Basic Observations of Permeability Evolution - Lab-to-field

Impacts on Permeability

Mechanical effects (pore pressure and thermal effects)
- Controls on effective stress
- Stress-porosity linkages for fractures
  - Compaction
  - Dilation
- Rate-state models

Porosity-permeability linkages to fracture dilation
Other mechanical effects (wear)

Reactive chemical effects
- Laboratory observations
- Linkages among porosity/permeability/dissolution/precipitation
- Mechanistic models for chemical-mechanical effects
- In situ observations/characterizations of chemical-mechanical effects
- Forward/reverse feedbacks on stress-permeability

Reservoir-Scale Evolution of Permeability

- Spatial distribution
- Timing
- Seismicity as an indicator

Summary
Basic Observations of Permeability Evolution

Challenges
- Prospecting (characterization)
- Accessing (drilling)
- Creating reservoir
- Sustaining reservoir
- Environmental issues

Observation
- Stress-sensitive reservoirs
- THMC all influence via effective stress
- Effective stresses influence
  - Permeability
  - Reactive surface area
  - Induced seismicity

Understanding THMC 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 50y)

Permeability
Reactive surface area
Induced seismicity
Scaling Between Laboratory and Observation

Model (linkage)

Prototype (reality)

Pressure (20y)

Temperature (20y)

Deviatoric stress (20y)

Permeability (20y)

Experiment (constitutive behavior):
\[ K = f(\text{THMC}) \]
Controls on Reservoir Evolution

Many processes of vital importance to EGS are defined by coupled THMC processes.
Thermal sweep/ﬂuid residence time
Short circuiting
Induced seismicity
Prolonged sustainability of ﬂuid transmission

Fractures dominate the ﬂuid transfer system
Transmission characterized by:
  History of mineral deposition
  Chemo-mechanical creep at contacting asperities
  Mechanical compaction
  Shear dilation and the reactivation of relic fractures
**Typical Response of Fractures (Dissolution)**

- **Dry and wet scan**
- **80°C scan**
- **120°C scan**
- **System shut for 2 min**
- **System shut for 1.5 h**
- **System shut for 4 h**

**Graph Details:**
- **Y-axis:** Hydraulie aperture (µm)
- **X-axis:** Time (h)
- **Legend:**
  - Red line with black dots: System shut for 2 min
  - Red line with black triangles: System shut for 1.5 h
  - Red line with black squares: System shut for 4 h

**Additional Notes:**
- **[Polak et al., GRL, 2003]**
- **Temperature Ranges:**
  - 20°C
  - 80°C
  - 120°C
  - 150°C

**Si concentration (ppm):**
- 0.4
- 0.5
- 0.6
- 0.7
- 0.8
- 0.9
- 1.0
Typical Response of Fractures (Precipitation)

Experimental arrangement

[Diagram showing experimental arrangement with labeled components]

Precipitation

Thermal gradient along fracture

[Images showing temperature distribution and fracture patterns]

[Dobson et al., 2001]
Reactive Transport [1]

Advection-Dispersion Equation

\[ \frac{\partial c_i}{\partial t} + \nabla \cdot (c_i u) - \nabla \cdot (D_i \nabla c_i) = R_i + k_{i+}(c_i - c^{eq}_i) \]  

For the reaction:

\[ A + B \xrightleftharpoons[k_2]{k_1} C \]  

Forward rate \( = k_1[A][B] \)

Reverse rate \( = k_2[C] \)  

At equilibrium: \( k_1[A][B] = k_2[C] \)

\[ \therefore [A][B] = \frac{k_2}{k_1} [C] \]

For closed system and one mole each of \([A]\) and \([B]\), with \(k_1 = 1\) and \(k_2 = 10\), then:

\[ \frac{[A][B]}{[C]} = \frac{(1 - X)^2}{X} = \frac{10}{1} \]

And \((1 - X) = [A] = [B] = 0.916\) and \(X = [C] = 0.0839\).
Reactive Transport [2]

Implementation:

\[ R_A = -k_1[A][B] + k_2[C] \]
\[ R_B = -k_1[A][B] + k_2[C] \]
\[ R_C = +k_1[A][B] - k_2[C] \]  \hspace{1cm} (7)

Generalized:

\[ R_i = -k_{i,f} \prod_{j=1}^{N} [c_{j,f}]^{\alpha_j} + k_{i,r} \prod_{j=1}^{N} [c_{j,r}]^{\alpha_j} \]  \hspace{1cm} (8)

Heats of reaction:

\[ H_i = R_i \Delta H_i \]  \hspace{1cm} (9)

And heat balance requires:

\[ \rho c \frac{\partial T}{\partial t} + \nabla \cdot (T \mathbf{u}) - \nabla \cdot (\lambda \nabla T) = H_i \]  \hspace{1cm} (10)
Reactive Flow and Permeability Dynamics
Derek Elsworth, Penn State

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

Stress Changes
Inert changes (THM)
Reactive changes (MC)

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 50y)
Permeability Changes in Fractures - Deformation

Normal Mode:

Shear Mode:

\[ \sigma \quad \tau \quad u_s \quad \Delta b \]

\[ \sigma_0 \quad k_n \quad b_0 \quad b_{\text{residual}} \]

\[ \sigma_{\text{high}} \quad k_s \quad 1 \]

\[ \sigma_{\text{low}} \quad u_s \]
Normal Compression of Fractures

Mechanical closure with stress

\[ b_{normal} = b_r + b_{max} \exp(-\alpha \sigma') \]
\[ \Delta b_{normal} = b_{max} \exp(-\alpha \Delta \sigma') \]

Role of stress and hysteresis

Role of temperature and hysteresis

[Min et al., IJRM, 2009]
Shear Dilation of Fractures

Normal closure behavior

Shear dilatancy behavior

\[ \Delta b_{\text{shear}} = \tau \left( \frac{s}{G} + \frac{1}{K_{\text{shear}}} \right) \tan(\phi_{\text{dilation}}) \]

Stress-displacement behavior
**Rate-State Friction [1]**

### R-S Friction

\[
\mu = \mu_0 + a \ln \left( \frac{v}{v_0} \right) + b \ln \left( \frac{v_0 \theta}{D_c} \right)
\]

\[
\frac{d\theta}{dt} = 1 - \frac{v\theta}{D_c} \quad \text{(Dieterich Evolution)}
\]

\[
\frac{d\theta}{dt} = -\frac{v\theta}{D_c} \ln \left( \frac{v\theta}{D_c} \right) \quad \text{(Ruina Evolution)}
\]

### Dilation

\[
\frac{\Delta H}{H} \equiv \Delta \phi = -\epsilon \ln \left( \frac{v}{v_0} \right) = -\epsilon \ln \left( \frac{v_0 \theta}{D_c} \right)
\]

### Permeability Evolution

\[
\frac{k}{k_0} = \left( 1 + \frac{\Delta b}{b_0} \right)^3 = \left( 1 + \frac{\Delta H}{H} \right)^3
\]

---

**Velocity Steps**

**Multiple Velocity Steps**

**Single Velocity Step**
Rate-State Friction [2]

Concurrent Displacement and Fluid Measurements

Summary Data – Delta H

Summary Data – Epsilon
Porosity-Permeability Relationships

Single fracture versus bulk permeability

Single:
\[ \bar{v}_i = \frac{k_i \partial p}{\mu \partial x} = \frac{b^2}{12 \mu} \frac{1}{\partial x} \]

Bulk:
\[ \bar{v}_b = \frac{b}{s} \bar{v}_i = \frac{b^2}{12s} \frac{1}{\mu} \frac{1}{\partial x} = \frac{k_b}{\mu} \frac{\partial p}{\partial x} \]

Bulk permeability

\[ k = \frac{b^3}{12s}; \text{ therefore } k_0 = \frac{b_0^3}{12s} \]

Initial fracture aperture \((b_0)\)

\[ b_0 = \sqrt[3]{k_0 12s} \]

Change to new permeability \((k)\)

\[ \frac{k}{k_0} = (1 + \frac{\Delta b}{b_0})^3 \]
Role of Wear Products

Sample Holder

Shear-Permeability Evolution

Sample

Dissolution Products
Basic Observations of Permeability Evolution - Lab-to-field Impacts on Permeability

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Summary
Fractured Limestone – Features of Response

[Polak et al., WRR, 2004]
Fractured Limestone – Features of Response

Aperture \( <b> \) [\( \mu \text{m} \)]

- **0 hr**
  - Ground water
  - Distilled water
  - No free-face dissolution
  - Experimental data
  - Prediction

- **1462 hr**
  - Ground water
  - Distilled water
  - Concentration \( (\text{Ca}^{2+}) \) [ppm]
  - Experimental data
  - Prediction

\( A_{pore} \) increased linearly in Stage III
Reactive - Hydrodynamic Controls

Peclet No. (Pe)

\[ Pe = \frac{\text{Advective flux}}{\text{Dispersive flux}} = \frac{\langle q \rangle}{D_m} = \frac{v b_0}{D_m} \]

- \( Pe < 1 \) Dispersion dominated – Perturbations damped
- \( Pe > 1 \) Advection dominated – Perturbations enhanced

Damköhler No. (Da)

\[ Da = \frac{\text{Reactive flux}}{\text{Advective flux}} = \frac{\langle q \rangle}{\langle q \rangle} = \frac{2k_+L}{v b_0} \]

- \( Da << 1 \) Reaction slow -
  - Undersaturated along fracture – Perturbations damped
- \( Da \) larger \( << 1 \) – Reaction faster
  - Saturated along fracture – Perturbations enhanced

PeDa No. (Removes \( \langle q \rangle \))

\[ Pe Da = \frac{\text{Reactive flux}}{\text{Dispersive flux}} = \frac{2k_+L}{D_m} \]
Reactive Hydrodynamics: Role of Damkohler Number (PeDa)

15 cm x 10 cm
Voxel = 1 mm
Aperture:
Black (0)-White(0.25 mm)

High PeDa
Low PeDa

[Detwiler and Rajaram, WRR, 2007]
**Reactive - Mechanical Controls**

**Stress-Assisted Dissolution (PS)**

\[
\frac{dM_{\text{diss}}^{PS}}{dt} = \frac{3\pi V_m^2 (\sigma_a - \sigma_c) k_+ \rho_g d_c^2}{4RT}
\]

**Free-Face Effects (FF)**

**Dissolution (diss)**

\[
\frac{dM_{\text{diss}}^{FF}}{dt} = k_+ A_{\text{pore}} \rho_g V_m \left(1 - \frac{C_{\text{pore}}}{C_{eq}}\right)^n
\]

**Precipitation (prec)**

\[
\frac{dM_{\text{prec}}}{dt} = k_- A_{\text{pore}} \rho_g V_m \left(\frac{C_{\text{pore}}}{C_{eq}} - 1\right)^n
\]

**Mass-Flux Ratio**

\[
\chi = \frac{\text{Stress-Driven Flux}}{\text{Dissolution-Driven Flux}}
\]

\[
\chi = \left(\frac{\dot{M}^{PS}}{\dot{M}^{FF}}\right)_{\text{diss}} = \frac{3\pi}{4} \frac{d_c^2}{A_{\text{pore}}} \frac{V_m}{RT} \frac{(\sigma_a - \sigma_c)}{(1 - C_{\text{pore}}/C_{eq})^n}
\]
Modes of Permeability Evolution

Fracture dilation and closure

\[ \Delta b = \frac{\partial b}{\partial t} \Delta t \]

Change in aperture (positive in dilation):

\[ \frac{\partial b}{\partial t} = \frac{\partial V_{ps}}{\partial t} \frac{1}{R_c A_f} + \frac{\partial V_{ff}}{\partial t} \frac{1}{(1 - R_c) A_f} \]

Link aperture change to fracture volume (porosity) change:

Fracture closure

Link fracture volume (porosity) change to fluid concentration change:

\[ \frac{\partial V_i}{\partial t} = \left\{ \begin{array}{c} -\frac{\partial c_{ps}}{\partial t} \frac{V_p}{\rho} \\ \frac{\partial c_{ff}}{\partial t} \frac{V_p}{\rho} \end{array} \right\} \]

[Elsworth and Yasuhara, IJNAMG, 2009]
 Modes of Lumped Parameter Permeability Evolution

Flow geometry

\[ \frac{\partial c}{\partial t} - A e^{-Ft} + B(c - c_{eq}) + Q (c - c_{in}) = 0 \]

Isothermal response

[Elsworth and Yasuhara, IJNAMG, 2009]

[Image of flow geometry and concentration graphs]
Modes of Lumped Parameter Permeability Evolution

Flow geometry

Lumped mass balance equation

\[ \frac{\partial c}{\partial t} - Ae^{-Ft} + B(c - ceq) + Q(c - cin) = 0 \]

Non-isothermal response

[Elsworth and Yasuhara, IJNAMG, 2009]
Component Model

Interface Dissolution

\[
\frac{dM_{\text{diss}}}{dt} = \dot{\varepsilon}_{\text{diss}} \frac{d}{\omega} \rho g \left( \frac{\pi}{4} d_c^2 \omega \right)
= \frac{3\pi V_m^2 \sigma_{\text{eff}} k_+ \rho g d_c^2}{4RT}
\]

\[
\frac{dM_{\text{diss}}}{dt} = \frac{3\pi V_m^2 (\sigma_a - \sigma_c) k_+ \rho g d_c^2}{4RT}
\]

\[
\sigma_c = \frac{E_m \left(1 - \frac{T}{T_m} \right)}{4V_m}
\]

Interface Diffusion

\[
J = -D_b \frac{dC}{dx}, \quad J_m = -2\pi r \sigma D_b \left( \frac{dC}{dr} \right)_{r=d_c}
\]

\[
J_m = \frac{dM_{\text{diff}}}{dt} = \frac{2\pi \omega D_b}{\ln \left( \frac{d_c}{2a} \right)} \left( C_{\text{int}} - C_{\text{pore}} \right)
\]

Pore Precipitation

\[
\frac{dM_{\text{prec}}}{dt} = V_{\text{pore}} \frac{A}{M} k_- (C_{\text{pore}} - C_{eq})
\]

[Yasuhara et al., JGR, 2003]
Mass Transfer Modes – Essential Components

Figure 3. Schematic of discrete technique. (a) Pore space is divided into two elements of axisymmetric form, where each has the volume of $V_p/2$. Node 1, 2, and 3 are placed at the interface of the grain-to-grain contact, pore space, and interface between pore fluid and the free-face of grain, respectively. Thus, concentrations at nodes 1, 2, and 3 are regarded as $C_{int}$, $C_{pore}$, and $C_{eq}$. (b) Elements 1 and 2 are only controlled by diffusion and precipitation, respectively. Each one can be formulated by considering mass conservation.

Contact geometry evolves with interpenetration

Pore concentration allows mass balance for arbitrarily open or closed systems
Matching Compaction Data

[Experimental data from Elias and Hajash, 1992]
System Evolution at 35-70 MPa and 150°C

**Observation**

70 MPa and 150°C

![Graph showing porosity over time at 70 MPa and 150°C.](image)

*Experimental data from Elias and Hajash, 1992*

[Experimental data from Elias and Hajash, 1992]

[Yasuhara et al., JGR, 2003]

**Extension**

35 MPa and 150°C

![Graph showing porosity over time at 35 MPa and 150°C.](image)

*Experimental data (σ_eff = 34.96 MPa)*

[Yasuhara et al., JGR, 2003]
Timescales of Evolution of Granular Systems at 35 MPa and 75–150°C

[Yasuhara et al., JGR, 2003]
Permeability Evolution in Granular Systems at 35 MPa and 75-300°C

Capillary Model: \[ k = \frac{n\delta^2}{96} \]

Pore Evolution: \[ V_p = (\pi / 4)\delta^2 d_0 \]

Linked Permeability: \[ k \approx \frac{nV_p}{24\pi d_0} \]

[Yasuhara et al., JGR, 2003]
Constraint on Fracture Apertures and Fluid Concentrations

Asperity contacts

Local contact area, $A'_c$

\[
\langle b \rangle = b_r + b_{\text{max}} \exp\left(\frac{(R_c - R_{c0})}{a}\right)
\]

Increasing fracture closure

(a)

(b)

(c)

Asperity contacts

Local contact area, $A'_c$

\[
\langle b \rangle = 2.5 + 16.0 \exp\left(-\frac{(R_c - R_{c0})}{20}\right)
\]

$R^2 = 0.92$

$b_{\text{max}}$

$b_r$

$R_c$

$b_0 = 18.5 \mu m$

$R_c = 5.0 \%$

Contact-area ratio $R_c$ [%]

Mechanical aperture $\langle b \rangle$ [\mu m]

Result by profiling data
Regression curve

Increasing fracture closure

Increasing fracture closure
Modeling Results - Novaculite

[Yasuhara et al., JGR, 2004]

Kₚ ~ x300
Projected Response of Fracture

Define projected behavior for varied temperatures

…and mean stress magnitudes

[Yasuhara et al., JGR, 2004]
Fractured Limestone – Features of Response

Ca

Mg

[Polak et al., WRR, 2004]
Fractured Limestone - Features of Response

A_{pore} increased linearly in Stage III

0 hr

1462 hr
Novaculite - 20 week response

(a) Hydraulic aperture [μm]

(b) Si concentration [ppm]

Time [hr]

Normalized differential pressure [kPa]

1.0 mL/min

Reversed flow (20 °C)

0.5

0.25

0.125

0.0625

0.125
Novaculite - 20 week response

(a) Hydraulic aperture [μm]

(b) Si concentration [ppm]

Normalized differential pressure [kPa]

Temperature conditions:
- 20 °C
- 40 °C
- 80 °C
- 120 °C

Flow rates:
- 1.0 mL/min
- 0.25
- 0.125
- 0.0625
- 0.125

Shutdown flow (72 hours)
and Lumped Parameter Prognostic Model for Novaculite ...
1. Set initial aperture distribution

2. Apply I.C. and B.C. → Obtain velocity distr. in a fracture by solving Reynolds' equation

\[ \nabla \left( \frac{b^3}{12 \mu} \nabla p \right) = 0 \]

3. Dissolution at contact area and free-face (reaction) → Obtain concentration distribution + Modify aperture distribution due to dissolution

\[ \frac{dM^{PS}}{dt} = \frac{3\pi V^2 m \rho g k_+ (\sigma_a - \sigma_c) A_e}{4RT} \quad \frac{dM^{FF}}{dt} = 2 A_e k_+ \frac{C_{eq} - C_i}{C_{eq}} \]

4. Lagrangian-Eulerian method (Advection-diffusion) → Obtain concentration distribution within and out of domain
• Numerical model is capable of better replicating experiment – multiplier on $k_+$ is greatly reduced over lumped parameter case.
Application to novaculite (laboratory) data under stress control
Sparse data but available data conform to the expected response based on micro-mechanical arguments
Experimental data needed at a variety of scales
TMC-Induced Aperture Change – Stress Control

Application to granodiorite data (field) under stress control
Replicates most features on curve
Experimental data needed at a variety of scales

[Handin et al., 1982]
The Role of Irreversible “Chemical” Strains on Mechanical and Transport Properties
Basic Observations of Permeability Evolution – Lab-to-field

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Summary
**Coupled THMC Modeling**

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

\[
\frac{\partial M}{\partial t} = -\nabla \cdot F + q
\]

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

\[
\nabla \cdot \sigma^T = -\rho b
\]

[Taron et al., 2009]

---

TOUGHREACT

Hydraulic, Thermal Transport
Chemical Precipitation/Dissolution

\[ \Delta k_{TMC}, \varepsilon_c \]

\[ \delta p \]

Interpolation
Module
Permeability Evolution
Dual-Porosity Poroelasticity
Chemical Strain
Time-Step Control
Data Interpolation

\[ p_r^{(1)}, p_r^{(2)} \]

Stress Equilibrium
FLAC3D

\[ \sigma \]

\[ \alpha \]

Output

FLAC3D

TOUGHREACT Central Nodes

Aperture reduction [b]

Irreversible stress loss

Stress loss due to chemical strain

Irreversible aperture reduction

Cumulative stress loss (acquired during loading period)

Thermal unloading

Thermal loading

[Sarmor et al., 2009]
Coupled THMC Modeling
Chemical -vs- Mechanical Influence

[Taron et al., 2009]
Thermo-hydraulic processes combined in this model.

Onset of chemical permeability change a longer time-scale process.

Sharp onset of chemical change due to complete dissolution of all calcite in veins.
Triggered 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
Link seismicity to permeability evolution

THMC Model:

Reservoir Conditions:
Approaches – Rate-State versus Brittle Behavior

**Rate-State**

\[ \mu \left( a - b \right) \ln \left( \frac{v}{v_0} \right) \]

**Brittle**

\[ \tau_{\text{max}} \]

\[ \Delta \tau \]

Coefficient of friction

- Low velocity
- High velocity
- Low velocity

System Stiffness (Stored Energy)

Failure Criterion (Trigger)

Displacement

\[ D_C \]
Component Behavior - Reservoir stiffness

Stiffness:

\[ K_s = \frac{\tau}{u_m} = \frac{3G\pi(3\lambda + 4G)}{8(\lambda + 2G)} \frac{1}{a} = \frac{3G\pi(2 - \nu)}{8(1 - \nu)} \frac{1}{a} \]

Penny-shaped Crack

Energy:

\[ E_p = \frac{2\tau^2 a^3}{3G} \]

Magnitude:

\[ \log E_p = 1.5M_s + 9.1 \]
Continuum THMC Model

Reservoir Conditions:

- $\sigma_h = 35.0$ MPa
- $\sigma_v = 55.0$ MPa
- $P_{ext} = 13.8$ MPa
- $T_{ext} = 250.0$ MPa
- $P_{p} = 18.8$ MPa
- $P_{inj} = 23.8$ MPa
- $T_{inj} = 70.0$ MPa

Model:

- THMC Simulator
- TOUGHREACT
- FLAC3D
- Numerical Model
- Large Single Fractures
- Multiple Micro-Fracture
Large Fracture Geometry

Penny Shaped Crack

Injection

Pressure (20 years)
Temperature (20 years)
Deviatoric Stress (20 years)
Permeability (20 years)
Short-term Validation

Model Results:

Observed b-value: ~0.7-0.8
Migration of Triggered Seismicity

200 m Fractures

-0.2 < M < 0
0 < M < 0.8
0.8 < M < 1.2

6 Months

6 years

2 years

8 years

4 years

10 years
Observations of Induced Seismicity (Basel)

[Goertz-Allmann et al, 2011]  [Shapiro and Dinske, 2009]
**r-t Plot - Fluid and Thermal Fronts and Induced Seismicity**

**Parameters utilized in simulation**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_0$</td>
<td>Permeability $[m^2]$</td>
<td>$10^{-17}$</td>
</tr>
<tr>
<td>$P_P$</td>
<td>Pore Pressure $[Mpa]$</td>
<td>14.8</td>
</tr>
<tr>
<td>$P_{inj}$</td>
<td>Fluid Pressure $[Mpa]$</td>
<td>17.8</td>
</tr>
<tr>
<td>$T_{res}$</td>
<td>Reservoir Temperature $[°c]$</td>
<td>250</td>
</tr>
<tr>
<td>$T_{inj}$</td>
<td>Fluid Temperature $[°c]$</td>
<td>70</td>
</tr>
<tr>
<td>$S$</td>
<td>Fracture Spacing $[m]$</td>
<td>10 to 500</td>
</tr>
</tbody>
</table>

$r = \sqrt{\frac{2Qt}{\pi h\phi}}$,  \hspace{1cm} k_0 = \frac{b^3}{12S}$

- $Q$: Flow rate
- $t$: Time
- $h$: Thickness
- $\phi$: Porosity
- $b$: Aperture
Long-Term Projection

Fracture Spacing=1m
1m<Fracture size<10m

0<M_s<1
1<M_s<2

Hydrodynamic front
Thermal front
Long-Term Projection

Distance from injection [m]

Time [14 days (first month)]

Distance from injection [m]

Time [14 days (after 5 years)]

Distance from injection [m]

Time [14 days (after 10 years)]

Log (N_{event})

a value = 2.06
b value = 0.72

a value = 1.99
b value = 0.70

a value = 1.71
b value = 0.68

Number of events (14 days)

0 < M_s < 1
1 < M_s < 2

Moment Magnitude

0
1
2
3
4
5
6
7
8
9
10

0
500
1000
1500
2000
2500
3000

0
1
2
3
4
5
6
7
8
9
10

0
1
2
3
4
5
6
7
8
9
10

0
100
200
300
400
500
600
700

Hydrostatic Front
Internal Front

Fracture Spacing Due
Minimizing over 12hrs

A
B
C

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Newberry Stimulation

Stacked Reservoir Model

Location

Volcanic stratigraphy

Stimulation Sequence

Phase II - Injection Well Stimulation / Summer-Fall 2011 Drill and Test Production Wells / Fall 2011-Fall 2012

Pre-Stimulation Stimulation of First Interval Stimulation of Second Interval After Diverter Application Stimulation of Three Intervals Complete Drill Two Production Wells into EGS Reservoir
## Zone Characteristics

### Stimulation zones

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Depth[m]</th>
<th>Zone B</th>
<th>Zone C</th>
<th>Zone D</th>
<th>Zone E</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>2000</td>
<td>2500</td>
<td>2750</td>
<td>3000</td>
</tr>
<tr>
<td>$S_{h\text{min}}$</td>
<td>MPa</td>
<td></td>
<td>36</td>
<td>45</td>
<td>50</td>
<td>54</td>
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<tr>
<td>$S_{H\text{max}}$</td>
<td>MPa</td>
<td></td>
<td>48</td>
<td>58</td>
<td>64</td>
<td>70</td>
</tr>
<tr>
<td>$S_v$</td>
<td>MPa</td>
<td></td>
<td>48</td>
<td>60</td>
<td>66</td>
<td>72</td>
</tr>
<tr>
<td>$P_{\text{injection}}$</td>
<td>MPa</td>
<td></td>
<td>24</td>
<td>28</td>
<td>30</td>
<td>32</td>
</tr>
<tr>
<td>$P_{\text{reservoir}}$</td>
<td>MPa</td>
<td></td>
<td>29</td>
<td>33</td>
<td>35</td>
<td>37</td>
</tr>
<tr>
<td>$P_{\text{production}}$</td>
<td>MPa</td>
<td></td>
<td>19</td>
<td>23</td>
<td>25</td>
<td>27</td>
</tr>
<tr>
<td>Peak Strength</td>
<td>MPa</td>
<td></td>
<td>25</td>
<td>30</td>
<td>35</td>
<td>38</td>
</tr>
<tr>
<td>$T_{\text{rock}}$</td>
<td>°c</td>
<td></td>
<td>230</td>
<td>280</td>
<td>290</td>
<td>310</td>
</tr>
<tr>
<td>$T_{\text{injection}}$</td>
<td>°c</td>
<td></td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

$S_{h\text{min}} = 0.75\ S_v$

$\Delta p = 5\ MPa$
**Zone Characteristics**

**Fracture Network Characterization**

Fracture density is 0.5 m\(^{-1}\)

<table>
<thead>
<tr>
<th>Fracture Characterization</th>
<th>Unit</th>
<th>Depth[m]</th>
<th>2000</th>
<th>2500</th>
<th>2750</th>
<th>3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>m(^{-1})</td>
<td>15/30m</td>
<td>27/30m</td>
<td>27/30m</td>
<td>8/30m</td>
<td></td>
</tr>
<tr>
<td>Number of seeded fractures</td>
<td></td>
<td>-</td>
<td>1000</td>
<td>1800</td>
<td>1800</td>
<td>600</td>
</tr>
<tr>
<td>Fracture size</td>
<td>m</td>
<td>10-1200</td>
<td>10-1200</td>
<td>10-1200</td>
<td>10-1200</td>
<td></td>
</tr>
<tr>
<td>Fracture spacing</td>
<td>m</td>
<td>1-300</td>
<td>1-300</td>
<td>1-300</td>
<td>1-300</td>
<td></td>
</tr>
<tr>
<td>Standard deviation(σ)</td>
<td>-</td>
<td>19</td>
<td>19</td>
<td>19</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>Mean(μ)</td>
<td>-</td>
<td>360</td>
<td>360</td>
<td>360</td>
<td>360</td>
<td></td>
</tr>
</tbody>
</table>

Large fractures: density of 0.003 m\(^{-1}\) - spacing 300 m

200<Large Fracture<1200m
10<Small Fracture<200m
Cumulative Stress Drop

Models with various fracture densities:

The mean stress drop is limited to be smaller than the maximum prescribed stress drop.

Fracture density is $0.5 \text{ m}^{-1}$

Development of stress drop begins earlier, reaches further from injection in a given time (~21 days) and is completed fastest for zones C and D.
Comparison of average radial permeability changes for different fracture structures:

The mechanical shearing effect (dilation angle is 10°) occurs due to the change in effective stress driven by fluid and thermal effects and their influence on reservoir shear failure.

Permeability improvement in all zones is radially symmetric.
Parametric Analysis

\[ \log M_0 = 1.5M_s + 9.1 \]

- Shear stress drop
- Fracture size, spacing

Fracture density is the same at shallow to deep zones (0.9 m\(^{-1}\))

Fracture density is not the same at shallow to deep zones (0.5 m\(^{-1}\), 0.9 m\(^{-1}\), 0.26 m\(^{-1}\))

Two different models applied:

- Moment magnitude evolution
  
  1) Fracture density is the same at shallow to deep zones (0.9 m\(^{-1}\))
  2) Fracture density is not the same at shallow to deep zones (0.5 m\(^{-1}\), 0.9 m\(^{-1}\), 0.26 m\(^{-1}\))
For the same fracture density:

With increasing stresses (reaching the deeper reservoir):

Migration rate of seismic event with time and location changes little - these events may form at the same rate for shallow to deep zones when the same fracture network is present.
Moment Magnitudes – Variable Fracture Density

When we apply a differing fracture density:

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.
Event Distribution over 21 Days

Zone B

Zone C

Zone D

Zone E
b-value evolution over 21 Days

b-value magnitude [21 days Stimulation]

We characterize the induced seismicity by the $b$-value for three different fracture geometries (high to low density):

- **Zone B**: $a$-value=1.70, $b$-value=0.67
- **Zone C**: $a$-value=1.99, $b$-value=0.72
- **Zone D**: $a$-value=2.03, $b$-value=0.74
- **Zone E**: $a$-value=1.72, $b$-value=0.69

Deepest zone
Density=0.26 m$^{-1}$

Density=0.9 m$^{-1}$

Moment Magnitude
Discontinuum Approaches

Flow network
Fracture set
Reservoir Boundary

Water flows along natural fracture
Hydraulic fractures area
Conclusions

**Complex THM and THC Interactions Influence 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**
- Physical controls (perm, thermal diffusion, kinetics) control progress
- Effects occur in order of fluid pressure (M), thermal dilation (TM), chemical alteration (C)
- 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 controlled by fracture location and sizes (if no new fractures created)
- Timing controlled by:
  - 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 effect