U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

THMC Modeling of EGS Reservoirs – Continuum through Discontinuum Representations: Capturing Reservoir Stimulation, Evolution and Induced Seismicity

Project Officer: Lauren Boyd

Total Project Funding: $1.11M + $0.5M = $1.61M

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EGS: Reservoir Modeling

Challenges

- Prospecting (characterization)
- Accessing (drilling)
- *Creating reservoir*
- *Sustaining reservoir*
- *Environmental issues (e.g. seismicity)*

Observation

- Stress-sensitive reservoirs
- T H M C all influence via effective stress
- Effective stresses influence
    - Permeability
    - Reactive surface area
    - Induced seismicity

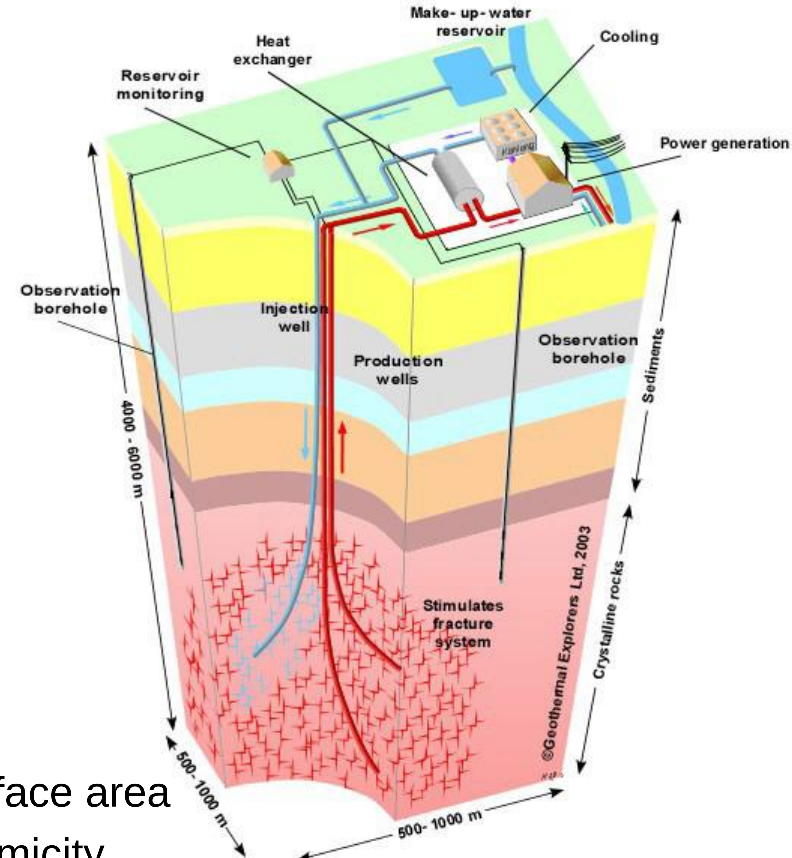
Understanding T H M C is key:

- Size of relative effects of THMC
- Timing of effects
- Migration within reservoir
- Using them to engineer the reservoir

{ Permeability
Reactive surface area
Induced seismicity

Resource

- **Hydrothermal (US:10^4 EJ)**
- **EGS (US:10^7 EJ; 100 GW in 50y)**



Relevance/Impact of Research [Objectives]

Towards the routine development of long-lived, high-volume, low-impedance and high-heat-transfer-area reservoirs at-will and at-depth with benign seismicity.

Develop a thorough understanding of complex THMC interactions through synthesis, modeling and verification:

- [Synthesis] Understand key modes of porosity, permeability evolution and the generation of reactive surface area.
- [Modeling] Develop distributed parameter models for upscaling in time and space:
  - Develop **discontinuum models** – stimulation
  - Improve **continuum representations** of coupled THMC behaviors
  - Examine the strength, sequence and timing of the various THMC effects

    For permeability, heat transfer area, seismicity
- [Verification] Demonstrate the effectiveness of these models against evolving datasets from EGS demonstration projects both currently (Soultz and Geysers) and newly in progress (Newberry Volcano).
- [Education] the next generation of geothermal engineers and scientists through integration of undergraduate and graduate scholars in science and in engineering in research and *via* the GEYSER initiative.

Scientific/Technical Approach Overview

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Approach

- *Critically examine key THMC process couplings*
- *Extend distributed parameter reactive-chemical models*
- *Extend coupled* ***production models (continuum) – Track 1***
- Develop **stimulation models (discontinuum) – Track 2**
- Understand performance *of past* and new EGS reservoirs
- Educate the next generation of geothermal engineers/scientists

Go/No-Go Decision Points

- **Close of Year 1:** No-Go if change in permeability predicted from M or C models is within 80% of prediction using MC models.
- **Close of Year 2:** No-Go if process interactions suggest that existing independent THC or THM models can predict permeability evolution within 80% of predictions using THMC.

Scientific/Technical Approach
Induced Seismicity – Key Questions

THMC-S Model:

Principal trigger - change in (effective) stress regime:

- Fluid pressure
- Thermal stress
- Chemical creep

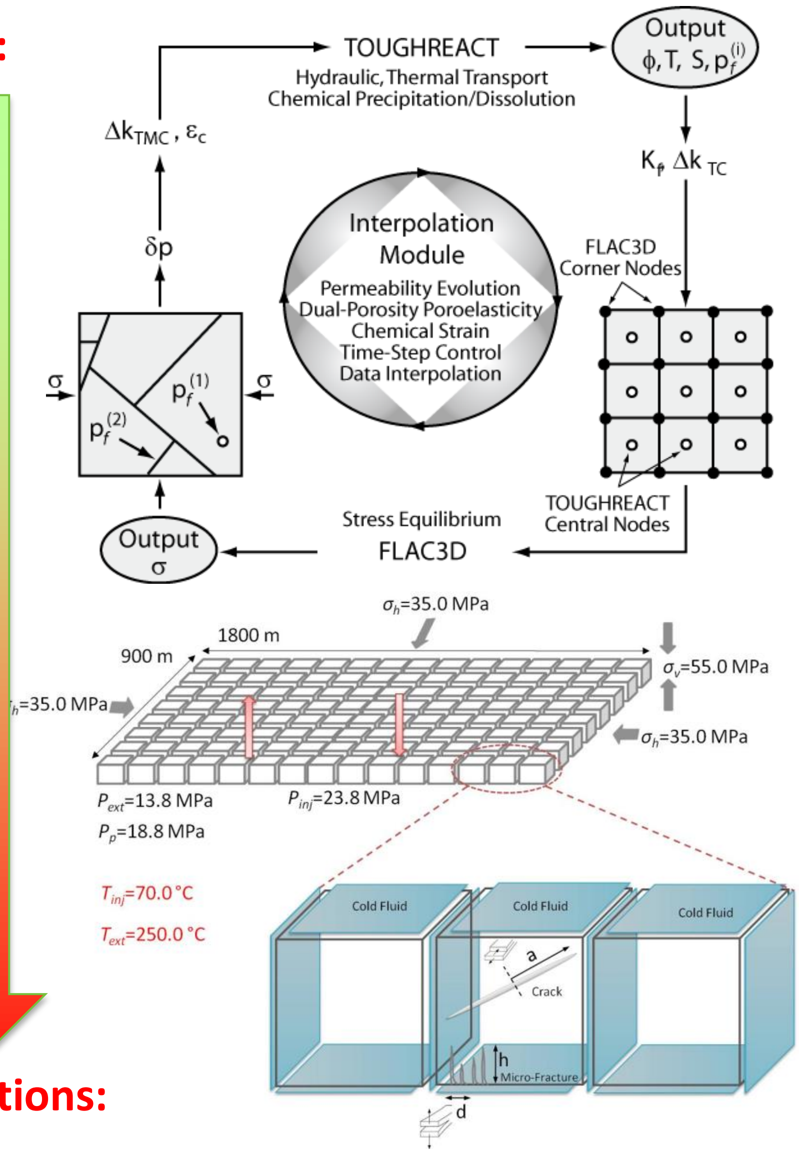
How do these processes contribute to:

- Rates and event size (frequency-magnitude)
- Spatial distribution
- Time history (migration)

How can this information be used to:

- Evaluate seismicity
- Manage/manipulate seismicity

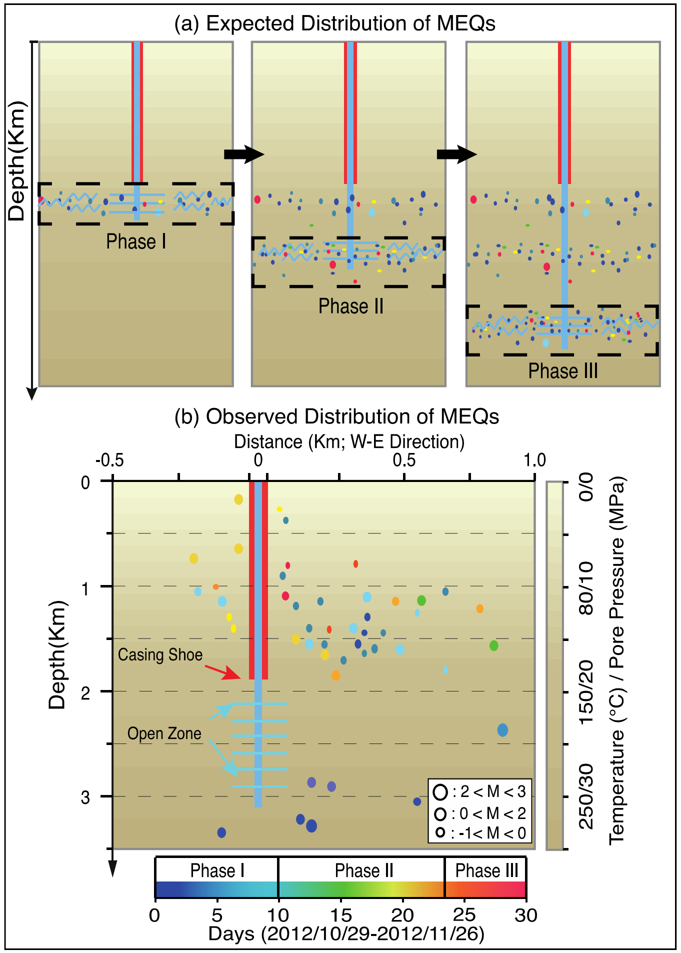
Reservoir Conditions:



Accomplishments, Results and Progress: Anomalous Seismicity – Newberry

Questions:

- What is the mechanism of this anomalous distribution of MEQs?
- What can this anomalous distribution of MEQs imply?



Wellbore Characteristics

- 0-2000m: Casing shoe
- 2000m-3000m: open zone

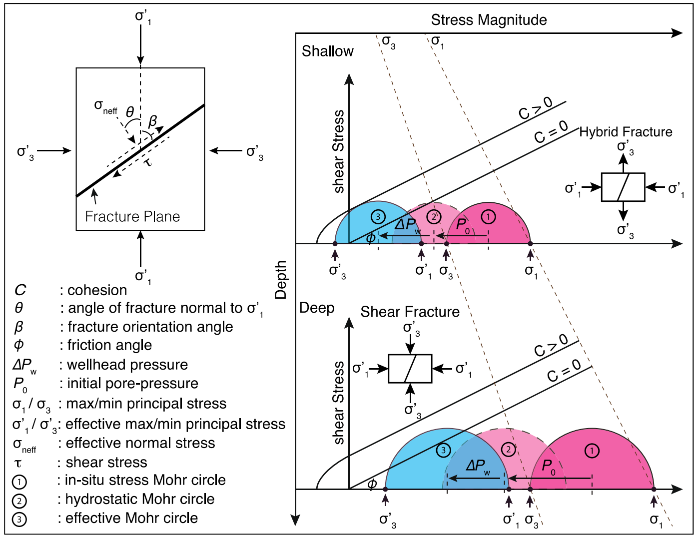
Spatial Anomaly

- Bimodal depth distribution
- Below 1950 m, only a few MEQs occurred.
- Between 500m and 1800m, 90% MEQs occurred adjacent to the cased part.

Temporal Anomaly

- Deep MEQs occurred within 4 days and diminished after that time.
- Shallow MEQs occurred since the 4th day.

Depth-Dependent Mohr-Coulomb Theory



ARP: Anomalous Seismicity – Newberry Demonstration Project

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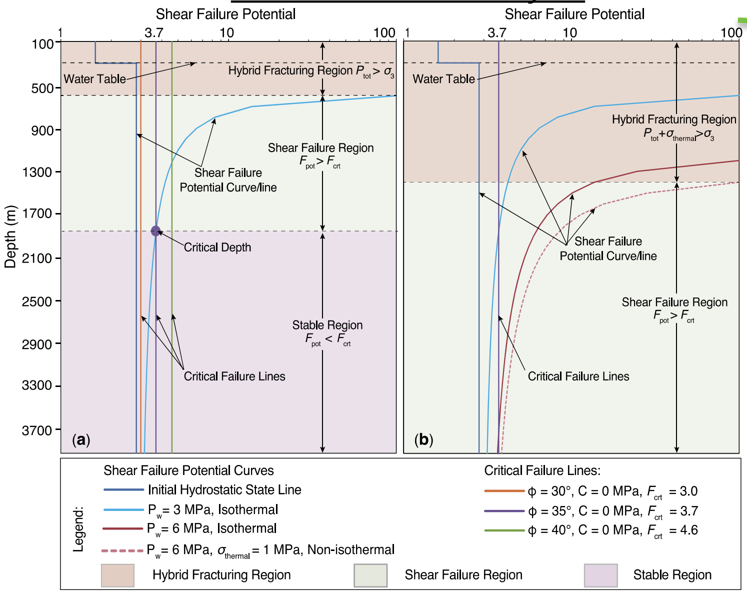
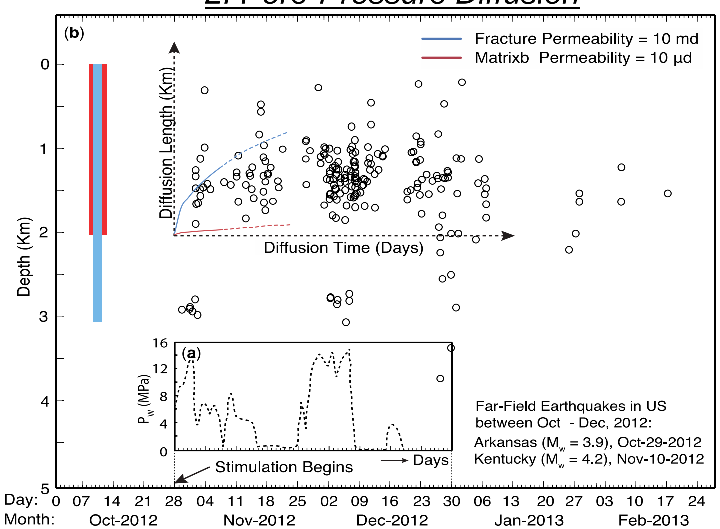
1. Shear Failure Analysis



2. Pore-Pressure Diffusion

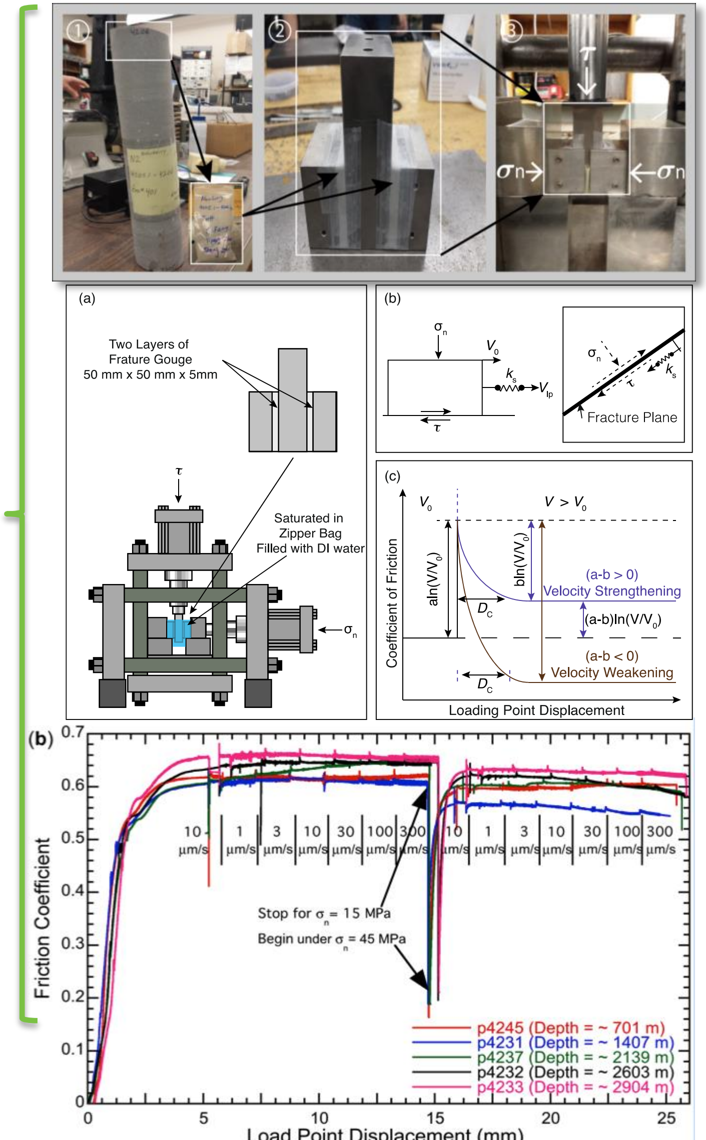


1. Shear Failure Analysis suggests that if seismicity occurs at great depth, it should occur continuously up the rock column, and not with a gap.

2. Pore-Pressure Diffusion suggests that seismicity in shallow reservoir is not due to fluid diffusion from deep open-cased wellbore.

3. Frictional Experiments are performed to explore the frictional stability with depth and to explore the mechanisms of the unexplained seismic gap.

3. Frictional Experiments



ARP: Anomalous Seismicity – Newberry Demonstration Project

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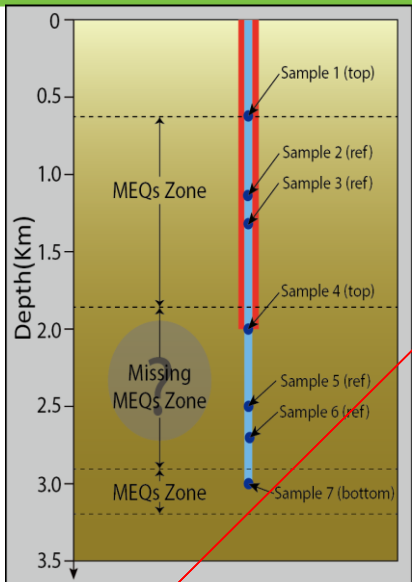
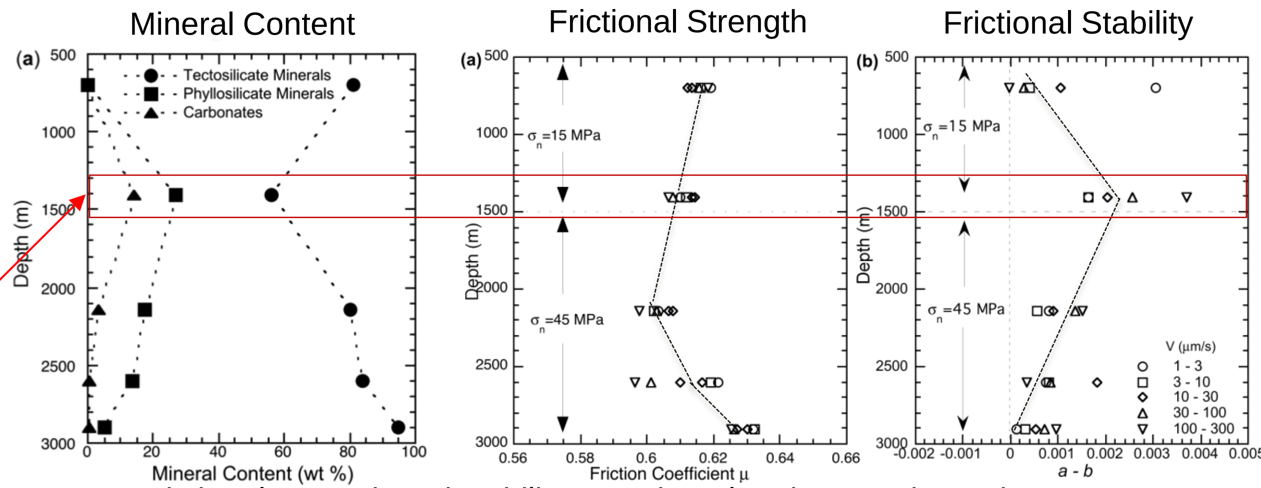
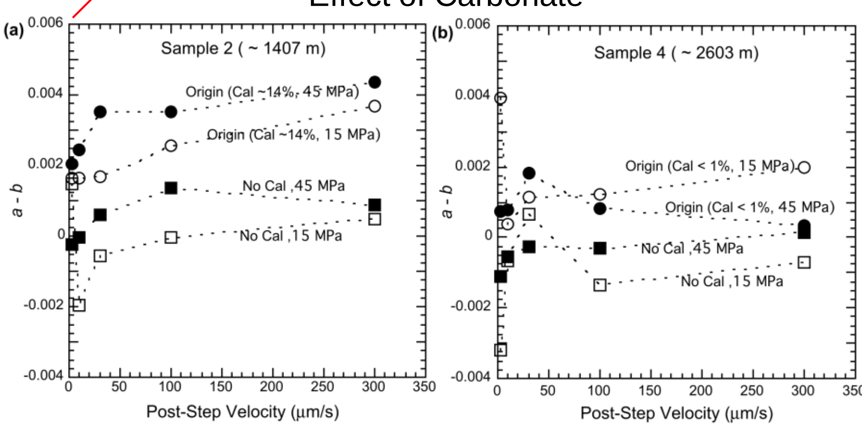




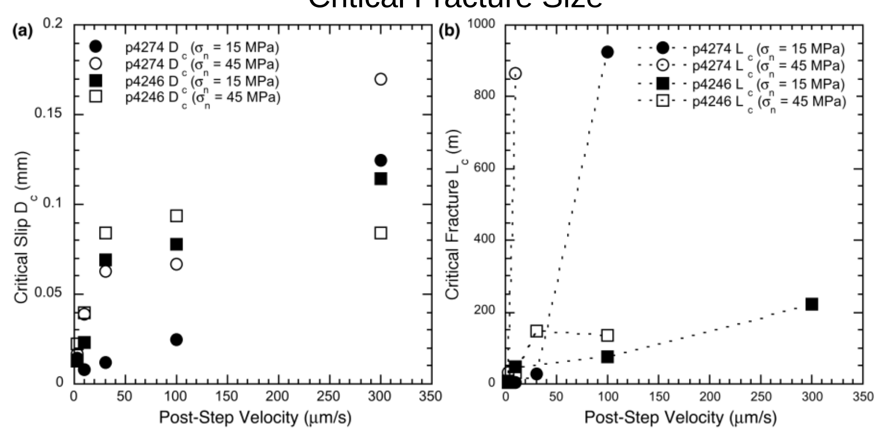
- Frictional strength and stability are mineral and stress dependent
- Samples in shallow reservoir and deep reservoir are velocity neutral to velocity weakening
- Samples at mid-depth are velocity strengthening to velocity neutral

Effect of Carbonate



- Removing calcite can reduce stability

Critical Fracture Size



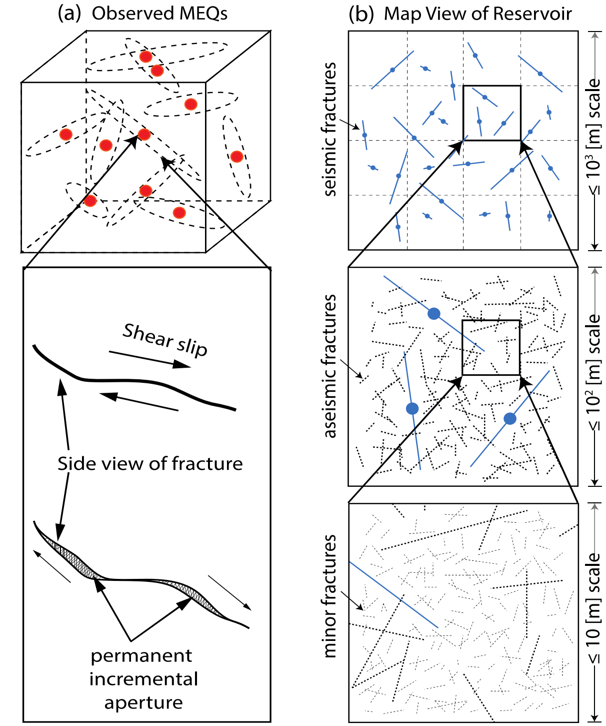
- Fracture radius less than ~7 m are aseismic fractures

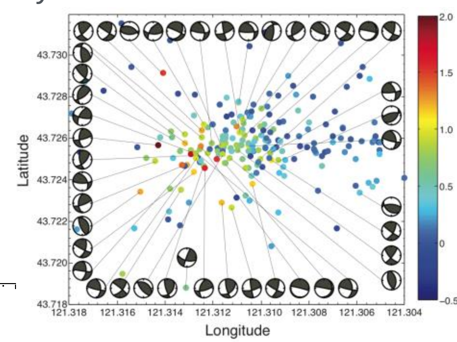
ARP: Linking Induced Microseismicity to Permeability Evolution

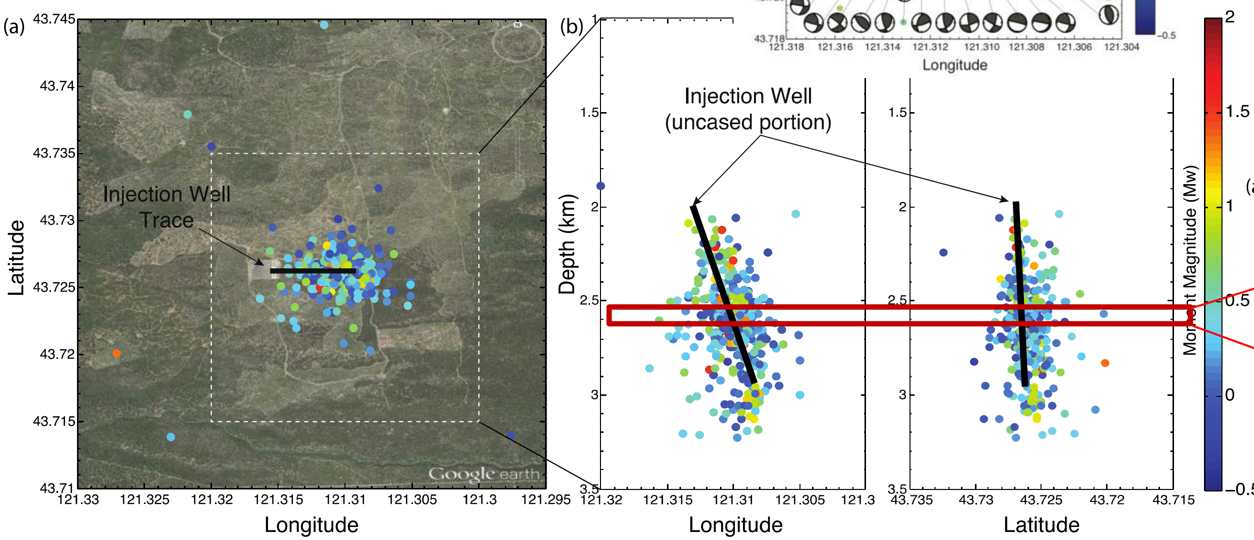
1. Seismicity induced by hydroshearing is controlled by the Mohr-Coulomb shear criterion.
2. The frictional coefficient evolves during seismic slip.
3. Two types of fractures:
   - Velocity-weakening/seismic fractures and,
   - Velocity-strengthening/aseismic fractures (fracture size smaller than the critical length).
4. Fracture interaction is ignored – consequently variations in the orientations of principal stresses are negligible

•Workflow:

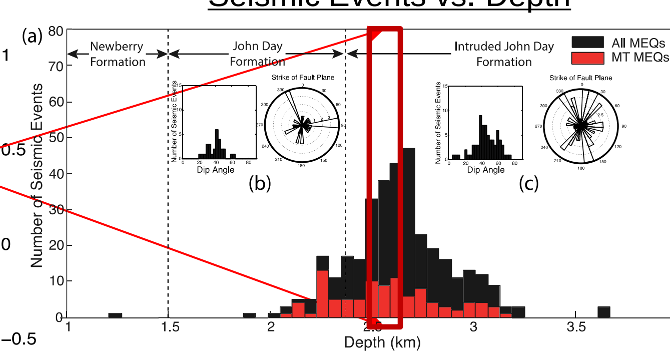
1. MT -> Orientation, mode of disp.
2. Magnitude, stress drop -> fracture size
3. Size -> roughness and dilation
4. Dilation/mode -> permeability evolution







Seismic Events vs. Depth



ARP: Linking Induced Microseismicity to Permeability Evolution

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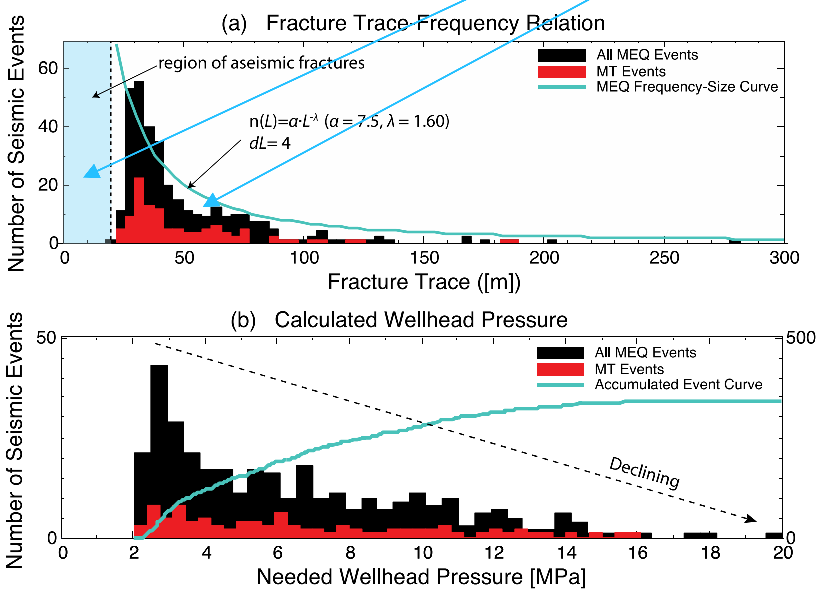
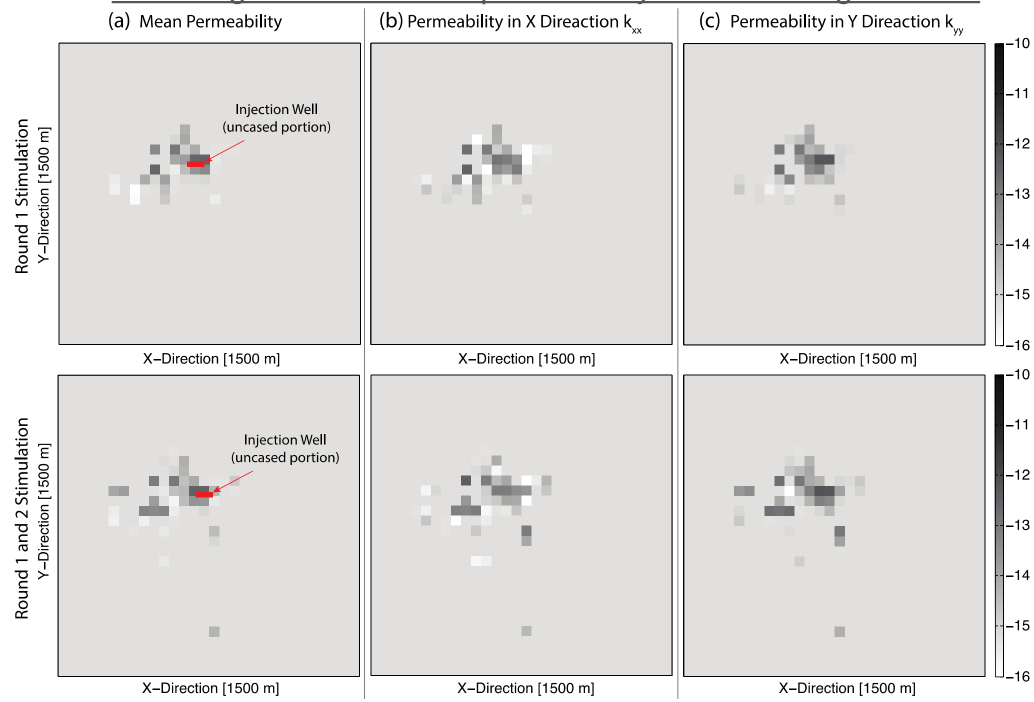
$$n_{tot} = n_{aseis} + n_{seis} = n_{aseis} + n_{f} + n_{uf}$$

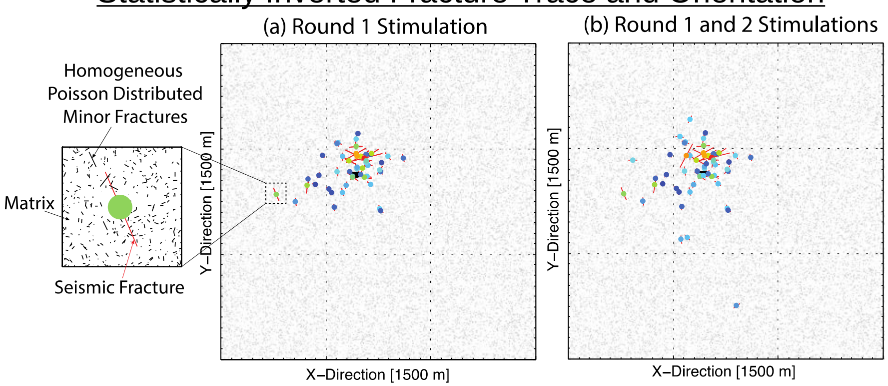
max (→ n_f) 0 (→ n_{uf})



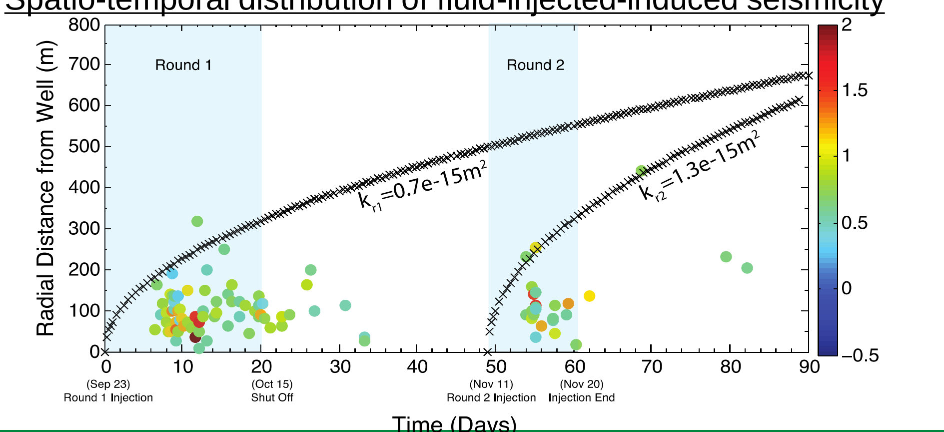
Cellular grid of stimulated permeability created using the DFN



Statistically Inverted Fracture Trace and Orientation



Spatio-temporal distribution of fluid-injected-induced seismicity



ARP: Thermal drawdown and late-stage seismic-slip fault reactivation

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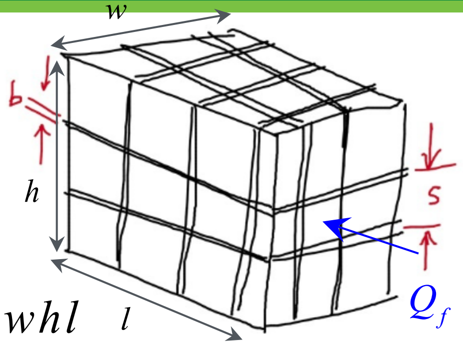


$V = volume = whl$

$$\dot{H}_{solid} \sim A\lambda_R \frac{dT}{dx} \sim \frac{V\lambda_R \Delta T}{s^2}$$

$$\dot{H}_{fluid} \sim Q_f \rho_W c_W \Delta T$$

$$\frac{\dot{H}_f}{\dot{H}_s} \sim \frac{\rho_W c_W}{\lambda_R} \frac{Q_f s^2}{V} = Q_D$$

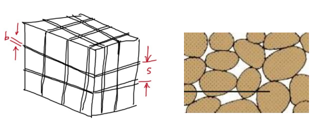
In-Reservoir Rock Temperature Distributions – Proxy for IS strains

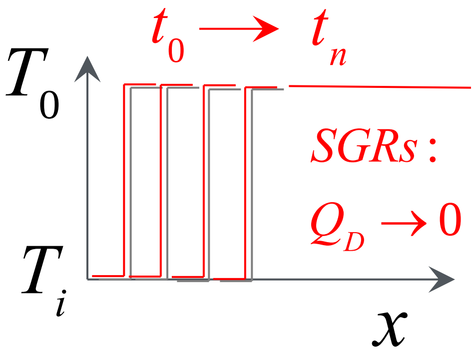
$SGRs:$

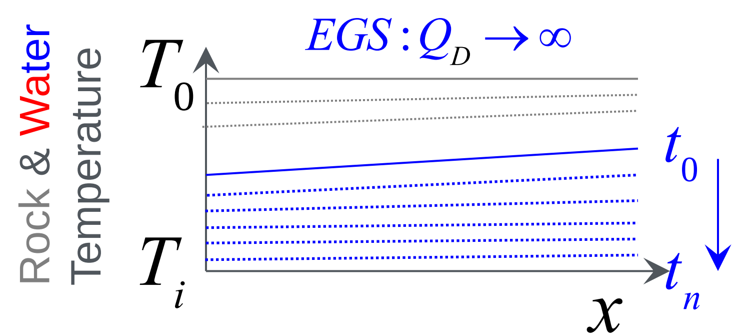
$\dot{H}_s \to 0$

$\dot{H}_f / \dot{H}_s \to 0$

$Q_D \to 0$





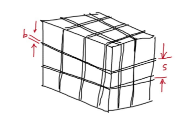


$EGS:$

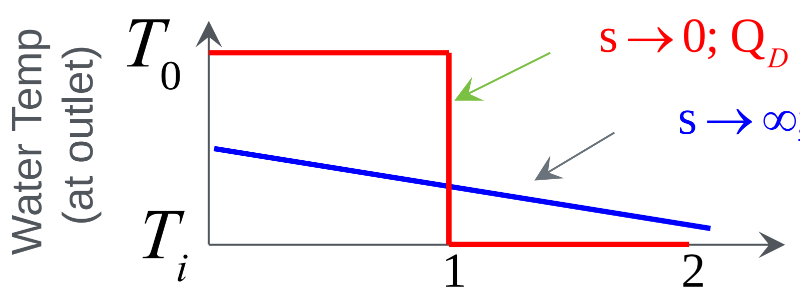
$\dot{H}_f \to \infty$

$\dot{H}_f / \dot{H}_s \to \infty$

$Q_D \to \infty$



Thermal Output:



$s \to 0$; $Q_D \to 0$; Thermal-front present

$s \to \infty$; $Q_D \to \infty$; Thermal front absent

$$t_D = \frac{r_W c_W}{r_R c_R} \frac{Q_f t}{V}$$

ARP: Thermal drawdown and late-stage seismic-slip fault reactivation

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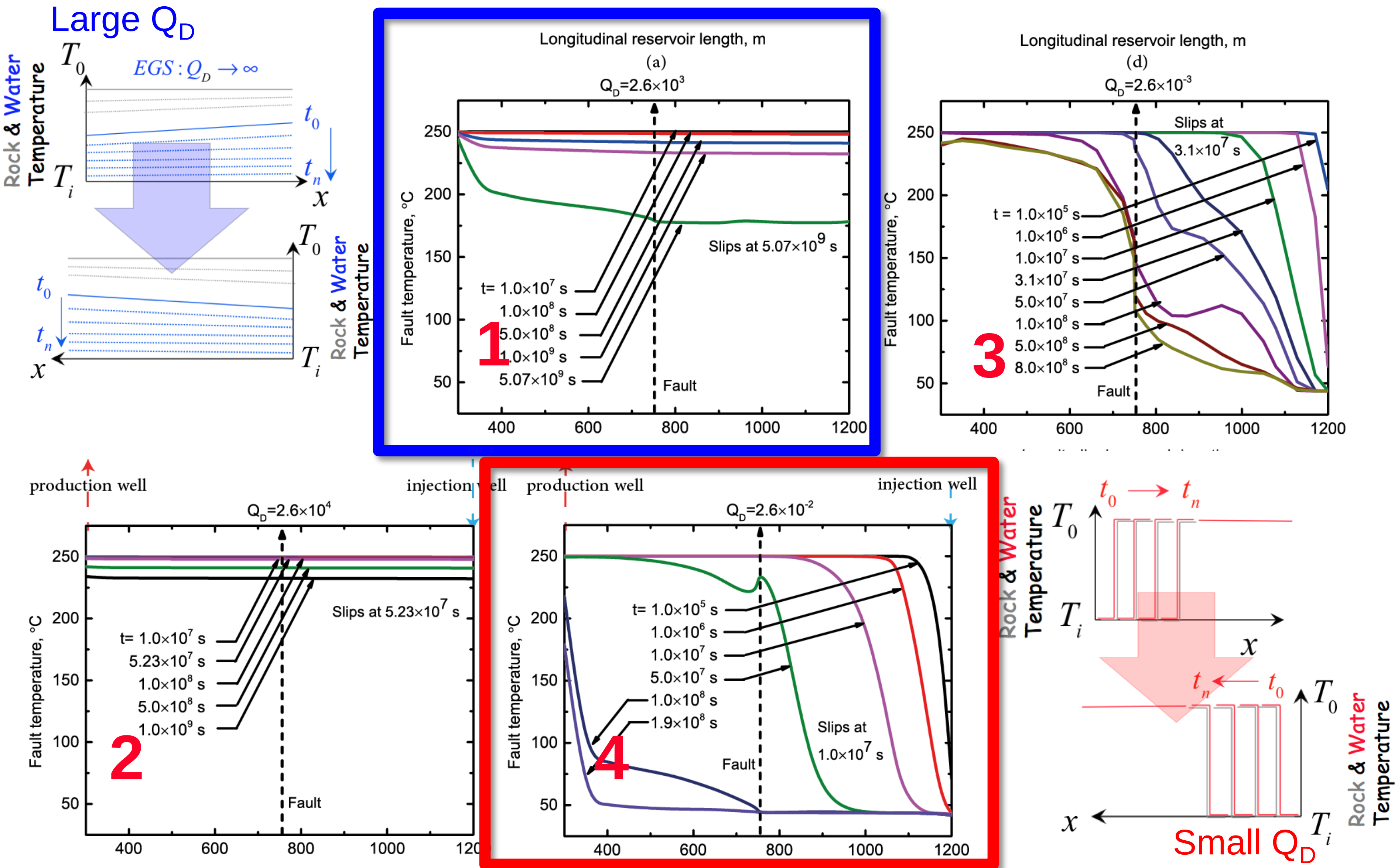

ARP: Thermal drawdown and late-stage seismic-slip fault reactivation

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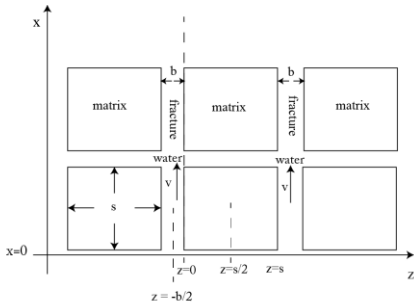
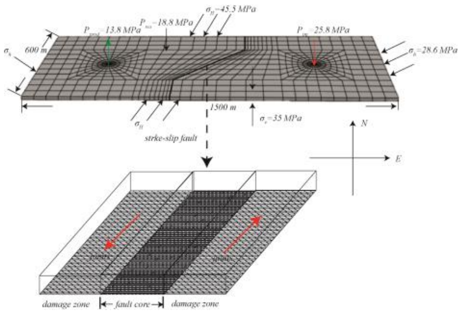
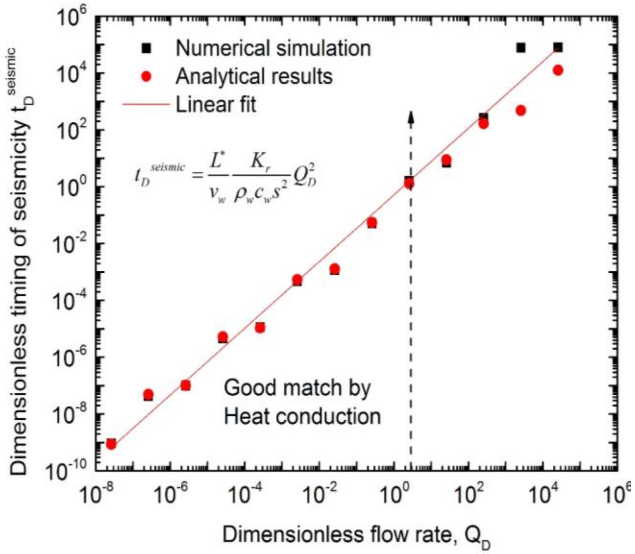
Dual porosity geometry



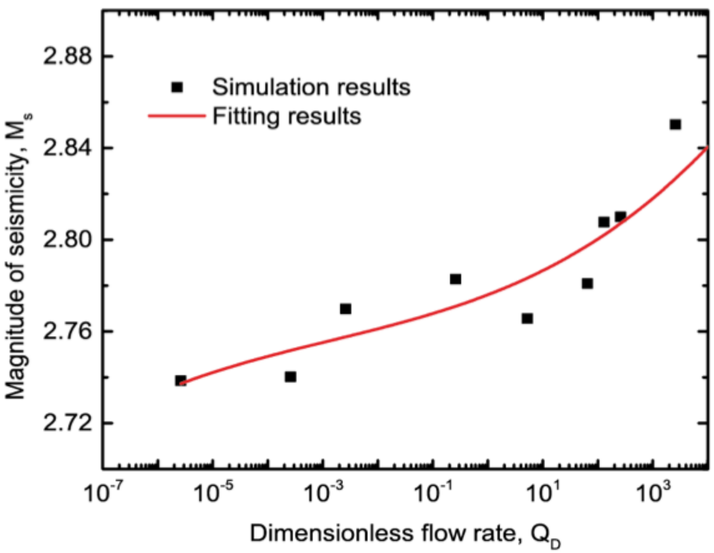
Reservoir geometry



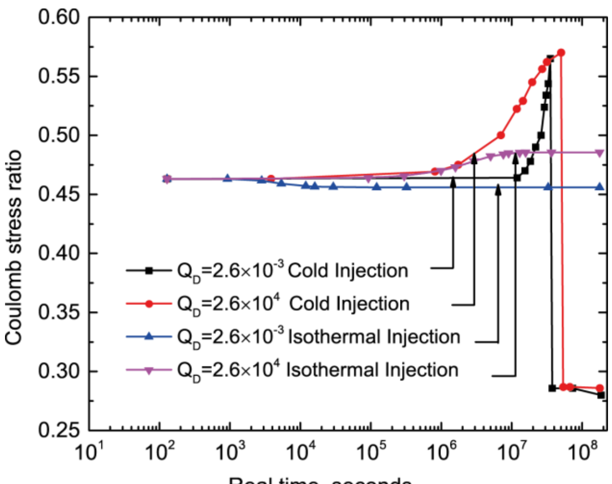
Event timing controlled by flow rate

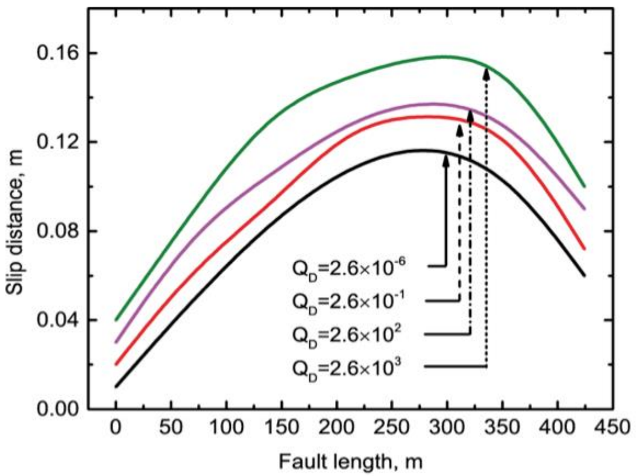


But, event magnitude independent



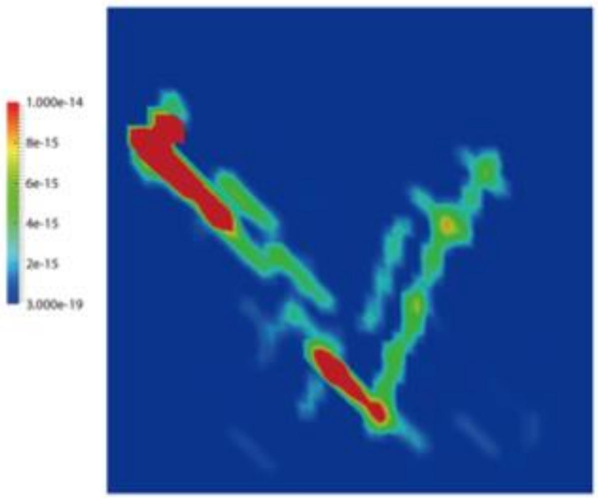
Although, thermal stresses trigger reactivation, their distribution is important



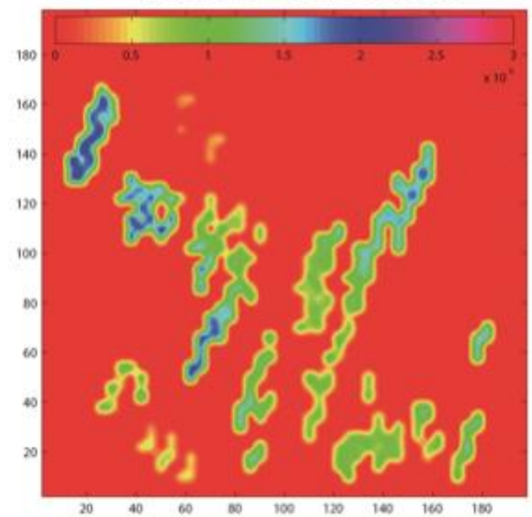


ARP: Equivalent Continuum DFN Model

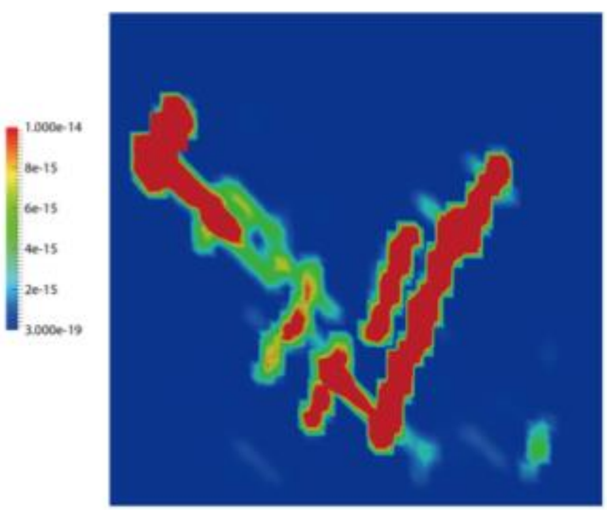
Fracture permeability k_x in x direction at 180 days



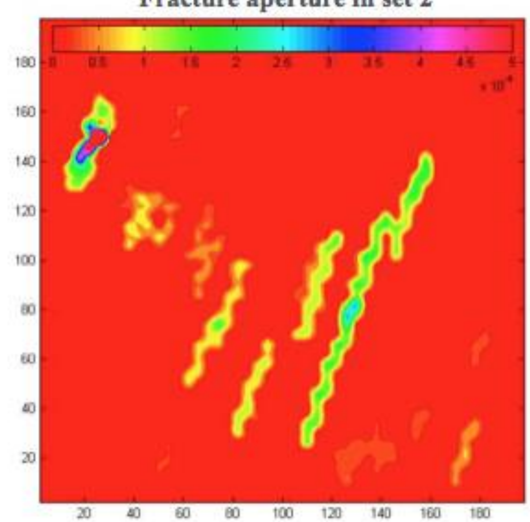
Shaer stress drop in fracture set 2



Fracture permeability k_y in y direction at 180 days

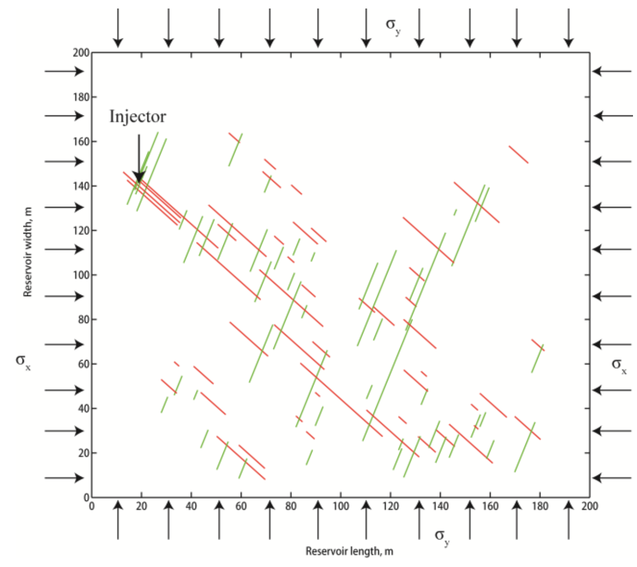


Fracture aperture in set 2



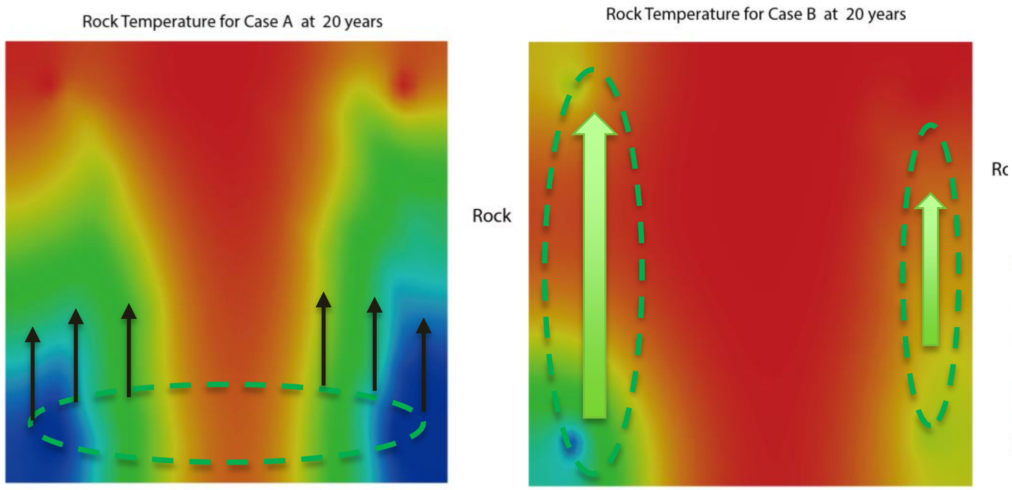
Equivalent Continuum DFN

- DFN to describe network
- Effective medium behavior
  - Inter-element fracture compliance
    - Scaled with length
  - Fracture permeability
    - Scaled with length
- THMC process couplings as TR_FLAC
  - Dual porosity thermal transport
  - Advective heat transport

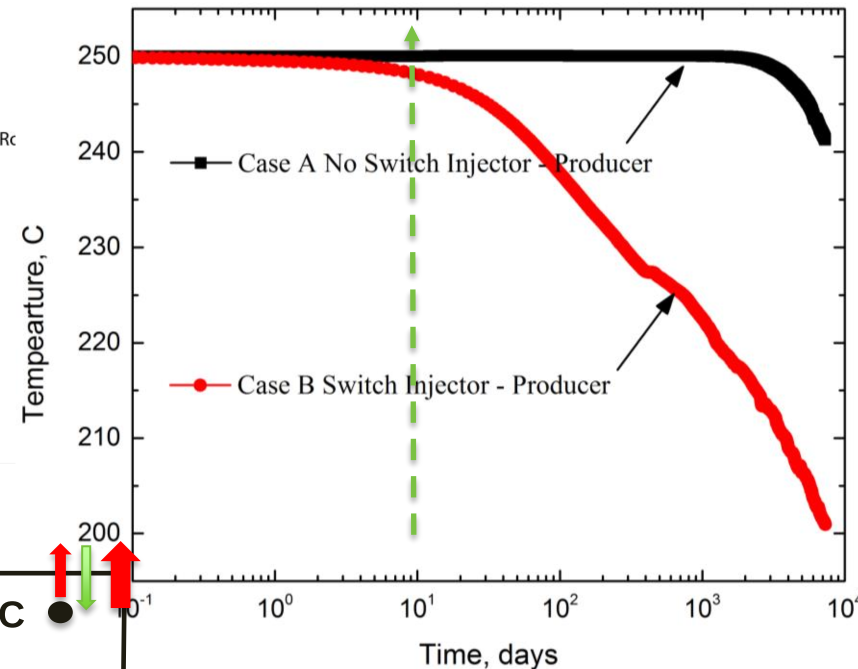


ARP: Equivalent Continuum DFN Model

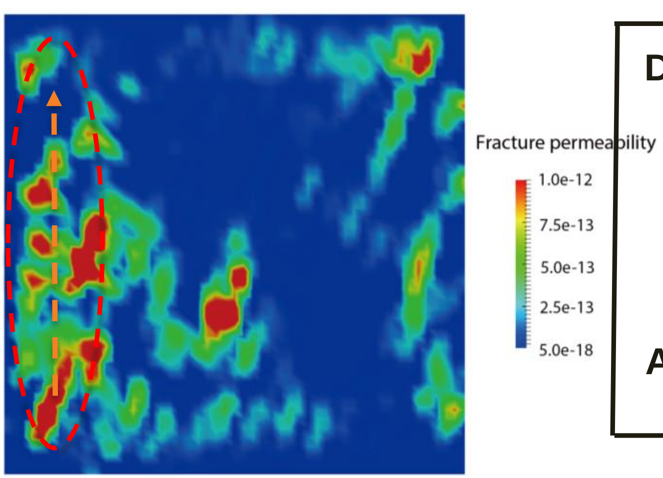
Reservoir rock temperatures

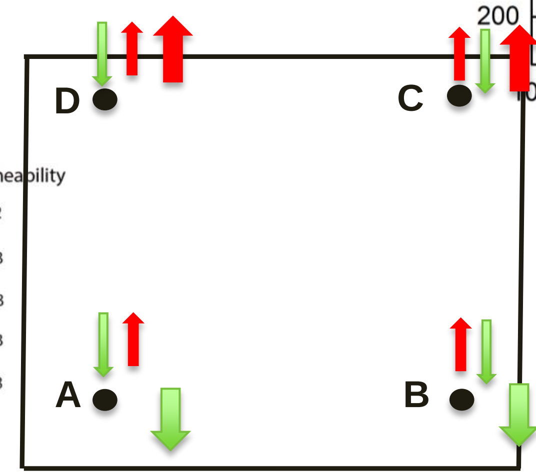


Comparative thermal drawdowns



Fracture permeability





Method

- Activate single and double fracture sets
- Hydroshear/hydro-jack single – manifold
- Develop second manifold
- Uniform thermal sweep between manifolds

Future Directions

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Project will end June 1, 2015

Enduring Interests

- Methods to link seismicity and permeability – observations and laboratory measurements
- Methods to recover reservoir performance/characteristics from geodetic and tool measurements
- Methods to measure then “engineer” the reservoir
- Evaluate controls of stress and well placement on induced seismicity including large faults
- Magnitude of largest credible seismic event

Milestone or Go/No-Go	Status & Expected Completion Date
Production models	Completed
Stimulation models	Complete June 1, 2015

Summary Slide – Key Points

Energy Efficiency & Renewable Energy

- **Complex THM and THC Interactions Influencing Reservoir Evolution**
  - Permeability evolution is strongly influenced by these processes
  - In some instances the full THMC quadruplet is important
  - Effects are exacerbated by heterogeneity and anisotropy
- **Spatial and Temporal Evolution – Effective stress/permeability/seismicity**
  - Physical controls (perm, thermal diffusion, kinetics) control progress
  - Effects occur in order of fluid pressure (HM), thermal dilation (TM), chemical alteration (CM)
  - Spatial halos also propagate in this same order of pressure, temperature, chemistry
- **Induced Seismicity**
  - Distribution and propagation rate controlled by:
    - Stress magnitude (weakly for the same stress obliquity)
    - Fracture network geometry (strongly)
  - Crucial role of material properties in IS
  - Linkage between seismicity and permeability – characterization and control of reservoir
- **Discontinuum DFN Models**
  - Accommodate discontinuum effects on compliance and permeability
  - Embody all positive attributes of TR-FLAC – advection and heat storage/transport
  - Allow rapid prototyping of reservoir development ideas
- Key milestones for project met in top two items

Additional Information

Selected Publications (2013 & 2014) [www.ems.psu.edu/~elsworth/publications/pubs.htm]

1. Fang, Y., Elsworth, D., Cladouhos, T. (2015) Mapping permeability tensors in fractured reservoirs using MEQ data. Proc. 49th US Symposium on Rock Mechanics and Geomechanics. San Francisco. June 29-July 1.
2. Gan, Q., Elsworth, D. (2015) A continuum model for coupled stress, fluid flow and heat transfer in discrete fracture networks. Proc. 49th US Symposium on Rock Mechanics and Geomechanics. San Francisco. June 29-July 1.
3. Elsworth, D., Gan, Q., Fang, Y., Pogacnik, J., Taron, J., Izadi, G., Guglielmi, Y., Im, K.J., Ishibashi, T. (2015) Control of permeability and seismicity – keys to the successful development of EGS reservoirs. Proc. 10th Anniversary Int. Symp. of the Center of Environmental Science and Disaster Mitigation for Advanced Research, Muroran, Japan, March 13-14.
4. Fang, Y., Elsworth, D., Cladouhos, T. (2015) Estimating in-situ permeability of stimulated EGS reservoirs using MEQ moment magnitude: an analysis of Newberry MEQ data. Proc. 40th Workshop on Geothermal Reservoir Engineering, Stanford, California Jan 26-28. SGP-TR-204.
5. Gan, Q. and Elsworth, D. (2015) Fault reactivation due to thermal drawdown in enhanced geothermal reservoirs. Proc. 40th Workshop on Geothermal Reservoir Engineering, Stanford, California Jan 26-28. SGP-TR-204.
6. Fang, Y., den Hartog, S.A.M., Elsworth, D., Marone, C., Cladouhos, T. (2015) Anomalous distribution of microearthquakes in the Newberry geothermal reservoir: mechanisms and implications. Submitted for publication. Geothermics. 40 pp.
7. Mohan, A.R., Turaga, U., Viswanathan, S., Shembekar, V., Elsworth, D., Pisupati, S.V. (2015) Modeling the CO_2-based enhanced geothermal system (EGS) paired with integrated gasification combined cycle (IGCC) for symbiotic integration of carbon dioxide sequestration with geothermal heat utilization. Int. J. Greenhouse Gas Control. Vol. 32. pp. 197-212. http://dx.doi.org/10.1016/j.ijggc.2014.10.016
8. Izadi, G., Elsworth, D. (2015) The influence of thermal-hydraulic-mechanical-and chemical effects on the evolution of permeability, seismicity and heat production in geothermal reservoirs. Geothermics. Vol 53. pp. 385-395. http://dx.doi.org/10.1016/j.geothermics.2014.08.005
9. Gan, Q. and Elsworth, D. (2014) Thermal drawdown and late-stage seismic-slip fault-reactivation in enhanced geothermal reservoirs. J. Geophys. Res. Vol. 119, pp. 8936-8949. http://dx.doi.org/10.1002/2014JB011323
10. Gan, Q., Elsworth, D. (2014) Analysis of fluid injection-induced fault reactivation and seismic slip in geothermal reservoirs. J. Geophys. Res. Vol. 119, No. 4, pp. 3340-3353. http://dx.doi.org/10.1002/2013JB010679.
11. Izadi, G., Elsworth, D. (2014) Reservoir stimulation and induced seismicity: role of fluid pressure and thermal transients on reactivated fracture networks. Geothermics. Vol. 51. pp. 368-379. http://dx.doi.org/10.1016/j.geothermics.2014.01.014
12. Izadi, G., Elsworth, D. (2013) The effects of thermal stress and fluid pressures on induced seismicity during stimulation to production within fractured reservoirs. Terra Nova. Vol. 25. pp. 774-380. http://dx.doi.org/10.1111/ter.12046
13. Zheng, B., and Elsworth, D. (2013) Strength evolution in heterogeneous granular aggregates during chemo-mechanical compaction. Int. J. R. Mechs. Vol. 60. pp. 217-226. http://dx.doi.org/10.1016/j.ijrmms.2012.12.031

Invited Presentations

2015: Int. Symp. Envt. Sci. and Disaster Management, Muroran, Japan

2014: AGU; ETH Zurich

2013: AGU; SPE/AAPG Western Regional Meeting

2012: AGU; GRC Stimulation Workshop; EnergyPath 2012; US–New Zealand Joint Geothermal Workshop; 9th Int. Workshop on Water Dynamics, Tohoku University

2011: AGU; GeoProc2011 Perth [Keynote]; SIAM Comp. in Geosciences [2]; Hedberg EGS

2010: EGU; JSPS Fellow [Kyoto, Tokyo, JSCE]

Education - Educating the next generation of geothermal engineers and scientists

- Combined Graduate/Undergraduate Education in Sustainable Subsurface Energy Recovery (**GEYSER**) – 2013 - http://www.ems.psu.edu/~elsworth/courses/cause2013/
- NREL National Geothermal Student Competition – 2011