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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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Chemistry, Reservoir and Integrated Models

Relevance/Impact of Research [Challenges]

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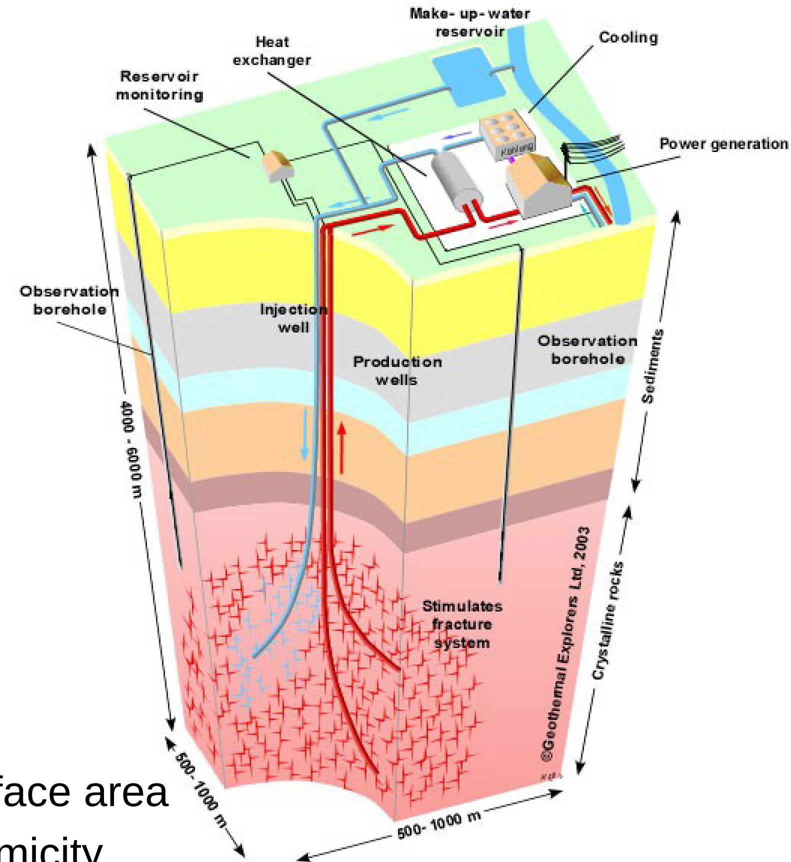
Challenges
- Prospecting (characterization)
- Accessing (drilling)
- *Creating reservoir*
- *Sustaining reservoir*
- *Environmental issues (e.g. seismicity)*

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 [Barriers]

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- *Barrier F:* "*Modeling – Insufficient modeling and validation capabilities to effectively couple fluid flow, geochemistry, and thermal-mechanical phenomena for:*
  - *(1) stimulation prediction and*
  - *(2) reservoir simulation.*"[Tables 4.8 and 4.9]
- *Barrier B* (site characterization),
- *Barrier G* (stimulation technology) to "*mitigate reservoir short –circuiting,*" and
- *Barrier M:* "*Improve[d] understanding of rock-fluid geochemistry for scale and dissolution prediction*" both during "*stimulation and management of the created reservoir*" and in "*maintaining fluid flow and reservoir lifetime*" [Table 4.29 in GTP-MYRDD]. This includes both managing reservoir productivity through "*keeping flow paths open*", but also "*managing induced seismicity*" [Table 4.30 in GTP-MYRDD] through the determination of influence of chemistry on the slip and seismic attributes of rupturing fractures.
- *New GTP Goals: "Model the reservoir conductivity at an EGS system demonstration by 2011."*

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

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 Continuum Models

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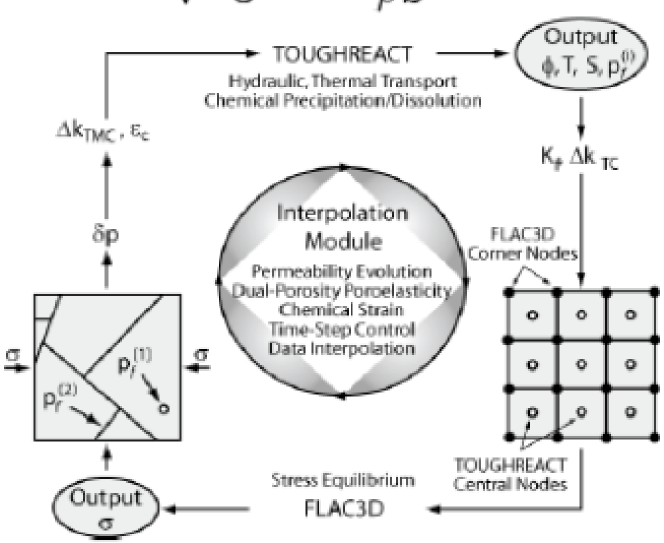
THMC-S – Linked codes

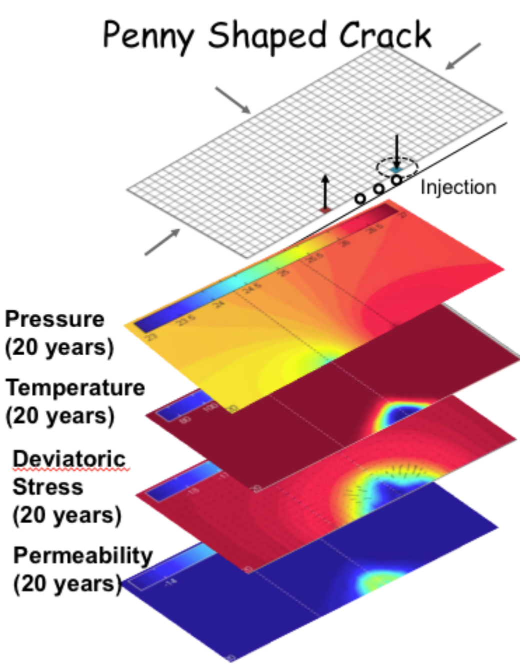
- **TOUGHREACT (THC)** – Accommodates non-isothermal, multi-component phase equilibria, pressure diffusion, multi-phase hydrologic transport, and chemical precipitation/dissolution (transient mass/energy balance)

$$\frac{\partial M}{\partial t} = -\nabla \cdot \mathbf{F} + q$$

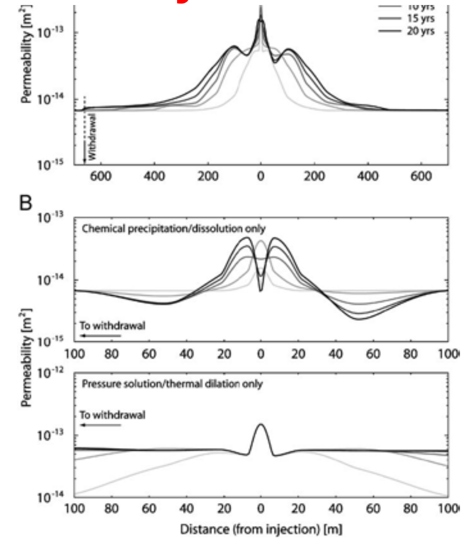
- **FLAC3D (M)** – Mechanical constitutive relations (force equilibrium, capable of THM)

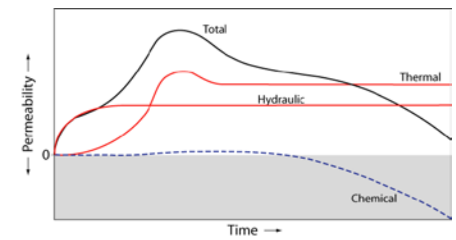
$$\nabla \cdot \boldsymbol{\sigma}^T = -\rho \mathbf{b}$$

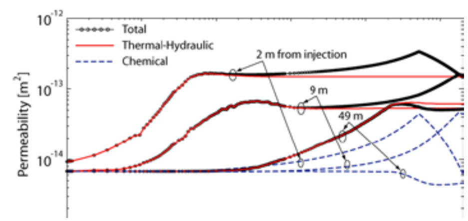




Spatial Permeability Evolution







Temporal Permeability Evolution

THMC-S Model:

Principal trigger - change in (effective) stress regime:

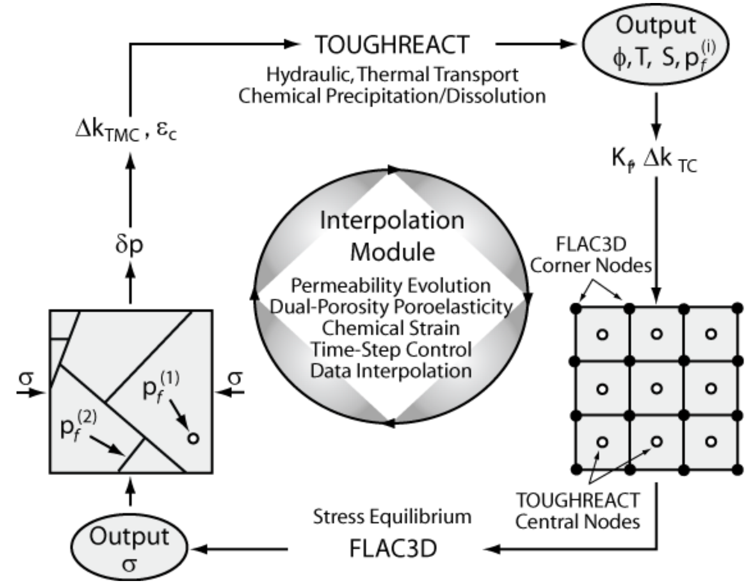
- Fluid pressure
- Thermal stress
- Chemical creep

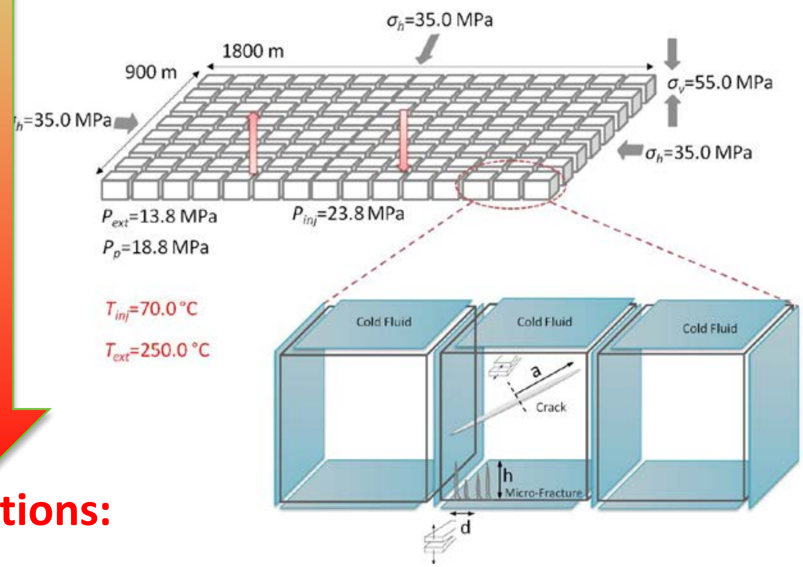
How do these processes contribute to:

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

How can this information be used to:

- Evaluate seismicity
- Manage/manipulate seismicity

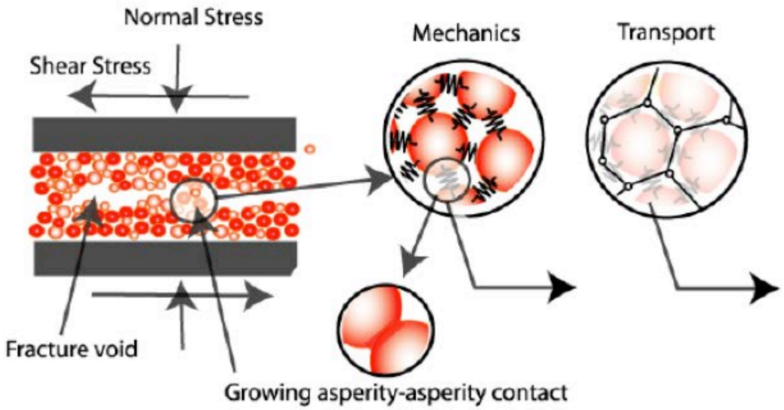




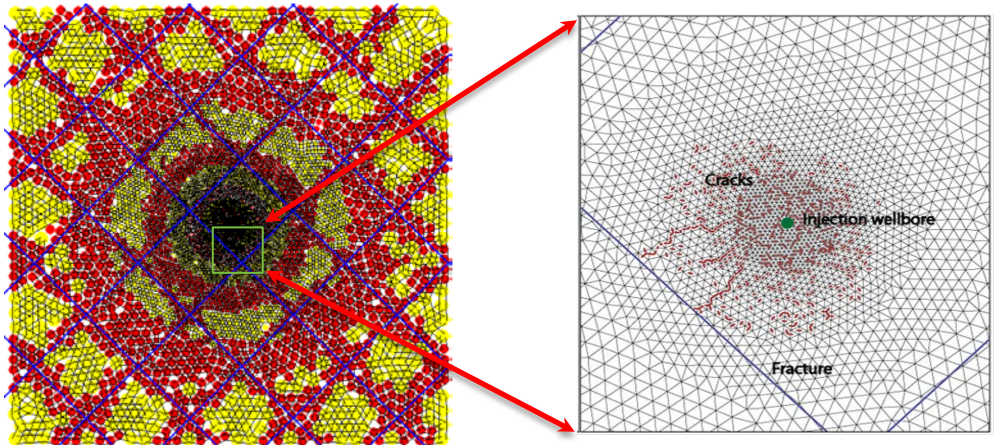
Reservoir Conditions:

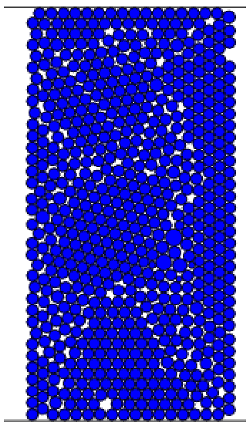
Granular Models for Synthetic Rock Masses

Micro-Model

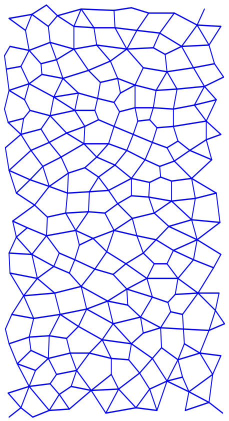


Nested Structured Model





Solid sample



Fluid network

Permeability distribution

Science questions:

Approaches to represent the complex failure and deformation response of structured media, e.g.:

1. Mechanisms of chemical compaction
2. Styles of failure
3. Event size/timing of induced seismicity, roles of:
    1. Healing rates for repeat seismicity
    2. Weakening rates for seismic vs aseismic
4. Stress-mediated reaction rates
5. Feedbacks between processes
6. ………………

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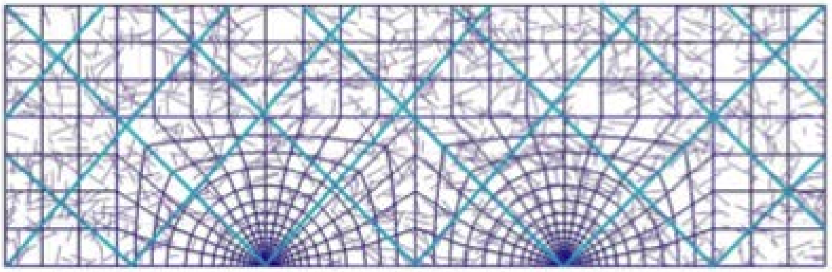
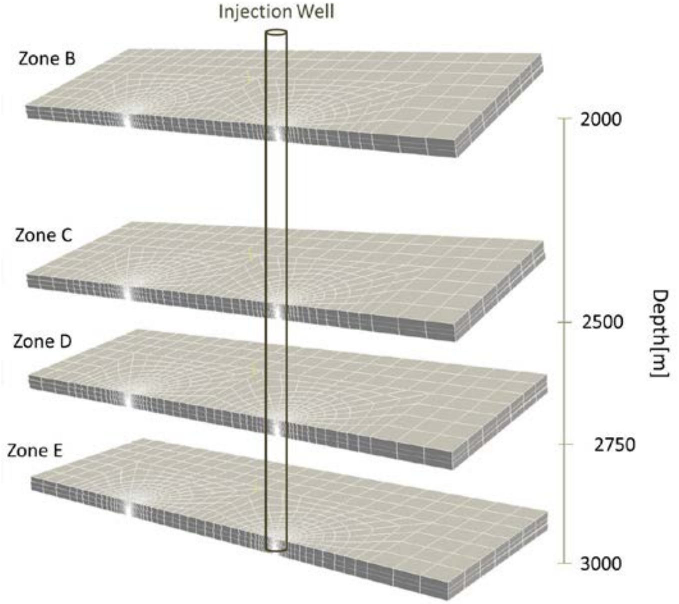
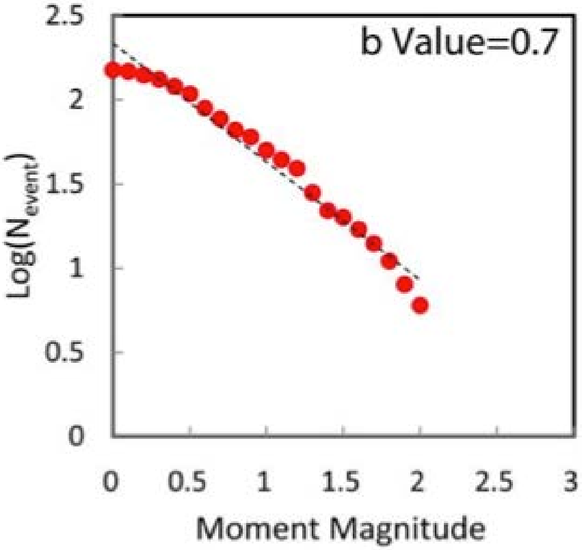
Fracture Geometry

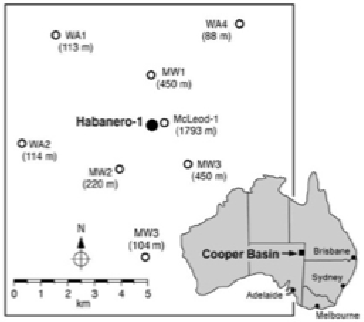


Stimulation Geometry



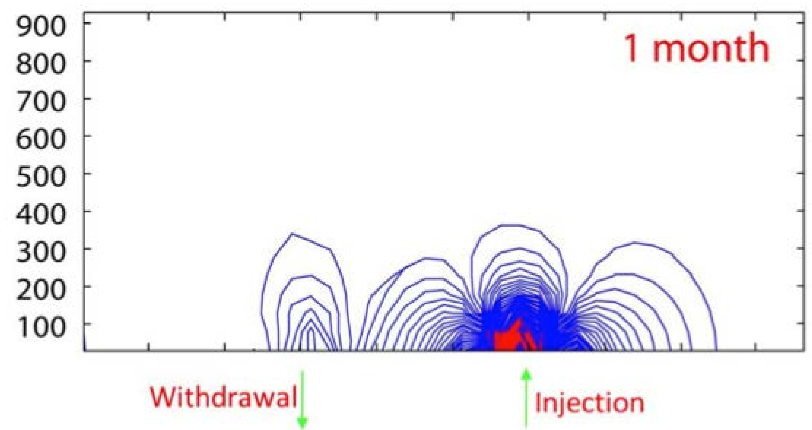
Observed b-value ~0.7-0.8





Map of Cooper Basin Geothermal Field, Australia

Event Distribution – by Magnitude



ARP: Newberry Stimulation

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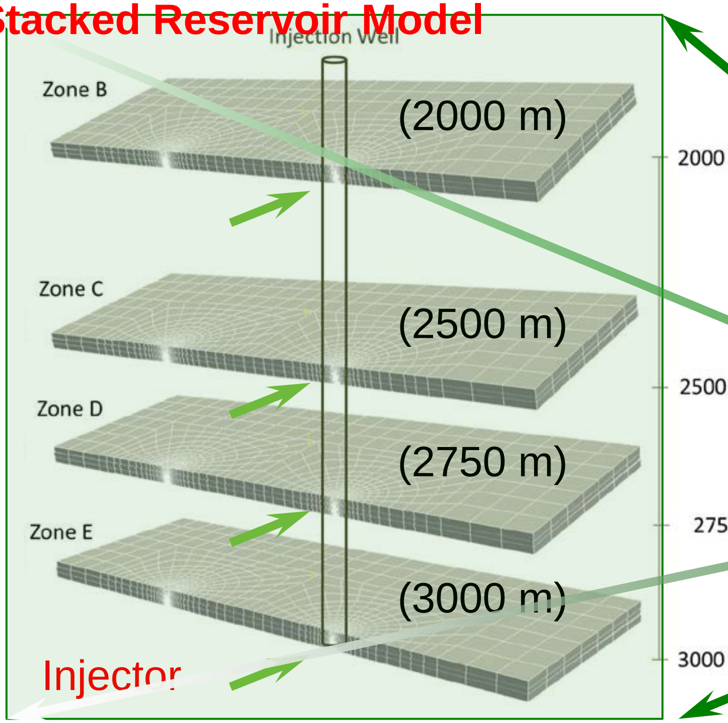
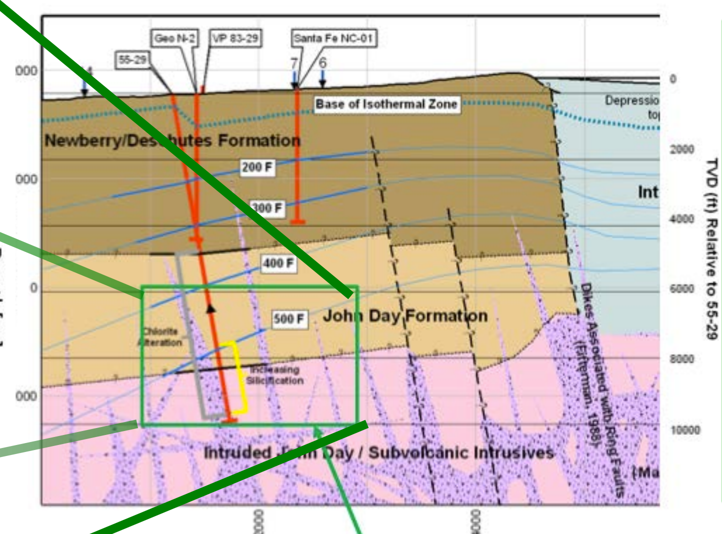
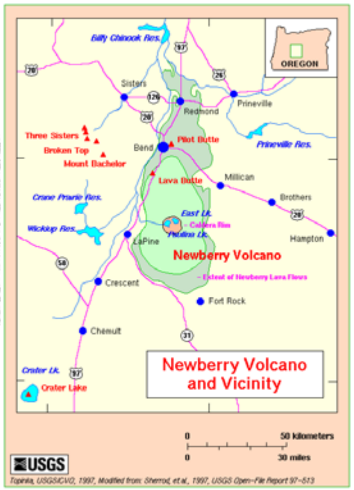
Stacked Reservoir Model



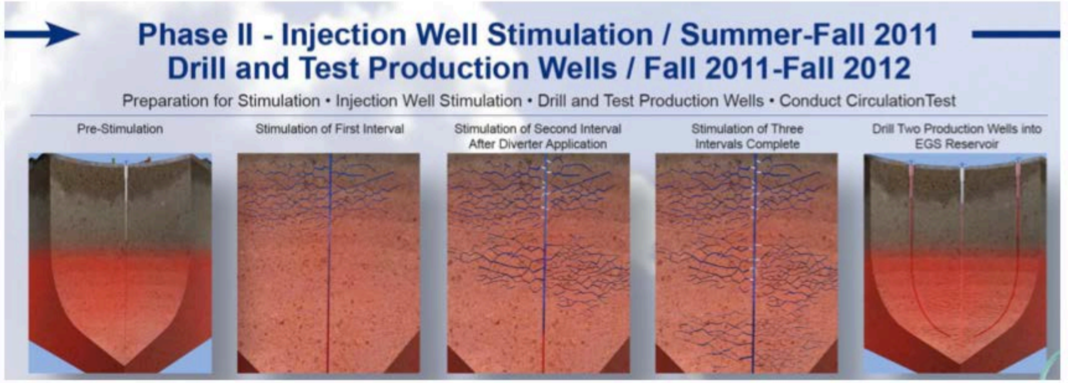
Volcanic stratigraphy



Location



ProposedStimulation Sequence



Stimulation zones:

- Four independent stacked zones
- $S_{max} = S_V$
- $S_{hmin} = 0.75\ S_v$
- Max stress drop 3 MPa
- Injection overpressure = 5 MPa

ARP: Geometric Control: Heterogeneous fracture density

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Heterogeneous fracture density: Min-Max

Stress increments with depth.

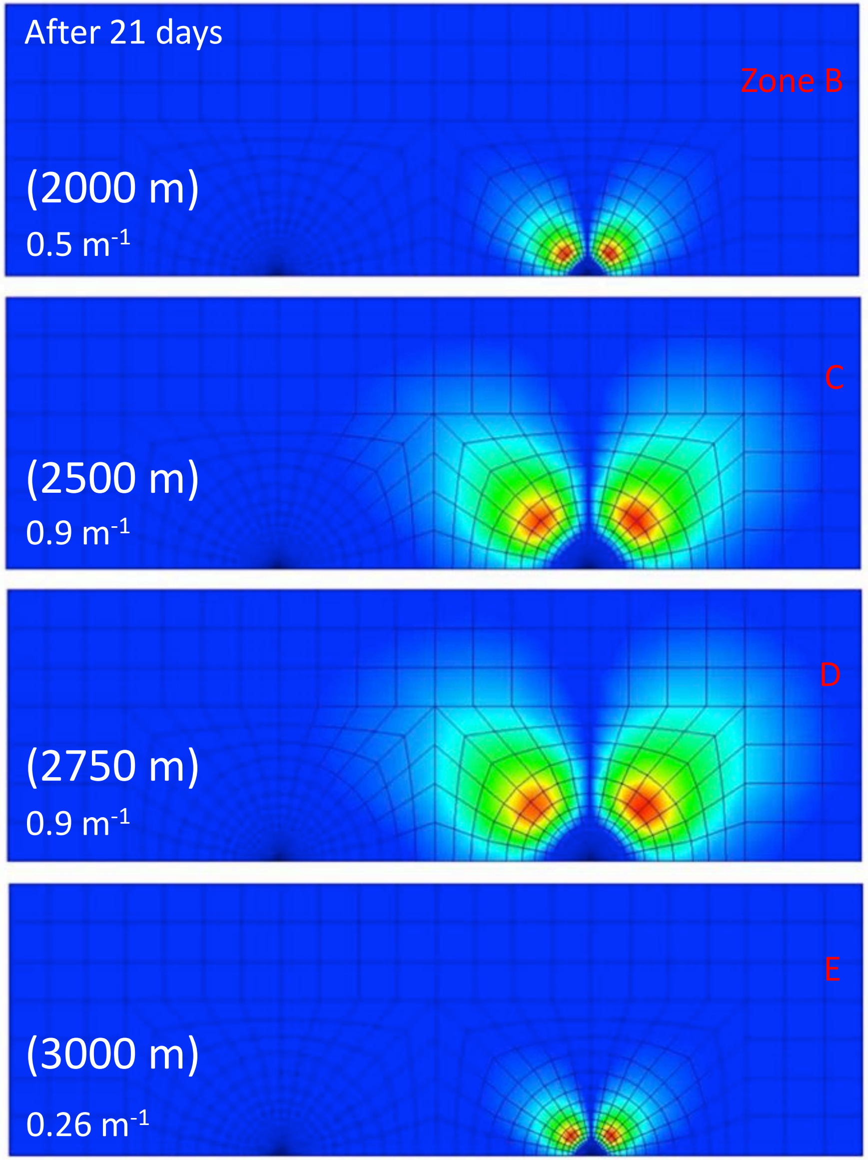
The rate of seismic event migration within the reservoir is controlled principally by the density and spacing of the fractures.

Highest fracture density generates both the most and the largest seismic events.

Feedbacks of:

Block cooling:
- Large fracture density
- High H-T surface area

Thermal strains:
- Large effective stress change
- Large perm change



ARP: Permeability - Cumulative

Permeability changes for:

1. Different fracture networks
2. Vertical stress profile

Observations:

1. Similar max k/k_0~x10
2. Greatest reach (~200m)in high frac density
3. Permeability improvement in all zones is ~radially symmetric.

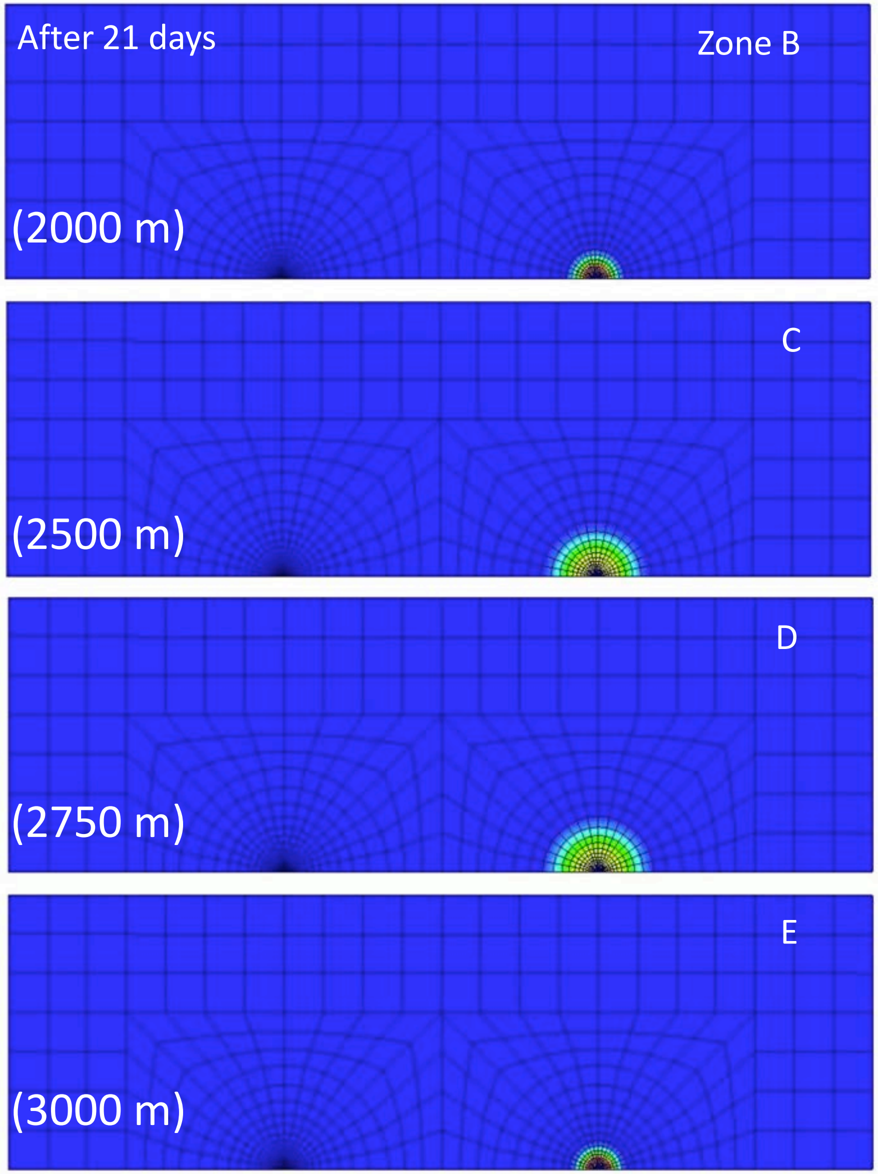
Fracture dilation angle is 10°

Fracture density:
(Int) 0.5 m^{-1}

(Max) 0.9m^{-1}

(Max) 0.9m^{-1}

(Min) 0.26m^{-1}



ARP: Event Distribution (radius-time)

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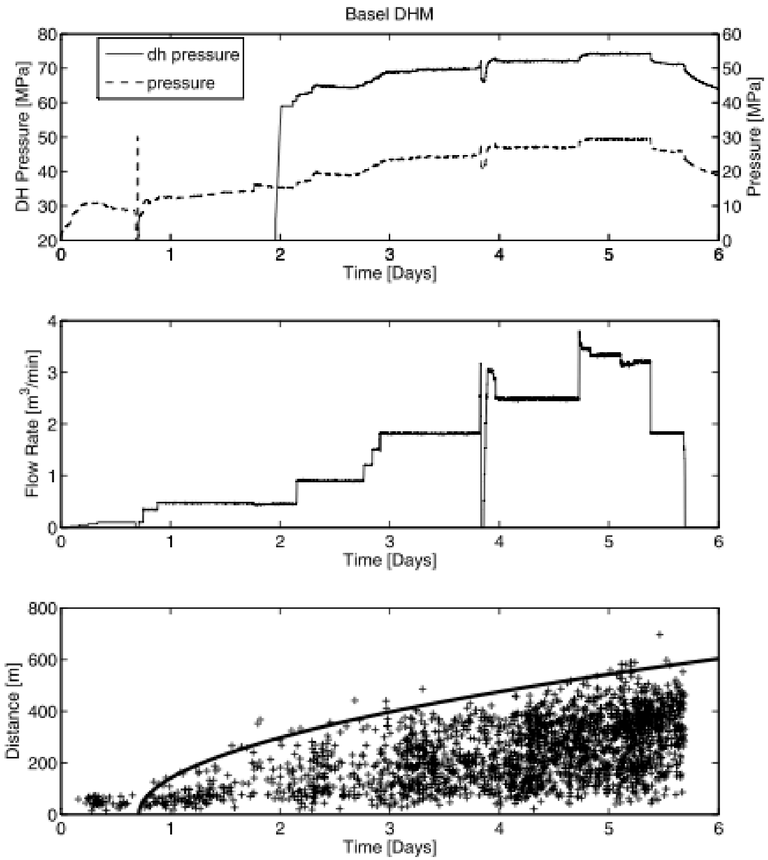
Seismicity: Basel over 6 days



[Shapiro and Dinske, 2009]

Newberry over 21 days

Fracture density:

(Int) 0.5 m^{-1}

(2000 m)

(Max) 0.9m^{-1}

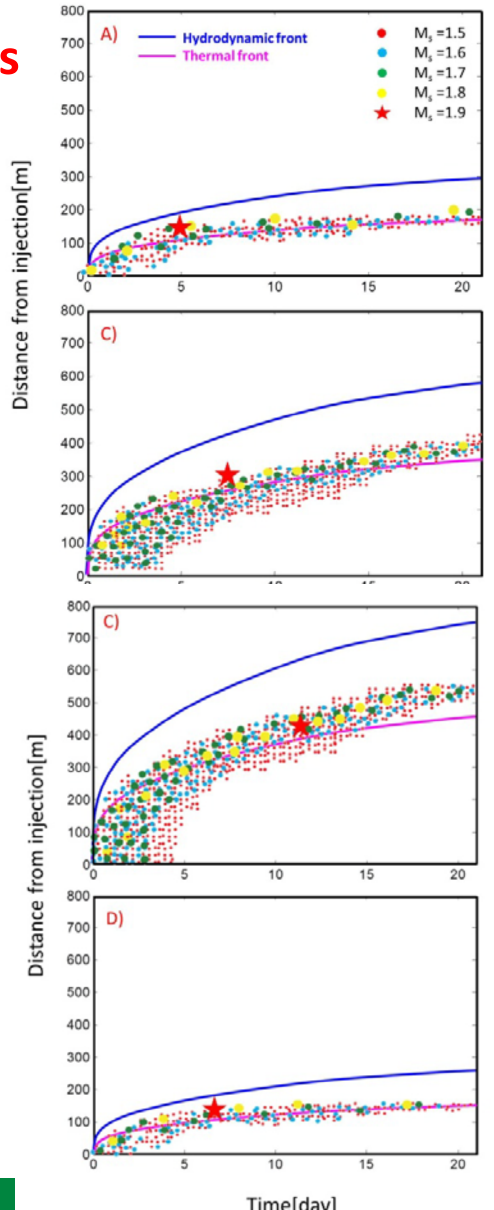
(2500 m)

(Max) 0.9m^{-1}

(2750 m)

(Min) 0.26m^{-1}

(3000 m)



ARP: Fault Reactivation (and Control)

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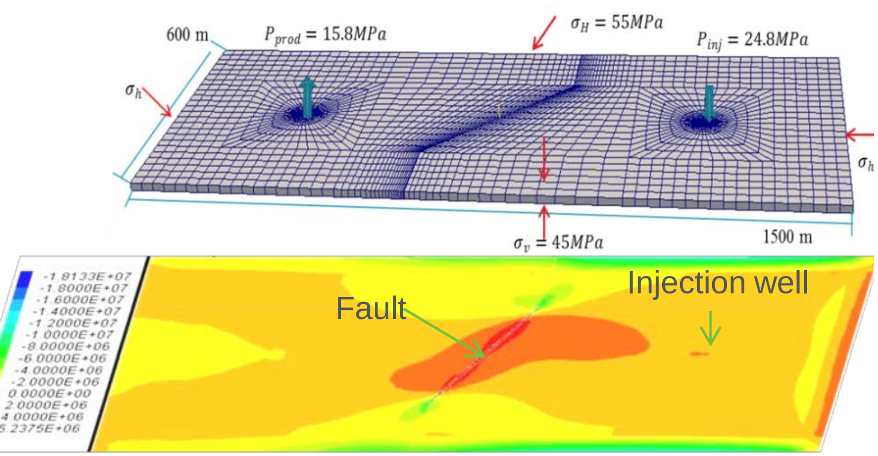
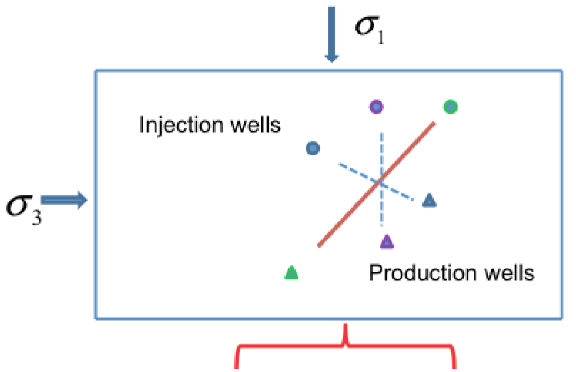
Controls on Magnitude and Timing:

k_{fault} & k_{medium}	[10-16 – 10-12 m2]
Injection temperature dT	[50C – 250C]
Stress field obliquity	[45-60 degrees]

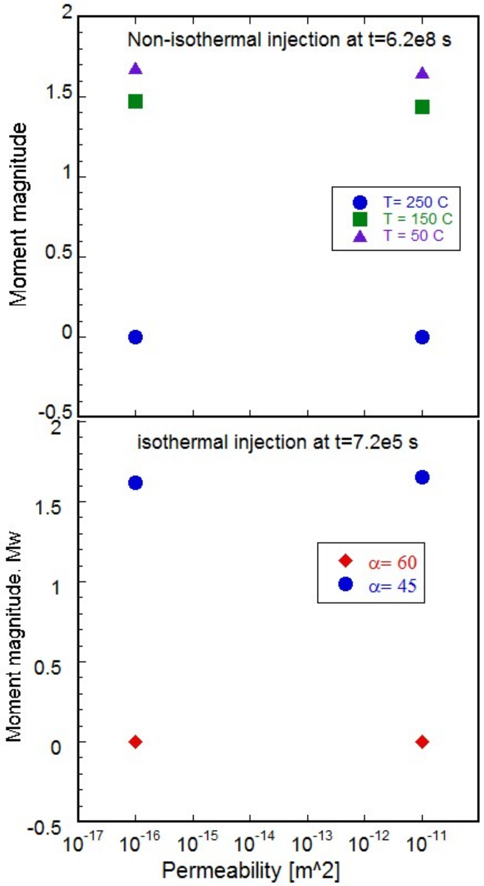




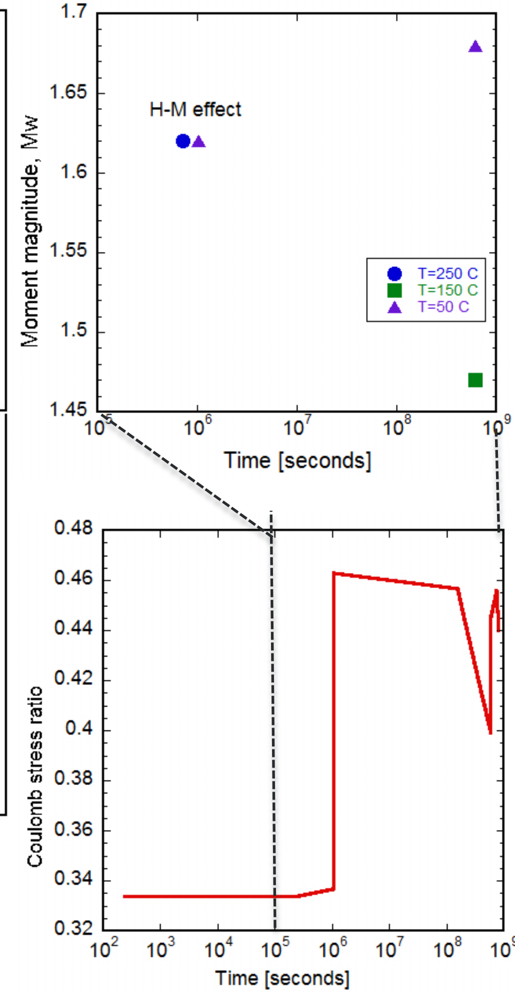
Magnitude vs. stress obliquity

Magnitude vs. timing

Permeability & Magnitude

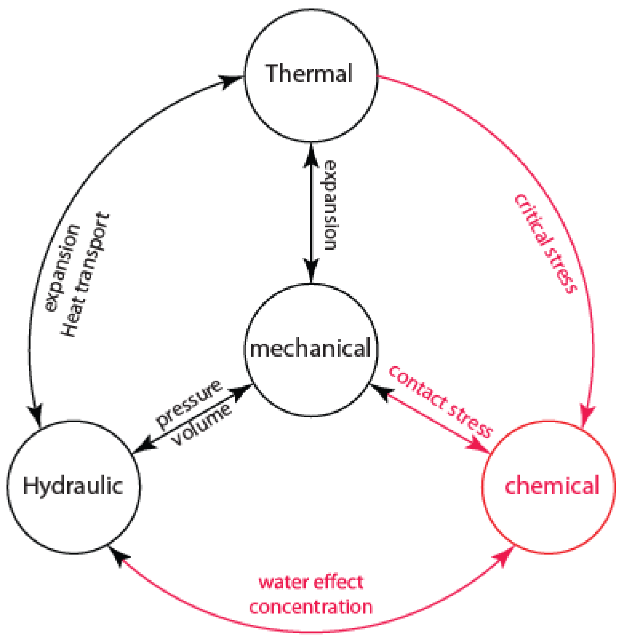


Timing



ARP: Discontinuum Models THMC-S Formulation

Feedbacks



Key Points:

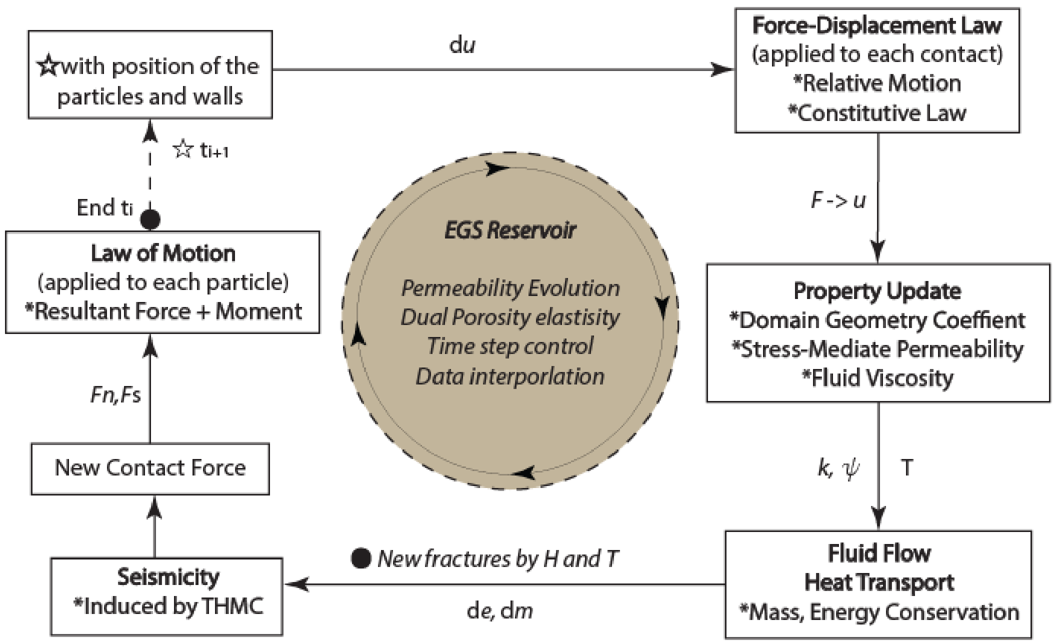
1. **Hydro-shears and -fractures created in the short term;**
2. **Thermal fracture created in relative longer term;**
3. **Chemical compaction of the new asperity to asperity contact will close the fracture to decrease the aperture;**
4. **Seismicity events represent the breakage of the bond and sliding behavior along fractures.**

Interactions

$$T \underset{contact \leftrightarrow pipe}{\overset{\Delta R = \alpha R \Delta T}{\rightleftharpoons}} M$$

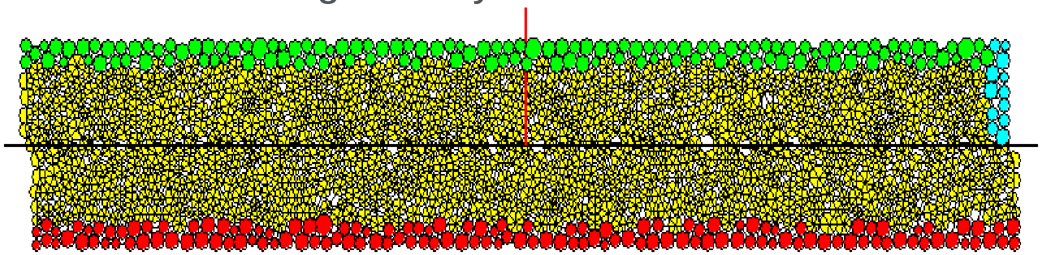
$$T \underset{heat\ exchange}{\overset{Viscosity}{\rightleftharpoons}} H$$

$$H \underset{void\ space}{\overset{pressure}{\rightleftharpoons}} M$$

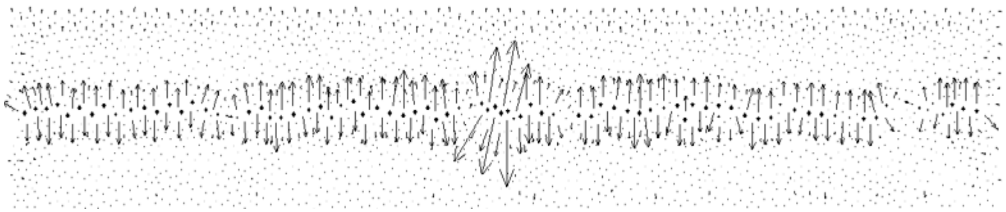


ARP: Discontinuum Models Rate-State Models of Faults/Fractures

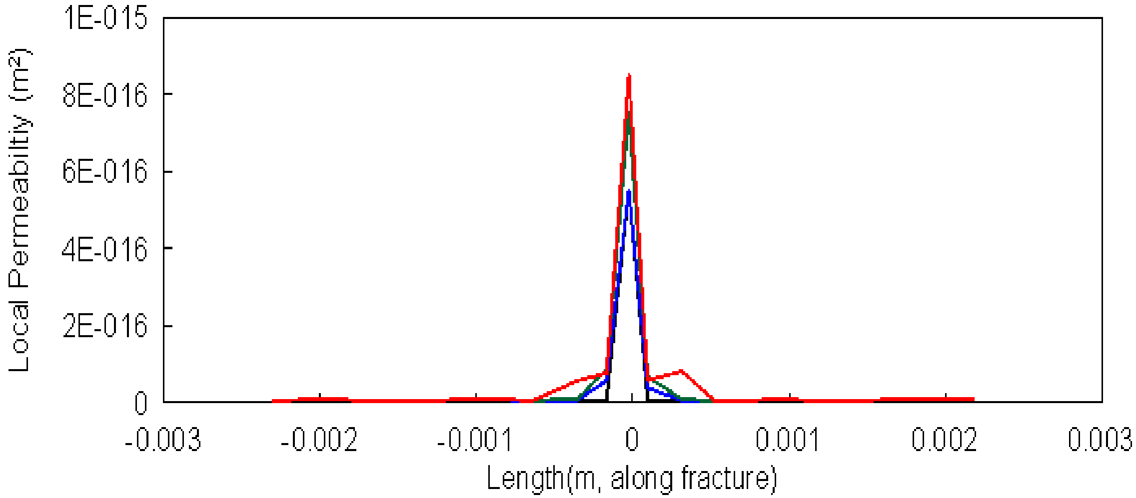
Sheared fracture geometry



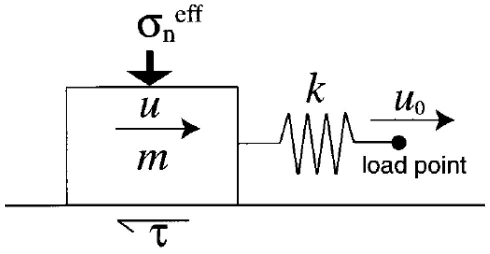
Displacement profile



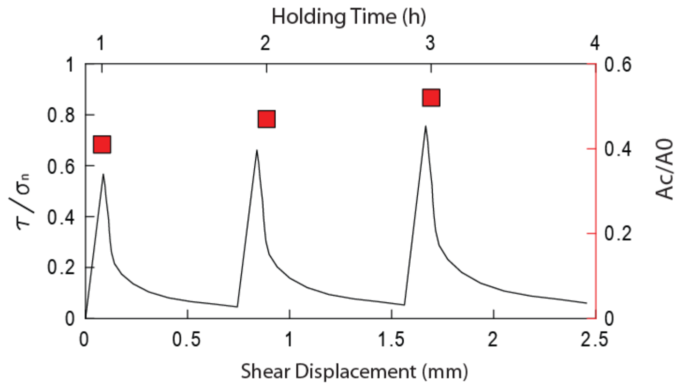
Permeability evolution



Block-slider model



Strength evolution



ARP: Discontinuum Models Reservoir Stimulation

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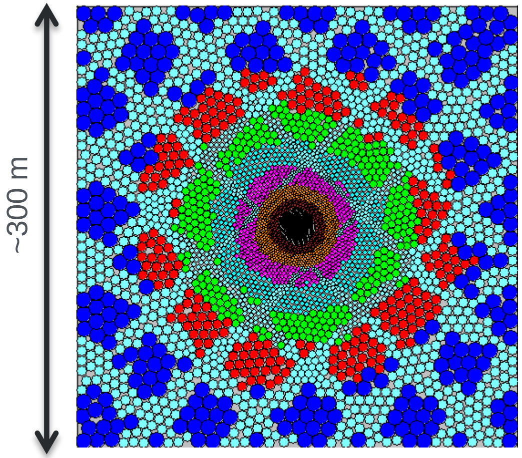
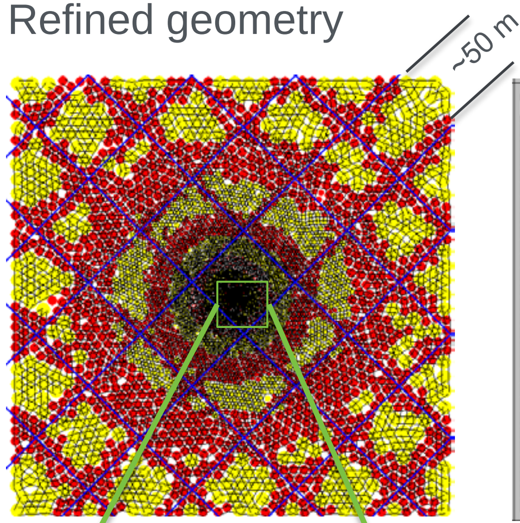
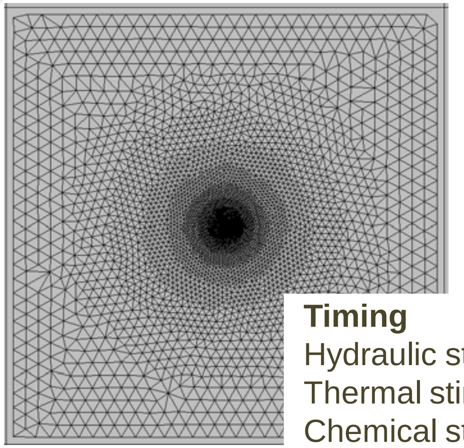
Reservoir geometry



Refined geometry

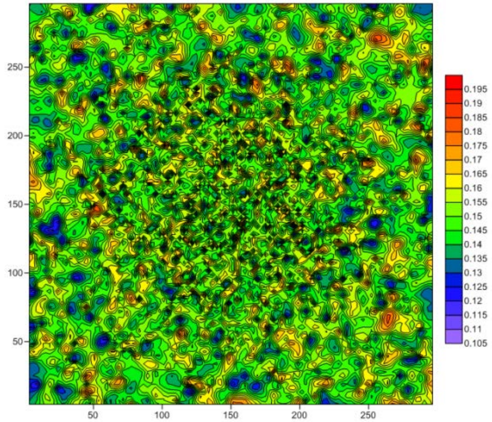


Fluid/energy/mass transport mesh

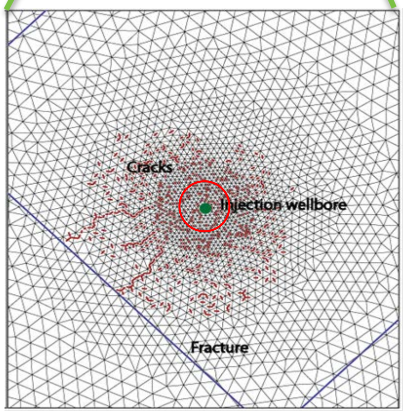


Timing
Hydraulic stimulation
Thermal stimulation
Chemical stimulation

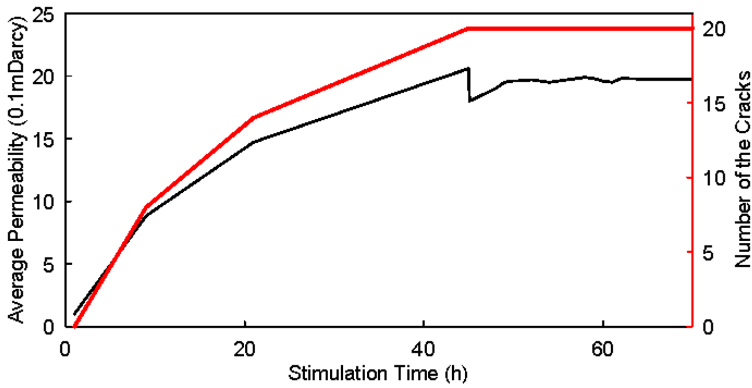
Porosity field



Fracture evolution

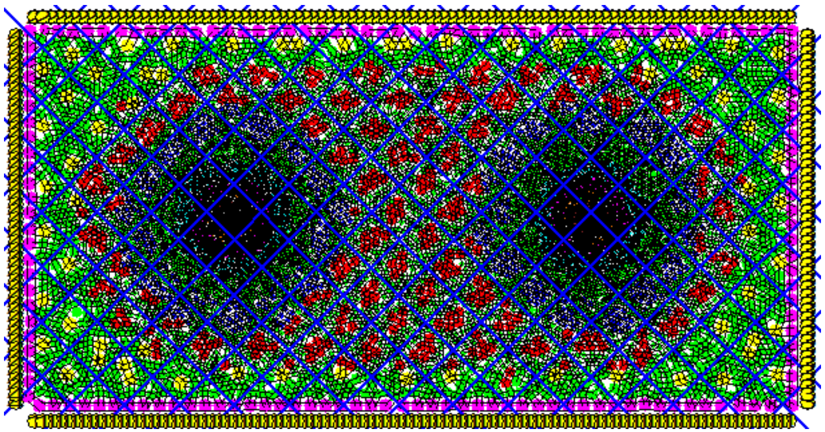


Permeability evolution

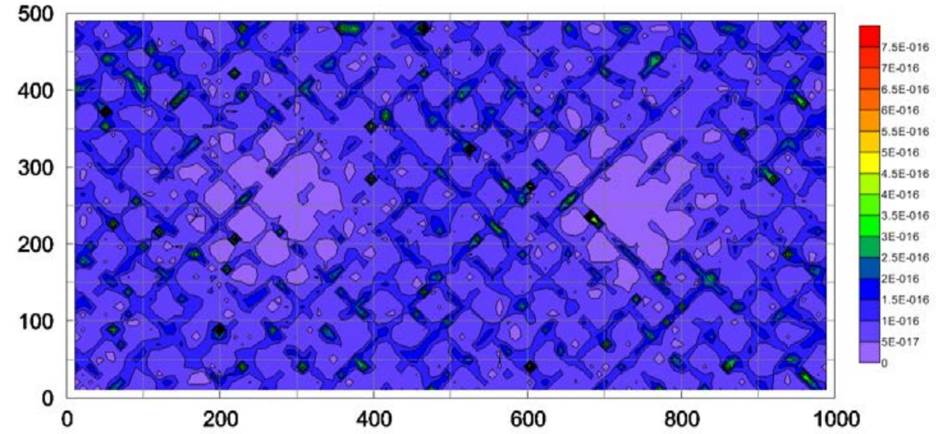


ARP: Discontinuum Models Reservoir Production

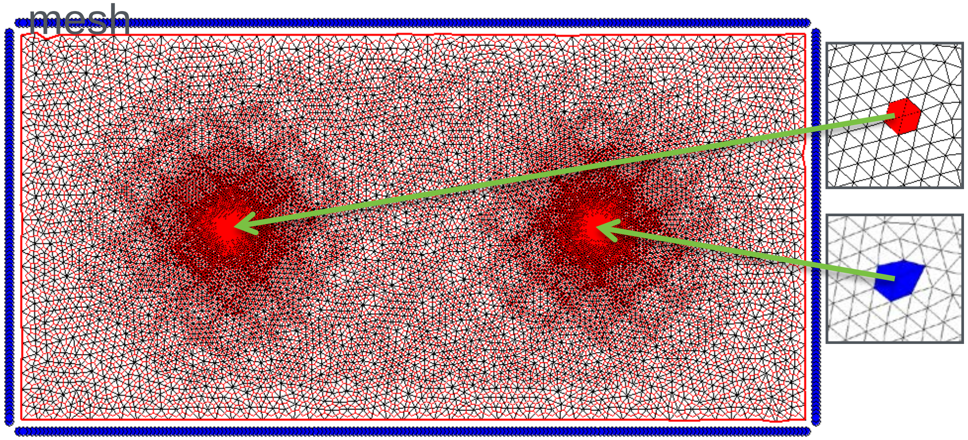
Reservoir geometry



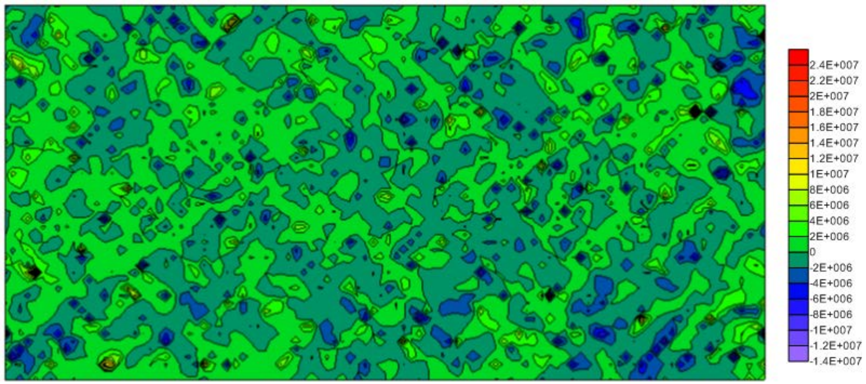
Permeability distribution



Fluid/energy/mass transport mesh



Shear stress distribution



Future Directions

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Continuum Analysis

- Newberry: Match stimulation observations (permeability and seismicity) -> key processes
- Newberry: Apply to second/new stimulation to inform hole placement and best practices
- Evaluate controls of stress and well placement on induced seismicity including large faults
- Incorporate models of rate state friction and examine the roles of healing and weakening on induced seismicity

Discontinuum Analysis

- Develop macroscale models for healing and weakening on seismicity
- Apply discontinuum models to represent stimulation response including Newberry

Milestone or Go/No-Go	Status & Expected Completion Date
Continuum models	In progress as ranked; Duration ~1.5y
Discontinuum models	In progress as ranked; Duration ~1.5y

Summary Slide – Key Points

- **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**
  - Mechanisms that control stress effects also influence seismicity
  - Event magnitudes controlled by stress-drop and fracture size
  - Distribution and propagation rate controlled by:
    - Stress magnitude (weakly for the same stress obliquity)
    - Fracture network geometry (strongly)
  - Principal feedbacks: H-T area->Cooling->Thermal strain-> Seismicity/Permeability
    - Relative magnitude of stress change effects (pressure, temp, chem)
    - Rates of propagation and self-propagation of those stress-change fronts
  - Isolating principal mechanisms is one key to mitigating effects
- Key milestones for 2013 met in top two items

Project Management

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Timeline:

Planned Start Date	Planned End Date	Actual Start Date	Current End Date
January 1, 2010	December 31, 2012	May 15, 2010	February 14, 2014

Budget:

Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	Value of Work Completed to Date	Funding needed to Complete Work
1,111,024	489,476	1,602,500	1,263,439	1,263,439	339,061

Project Links

- AltaRock Newberry Demonstration Project (*via* cost share and data)
- Desert Peak (*via* Stefano Benato as collaborating graduate student)
- LBNL (*via* co-PI Eric Sonnenthal)
- USGS (*via* collaorator Josh Taron)

Management

- Tele/video conference with AltaRock and co-investigators
  - ~Weekly
- Semi-annual meetings with co-investigator and collaborators
  - DOE Future of EGS committee, GRC, AGU, ARMA, PSU)

Schedule

- Project is on budget schedule

Additional Information

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

Publications (2011 & 2012) [www.ems.psu.edu/~elsworth/publications/pubs.htm]

1. 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.
2. Izadi, G., Elsworth, D. (2013) Role of thermal stresses on induced seismicity: evolution of frequency and moment magnitude during reservoir stimulation. Submitted for Publication. TerraNova. 20 pp.
3. Chandra, D., Conrad, C., Hall, D., Montebello, N., Weiner, A., Pisupati, S., Turaga, U., Izadi, G., Ram Mohan, A., Elsworth, D. (2013) Pairing integrated gasification and EGS geothermal systems to reduce consumptive water usage in arid environments. Energy & Fuels. 40 pp. In press.
4. Zheng, B., and Elsworth, D. (2012) Evolution of permeability in heterogeneous granular aggregates during chemical compaction: granular mechanics models. J. Geophys. Res. Vol. 117, No. B3, B03206. http://dx.doi.org/10.1029/2011JB008573 pdf
5. Izadi, G., Zheng, B., Taron, J., Elsworth, D. (2011) Evolution of permeability and triggered seismicity: fluid pressure, thermal and chemical effects in enhanced geothermal systems. Trans. Geotherm. Res. Council. 20 pp. October.
6. Chandra, D., Conrad, C., Hall, D., Montebello, N., Weiner, A., Narasimharaju, A., Rajput, V., Phelan, E., Pisupati, S., Turaga, U., Izadi, G., Ram Mohan, A., Elsworth, D. (2011) Combined $scCO_2$-EGS IGCC to reduce carbon emissions from power generation in the desert southwestern United States. Trans. Geotherm. Res. Council. 20 pp. October.

Invited Presentations

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

- NREL National Geothermal Student Competition – 2011
- Combined **G**raduate/Undergraduate **E**ducation in **S**ustainable **S**ubsurface **E**nergy **R**ecovery (**GEYSER**) – In progress 2013 with 13 students traveling to New Zealand - http://www.ems.psu.edu/~elsworth/courses/cause2013/