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
Relevance/Impact of Research [Challenges]

**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

**Resource**
- Hydrothermal (US: $10^4$ EJ)
- EGS (US: $10^7$ EJ; 100 GW in 50 years)
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
Induced Seismicity – Key Questions

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**
1. **Shear Failure Analysis**

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**

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

3. **Frictional Experiments**

Frictional Experiments are performed to explore the frictional stability with depth and to explore the mechanisms of the unexplained seismic gap.
ARP: Anomalous Seismicity – Newberry Demonstration Project

- 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
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

Seismic Events vs. Depth
ARP: Linking Induced Microseismicity to Permeability Evolution

Statistically Inverted Fracture Trace and Orientation

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\text{Statistically Inverted Fracture Trace and Orientation}
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Cellular grid of stimulated permeability created using the DFN

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\text{Cellular grid of stimulated permeability created using the DFN}
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\begin{align*}
\text{max} & \quad 0 \\
\text{n}_{\text{tot}} &= \text{n}_{\text{aseis}} + \text{n}_{\text{seis}} = \underbrace{\text{n}_{\text{aseis}}} + \underbrace{\text{n}_{\text{f}}} + \underbrace{\text{n}_{\text{uf}}} \\
\end{align*}
```

```
\text{Spatio-temporal distribution of fluid-injected-induced seismicity}
```

```
\begin{align*}
\text{radial distance from well (m)} \\
\text{time (days)} \\
\text{k}_{\text{xx}} = 0.7 \times 10^{-15} \text{m}^2 \\
\text{k}_{\text{yy}} = 1.3 \times 10^{-15} \text{m}^2
\end{align*}
```
ARP: Thermal drawdown and late-stage seismic-slip fault reactivation

\[ V = \text{volume} = whl \]

**In-Reservoir Rock Temperature Distributions – Proxy for IS strains**

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

\[ \dot{H}_{\text{fluid}} \sim Q_f \rho_W c_W \Delta T \]

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

**SGRs:**

- \( \dot{H}_s \rightarrow 0 \)
- \( \dot{H}_f / \dot{H}_s \rightarrow 0 \)
- \( Q_D \rightarrow 0 \)

**EGS:**

- \( \dot{H}_f \rightarrow \infty \)
- \( \dot{H}_f / \dot{H}_s \rightarrow \infty \)
- \( Q_D \rightarrow \infty \)

**Thermal Output:**

\[ t_D = \frac{w c_W Q_f t}{c_R} \]
ARP: Thermal drawdown and late-stage seismic-slip fault reactivation

Large \( Q_D \)

Small \( Q_D \)

**Figure 5:** Thermal front propagation from the injection well (right axis) towards the production well (left axis) under different \( Q_D \) values, the figures from (a) to (f) respectively represent the \( Q_D \) values varied from \( 4.26 \times 10^{-4} \) to \( 6.26 \times 10^{-3} \).
ARP: Thermal drawdown and late-stage seismic-slip fault reactivation

Event timing controlled by flow rate

But, event magnitude independent

Although, thermal stresses trigger reactivation, their distribution is important
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

Fracture permeability

Comparative thermal drawdowns

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

**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

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<thead>
<tr>
<th>Milestone or Go/No-Go</th>
<th>Status &amp; Expected Completion Date</th>
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<tbody>
<tr>
<td>Production models</td>
<td>Completed</td>
</tr>
<tr>
<td>Stimulation models</td>
<td>Complete June 1, 2015</td>
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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**
  - 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**
Selected Publications (2013 & 2014) [www.ems.psu.edu/~elsworth/publications/pubs.htm]


Invited Presentations
2015: Int. Symp. Env. 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