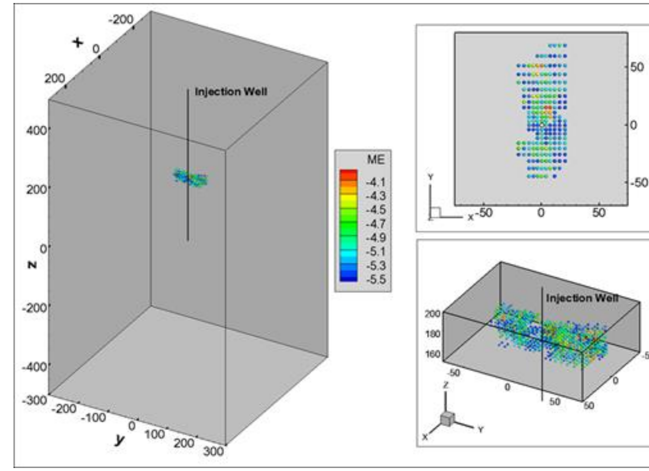
Based on field data from AltaRock, two injection zones are set at z = 161~184m (leak zone) and z = - 100 ~ -300m (target zone)

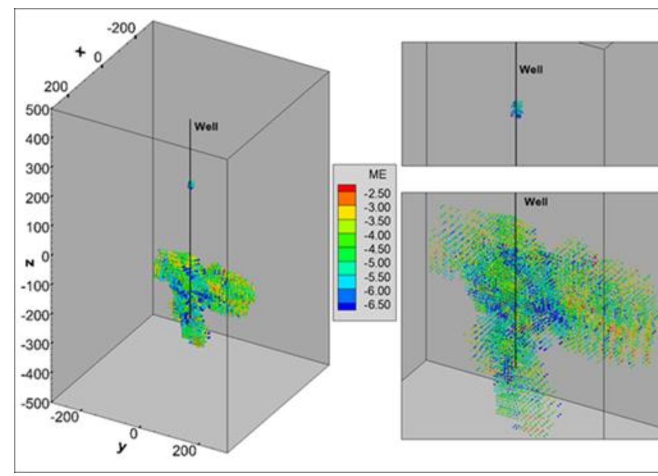
Fracture density data from logs indicate there are 500 natural fractures in the target zone

The upper injection zone has a relatively high permeability (10-8 m^2) compared to that of the surrounding rock matrix (10-16 m^2), and the average equivalent permeability of elements in fractured zone is ~10-7 m^2.

In the first test case, water is injected only through the upper well section; in the second case, both sections are taking water to the reservoir rock at same injection pressure.

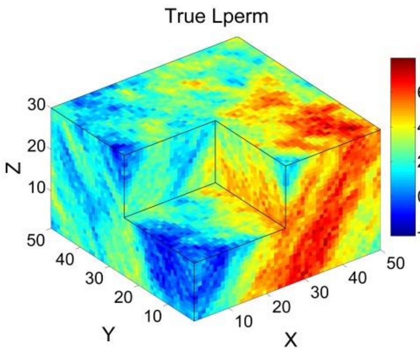




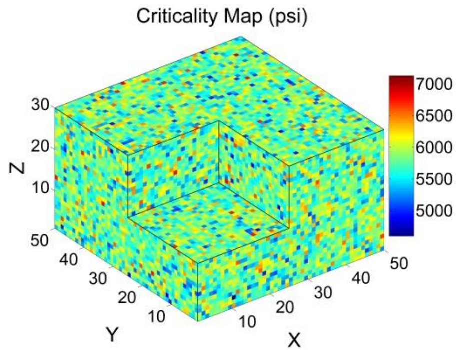


The purpose was to compare the results of simulations for the case where the communication of the injection well and natural fractures is poor and the injected fluid mainly stimulates the upper layer which was assumed to have a relatively higher permeability (leak zone)

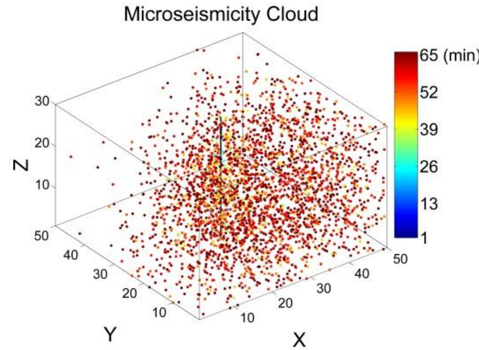
Accomplishments & Progress: EnKF Procedure for 3D Application



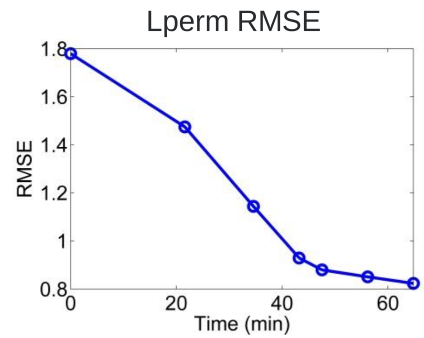
Assumed True permeability (Log-perm) distribution (the target parameter to be estimated)



Random criticality distribution (failure criterion)



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



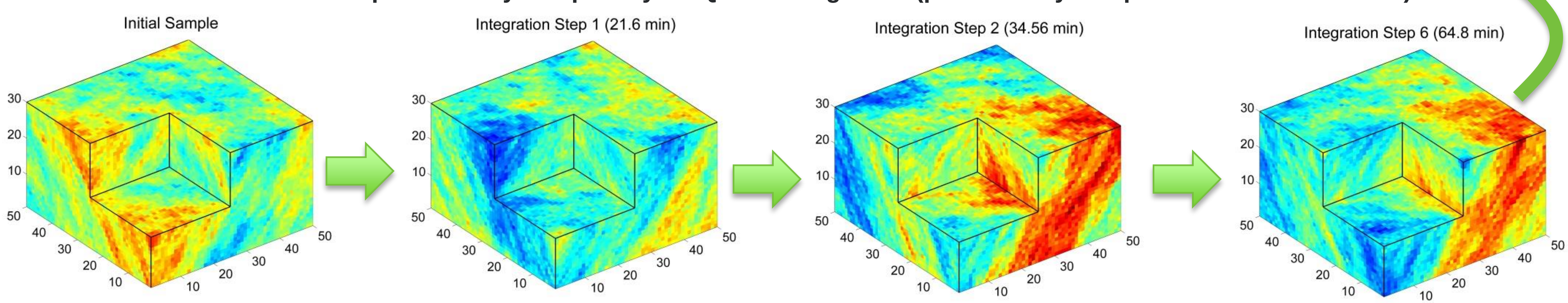
Log-perm estimation error (reduced by integrating true MEQ data through time)

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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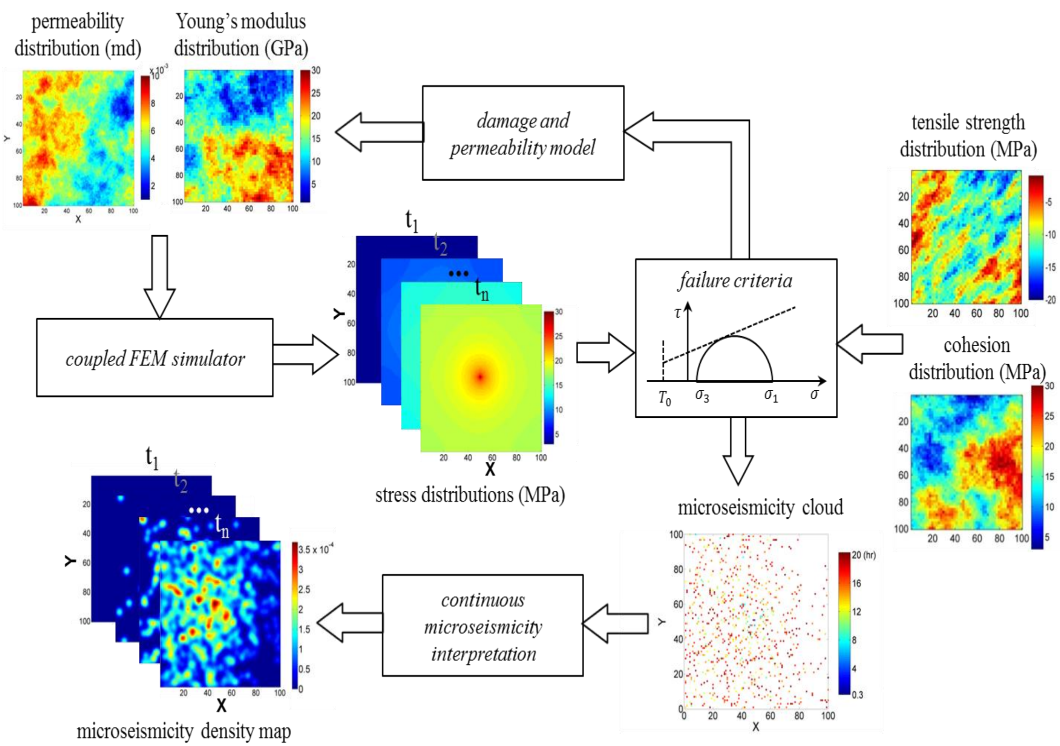
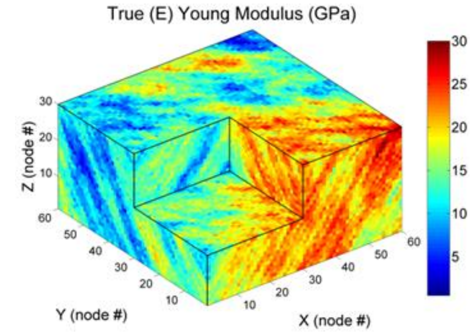
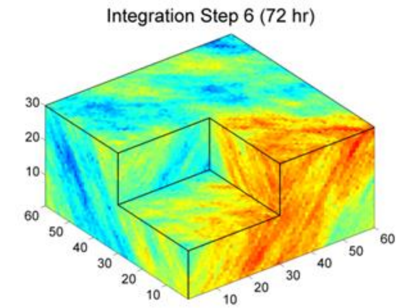
- Overall Procedure







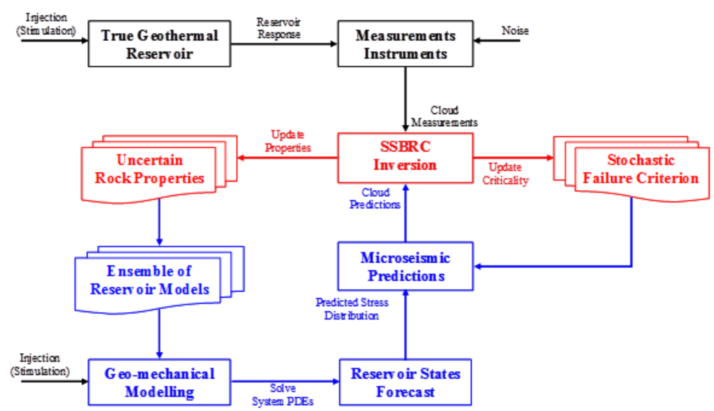


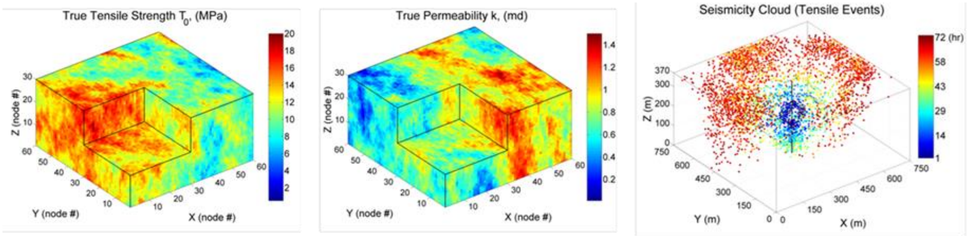
Figure 1. Proposed framework for stochastic seismicity-based reservoir characterization for enhanced geothermal systems.

Accomplishments & Progress: EnKF+geomechanics 3D Application

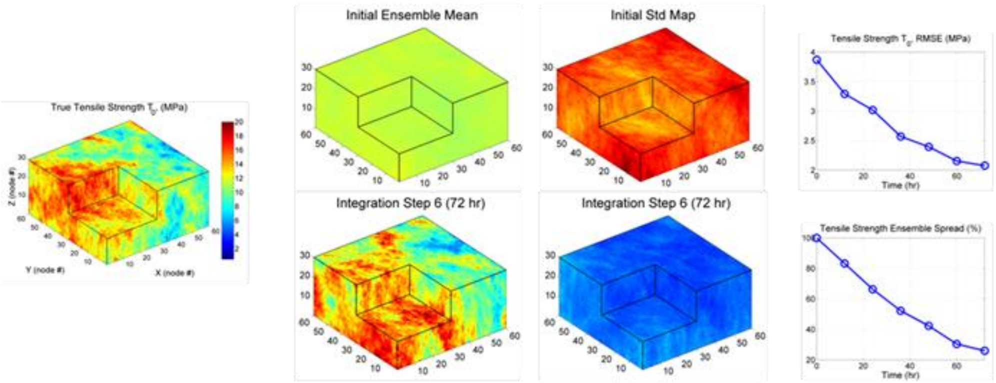
True tensile strength and k distribution along with MEQ forecast.

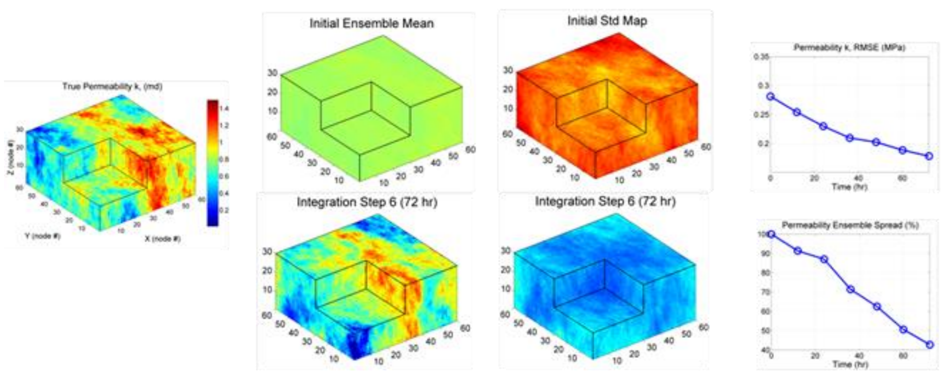
The middle row shows the calculated permeability related to MEQ

The lower row shows the calculated tensile strength based on minimizing the error between the true and estimated MEQ



(a) true tensile strength T_0, map (b) true permeability k, map (c) true microseismicity cloud





Accomplishments, Expected Outcomes and Progress

- Developed 2D and 3D coupled thermo-poroelastic reservoir geomechanics models
- Developed 2D and 3D fracture network capability
- 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

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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	2015

Future Directions

- 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 and fracture network

- 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

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	$1,000,000	$85

- The project is behind as we started late (funds not allocated).
- PI and research team moved to OU but significant project delays have resulted from difficulties in transferring the contract between the DOE and Texas A&M to the University of Oklahoma. This has prevented availability of funds necessary to continue the research, resulting in a gap in research activities.
- Although slowed down, work has been ongoing.

Supplemental Slides: Related Publications

1. Verde, A., Ghassemi, A. 2015. Modeling Injection/Extraction in a Fracture Network with Mechanically Interacting Fractures using an Efficient Displacement Discontinuity Method. International J. Rock Mech. (In press)
2. Safari, R., Ghassemi, A. 2015. Three-dimensional Thermo-poroelastic Analysis of Fracture Network Deformation and Induced Micro-seismicity in Enhanced Geothermal Systems. Geothermics (in press).
3. Verde, A., Ghassemi, A. 2015. Fast Multipole Displacement Discontinuity Method (FM-DDM) for Geomechanics Reservoir S Int. J. Num. and Anal. Methods in Geomech. (in Press)
4. Tarrahi M., Jafarpour B., Ghassemi A. (2015): Estimation of Rock Geomechanical Parameters From Micro-seismic Monitoring Data with Ensemble Kalman Filter. Water Resources Research, (in revision).
5. Ghassemi, A., and Rawal, A., Zhou, X. 2013. Rock failure and micro-seismicity around hydraulic fractures. J. Pet. Sci. and Engrg. (108), 118-127. DOI information: 10.1016/j.petrol.2013.06.005
6. Wang, X., Ghassemi, A., 2013. A three-dimensional poroelastic model for naturally fractured geothermal reservoir stimulation. GRC Annual Meeting. Las Vegas, Nevada.
7. Wang, X. and Ghassemi, A. 2012. A 3 D Thermal-poroelastic Model for Geothermal Reservoir Stimulation. Proc., 36th Workshop on Geothermal Reservoir Engineering, Stanford University.
8. Wang, X. and Ghassemi, A. 2011. A Three-Dimensional Stochastic Fracture Network Model for Geothermal Reservoir Stimulation. Proc., 36th Workshop on Geothermal Reservoir Engineering, Stanford University. Lee S. H. and Ghassemi, A. 2011. Three-Dimensional Thermo-Poro-Mechanical Modeling of Reservoir Stimulation and Induced Microseismicity in Geothermal Reservoir. Proc. 36th Stanford Geothermal Workshop, Stanford, CA
9. Ghassemi, A., X. Zhou. .2011. A three-dimensional Thermo-poroelastic model for Fracture Response to Injection/Extraction in Enhanced Geothermal Systems. Geothermics, 40 (1), 39-49.
10. Lee S. H. and Ghassemi, A. 2010. A Three-Dimensional Thermo-Poro-Mechanical Finite Element Analysis of a Wellbore on Damage Evolution. Proc., 44nd US Rock Mechanics Symposium, Salt Lake City, UT.
11. Lee S. H. and Ghassemi, A. 2010. Thermo-poroelastic Analysis of Injection-Induced Rock Deformation and Damage Evolution. Proc., 35th Stanford Geothermal Workshop, Stanford, CA
12. Lee S. H. and Ghassemi, A. 2009. Thermo-poroelastic Finite Element Analysis of Rock Deformation and Damage. Proc., 43rd US Rock Mechanics Symposium, Asheville, NC.
13. Akbarnejad-Nesheli, B., and Ghassemi, A. 2009. Undrained Poroelastic Response of Berea Sandstone and Indiana Limestone to Confining and Deviatoric Stress Change. Proc., 43rd US Rock Mech. Symp., Asheville, NC June 28th – July 1, 2009.
14. Tarrahi M., Jafarpour B. (2012): Inference of distribution from Injection Induced Discrete Micro-seismic Events. Water Resources Research, Vol. 48 (10), W10506, doi:10.1029/ 2012WR011920.
15. Jafarpour, B., and M. Tarrahi 2011. Assessing the Performance of the Ensemble Kalman Filter for Subsurface Flow Data Integration under Variogram Uncertainty, Water Resour. Res., 47, W05537, doi :10.1029/2010WR009090.
16. Tarrahi M., Jafarpour B. 2011. Inference of Geothermal Reservoir Properties from MicroSeismic Events with Ensemble Kalman Filter. American Geophysical Union Fall Meeting, December 2011, San Francisco, USA.
17. Tarrahi, M., and Jafarpour , B. 2011. Inference of Geothermal Reservoir Properties from Micro-Seismic Events with Ensemble Kalman Filter. In AGU Fall Meeting Abstracts (Vol. 1, p. 1163).
18. Tarrahi, M. and Jafarpour, B. 2012. Inference of Permeability Distribution from Injection-Induced Discrete Microseismic Events with Kernel Density Estimation and Ensemble Kalman Filter, Water Resour. Res., 48, W10506, doi:10.1029/2012WR011920.

Supplemental Slides: Related Publications

1. Zhang. Z., Peng, S., Ghassemi, A., Ge, X. 2015. Lattice bond cell modeling of dynamic hydraulic fracture. Proc. 49th US Rock Mechanics / Geomechanics Symposium held in San Francisco, CA.
2. Gao Q., and Ghassemi, A. 2015. Hydraulic Fracture Design in Heterogeneous Formations. The 5th International Conference on Coupled Thermo-Hydro-Mechanical-Chemical (THMC) Processes in Geosystems: Petroleum and Geothermal Reservoir Geomechanics and Energy Resource Extraction. Salt Lake City, Utah.
3. Huang, K., Ghassemi, A. 2015. Modeling 3D thermal fracture propagation by transient cooling using virtual multidimensional internal bonds. Int. J. Num. Anal. Methods. Geomech. (under review).
4. Tarasov, S. and Ghassemi, A. 2014. Self-similarity and scaling of thermal shock fractures. Physical Review E 90 (1), 012403-1-6.
5. Huang, J., Ghassemi, A. 2013. Simulating geomechanical evolution of fractured shale reservoir using a poro-viscoelastic constitutive model. Proc. 47th US Rock Mechanics/Geomechanics Symposium, San Francisco, USA.
6. Huang, K., Zhang, Z., Ghassemi, A. 2012. Modeling three-dimensional hydraulic fracture propagation using virtual multidimensional internal bonds. Int. J. Numer. Anal. Meth. Geomech. DOI: 10.1002/nag.2119.
7. Zhang, Z. Ghassemi, A. 2010. Simulation of Hydraulic Fracture Propagation near a Natural Fracture Using Virtual Multidimensional Internal Bonds. Int. J. Num. Anal. Methods. Geomech. DOI: 10.1002/nag.914.
8. Huang, K., Ghassemi, A. 2012. Modeling 3D Thermal Fracturing Using Virtual Multi-dimensinal Internal Bonds. Geothermal Resources Council 2012. Reno, Nevada. Sept. 30-Oct.
9. Min, K.S., Zhang, Z., Ghassemi, A. 2010. Hydraulic Fracturing Propagation in Heterogeneous Rock using the VMIB Method", 35th Stanford Geothermal Workshop, Stanford University, California, USA.
10. Min, K.S., Zhang, Z., Ghassemi, A. 2010, Numerical Analysis of Multiple Fracture Propagation in Heterogeneous Rock induced by Hydraulic Fracturing. 44th ARMA Conference, Salt Lake, Utah, USA
11. Min, K.S., K. Huang, A.Ghassemi, 2011. A Study of Numerical Simulations of Mixed-Mode Fracture Propagation in Rock. Proc. 36th Stanford Geothermal Workshop, Stanford, California, USA.
12. Huang, J., and Ghassemi, A. 2011. Poroelastic analysis of gas production from shale. 45th ARMA Conf., San Francisco, California, USA.
13. Min K.S., Ghassemi A. 2011. Three-dimensional numerical analysis of thermal fracturing in rock. 45th ARMA Conf., San Francisco, California, USA.

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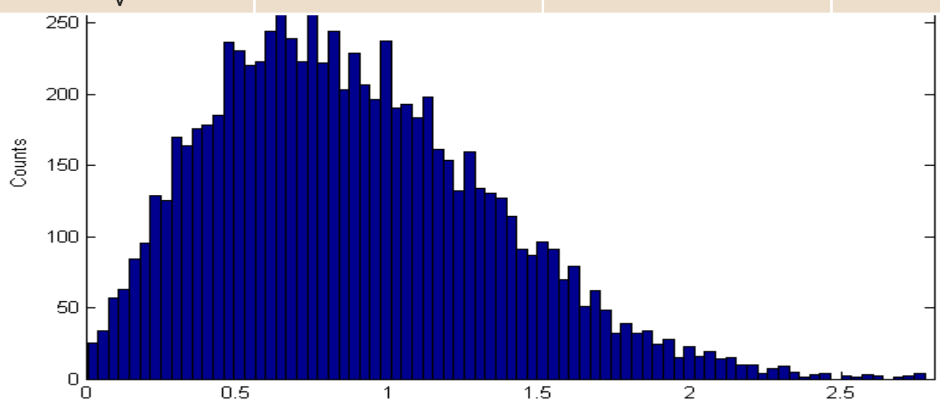
Simulation of Injection Experiment

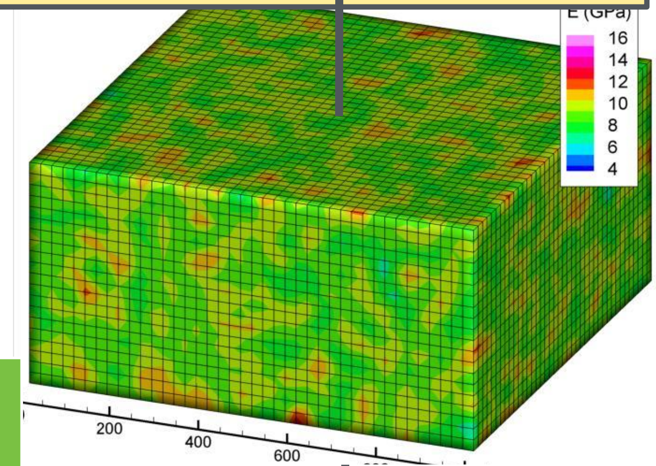
- 3D rock body of dimensions x =1000, 1000, 500 m
- Water is injected into the granitic rock from a central interval of 25 m at 2.5 Km
- Temperature difference of 50 C, Distribution of shear stress, potential seismicity , Pore pressure=8 MPa

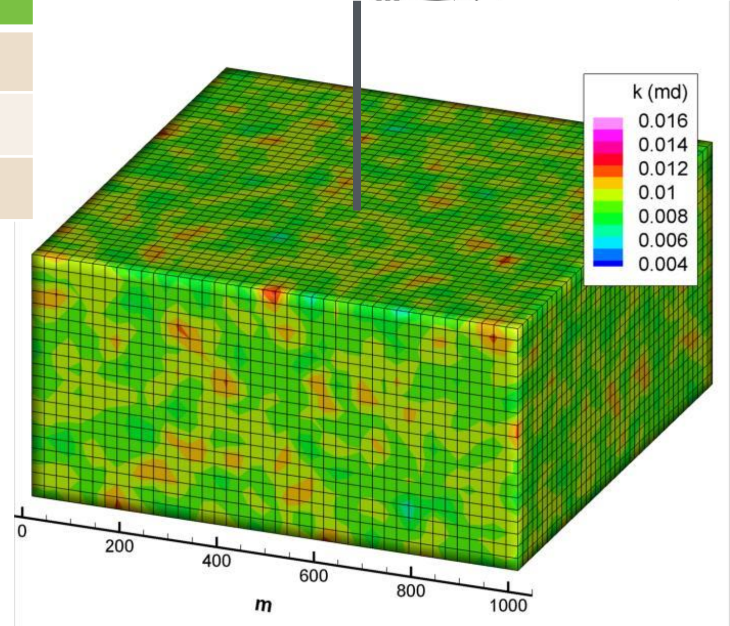
.

From 5 MPa to 32.5 MPa (hourly increase)
C=100 MPa, T=5MPa

Pore Pressure: 17.4 MPa	Normal	Strike-Slip	Thrust
$S_{H,max}$	20 MPa	40 MPa	35 MPa
$S_{h,min}$	10 MPa	20 MPa	20 MPa
S_v	30 MPa	30 MPa	10 MPa

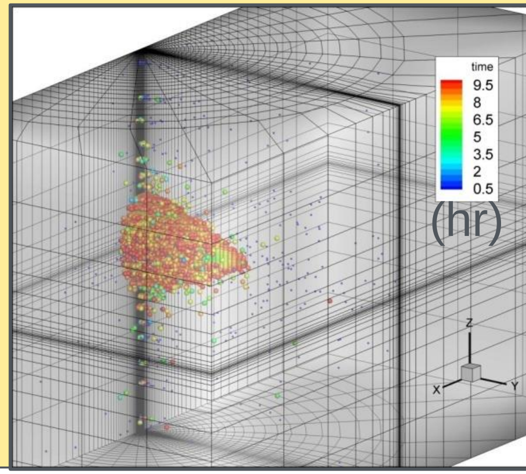




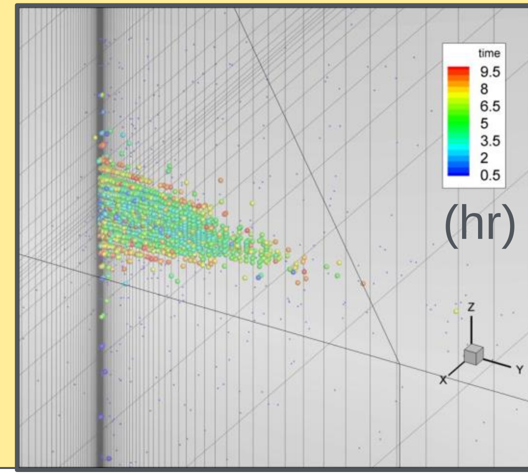


Strike-Slip Regime (wellbore)

$k_{H,max} = k_{h,min}$

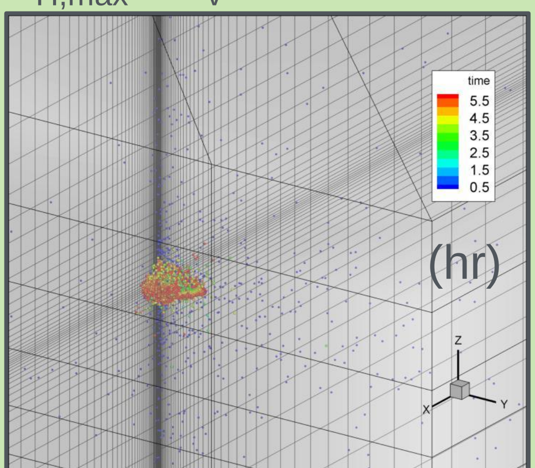


$k_{H,max} = 5 \times k_{h,min}$

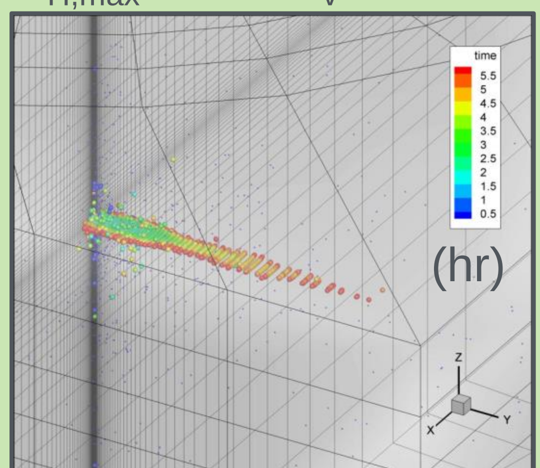


Thrust Regime (wellbore)

$k_{H,max} = k_v$



$k_{H,max} = 10 \times k_v$



Seismic Events (isotropic vs anisotropic k)

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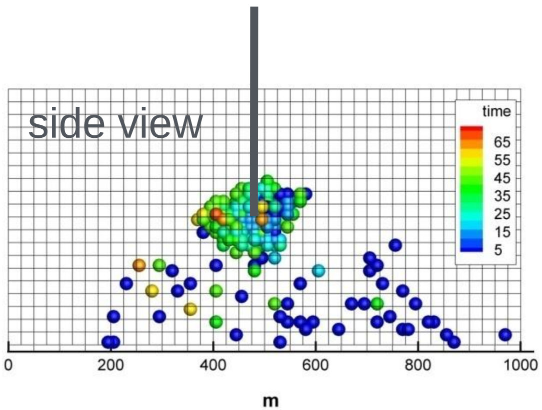
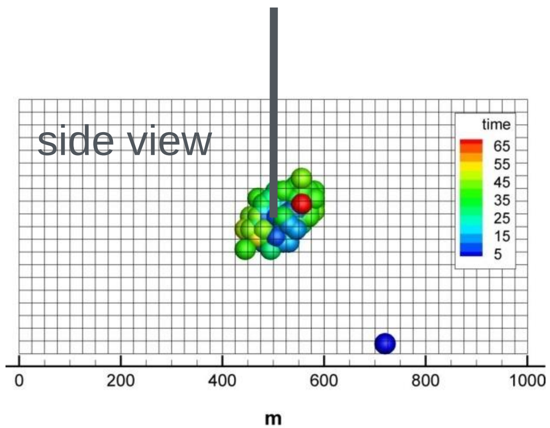
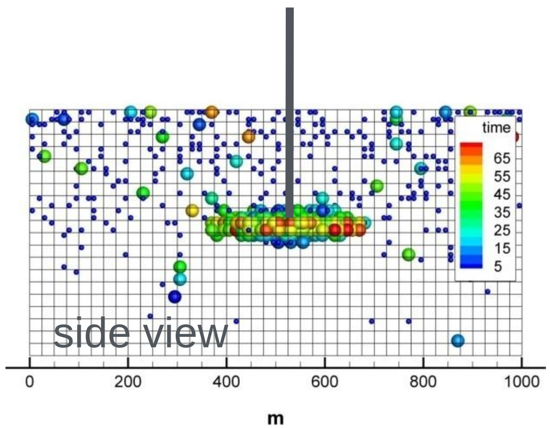
- Microseismic events propagation shape is influenced by **stress regime** and **fluid path**.



Normal Regime



Strike-Slip Regime



Thrust Regime

Injection Rate:
150 l/s ~ 250 l/s

Accomplishments & Progress: EnKF Procedure Development/Application

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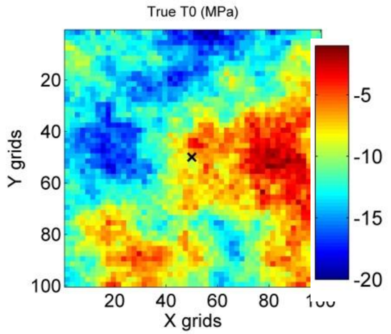
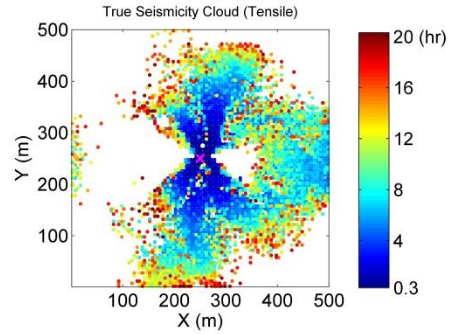
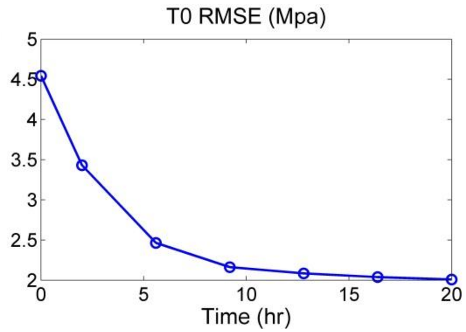


Assumed True T_0 distribution (the target parameter to be estimated)



Monitoring true MEQ data (resulted from true T_0) is used to estimate T_0



T^0 estimation error (reduced by integrating true MEQ data through time)

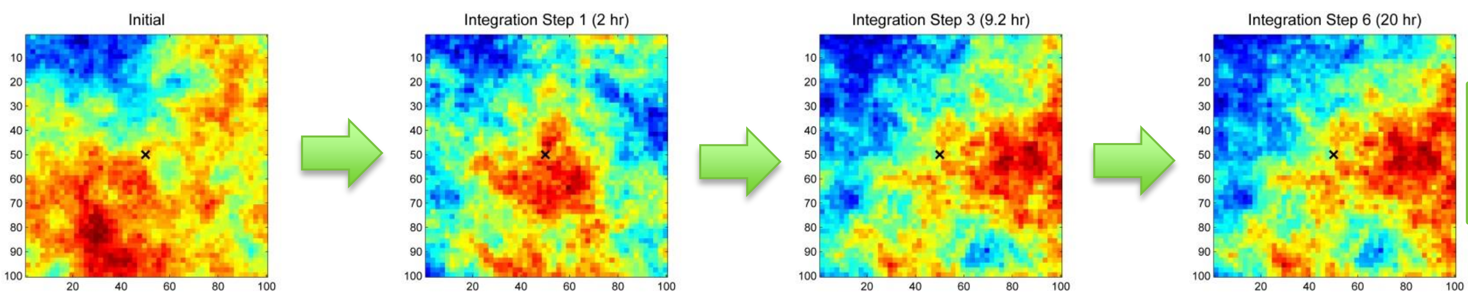
True model specification:

Stress BC= $[S_{min}, S_{max}, P_{init}] = [20\ 15\ 10]$ MPa, $R_{inj}(injection\ rate) = 0.006\ l/s, k = 0.005\ mD$, E with spatially random normal distribution. Cross shows the injection well location.

Ensemble size = 100 (number of T_0 samples or initial candidates for EnKF)

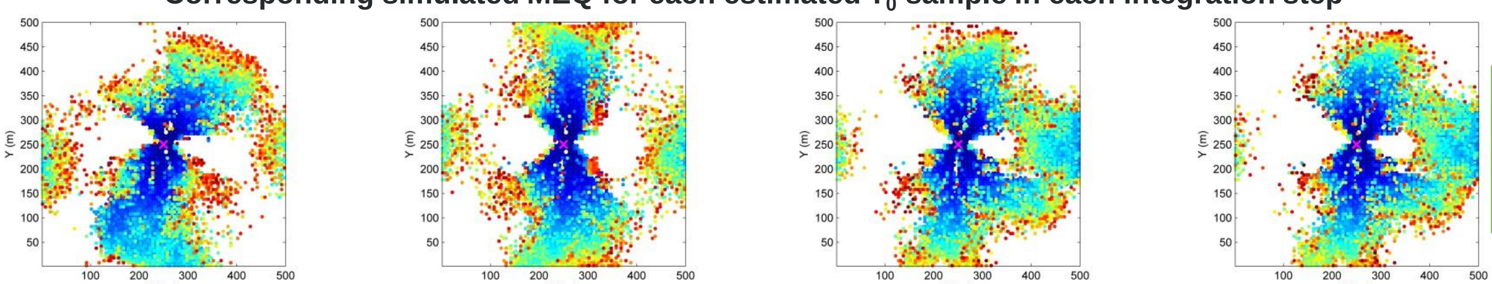
There are 6 steps of MEQ data integration

Evolution of one of the T_0 samples by MEQ data integration (T_0 sample estimation evolution)



Final estimated T_0 which is very similar to true T_0 distribution

Corresponding simulated MEQ for each estimated T_0 sample in each integration step



Corresponding MEQ of final estimated T_0 sample which is very similar to true MEQ