Cooling effects on induced seismicity in supercritical geothermal systems

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Cooling during re-injection affects mechanical stability

Thermal effects

Estimate of the re-injection temperature

<table>
<thead>
<tr>
<th>Category</th>
<th>$T_{\text{min}}$</th>
<th>$T_{\text{max}}$</th>
<th>$&lt; T &gt;$</th>
<th>$\Delta T$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>°C</td>
<td>°C</td>
<td>°C</td>
<td>°C</td>
</tr>
<tr>
<td>Hot Water</td>
<td>–</td>
<td>220</td>
<td>140</td>
<td>55</td>
</tr>
<tr>
<td>Low Enthalpy</td>
<td>220</td>
<td>250</td>
<td>235</td>
<td>131</td>
</tr>
<tr>
<td>Medium Enthalpy</td>
<td>250</td>
<td>300</td>
<td>275</td>
<td>186</td>
</tr>
<tr>
<td>High Enthalpy</td>
<td>250</td>
<td>330</td>
<td>290</td>
<td>169</td>
</tr>
<tr>
<td>Supercritical</td>
<td>–</td>
<td>–</td>
<td>457</td>
<td>322</td>
</tr>
</tbody>
</table>

Datum extrapolated for SC from Diaz et al. (2016) *Ren Sust Ener Rev*

$DT=300 \, ^\circ \text{C}$

Temperature and pressure changes affect stability

Strength reduction caused by geochemical reactions or in weak zones

Initial effective stress state

Thermo-mechanical effect

Poro-mechanical effect

Vilarrasa et al. (2019) *Solid Earth*
Original study

Induced seismicity in supercritical geothermal systems

ARTICLE

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The risks of long-term re-injection in supercritical geothermal systems

Francesco Parisio, Victor Vilarrasa, Wenqing Wang, Olaf Kolditz & Thomas Nagel

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Reykjanes, ISL, January 2017

IDDP2:
4.5 km deep
~436 °C

Fridleifsson et al (2017)
Sci Drill
Finite element model and permeability-porosity relationship

FEM model: IC and BC


\[ k_i = 4.979 \times 10^{-11} n^{3.11} \]
\[ k_f = 1.143 \times 10^{-11} n^{0.64} \]

\[ \log k = (1 - \omega) \log k_i + \omega \log k_f \]

Production

Injection

100m

500m

75° Fault

Permeability

\[ k / \text{m}^2 \]

\[ n \]

0.00 0.05 0.10 0.15 0.20

10^{-17} 10^{-14} 10^{-11} 10^{-18} 10^{-15} 10^{-12}
Finite element model and permeability-porosity relationship

FEM model: IC and BC

- Mass balance of solid skeleton

\[
\frac{d_s n}{dt} = (1 - n) \left( \frac{1}{\rho_s} \frac{d_s \rho_s}{dt} \right) + (1 - n) \nabla \cdot \mathbf{v_s} = (1 - n) \left( \frac{1}{\rho_s} \frac{d_s \rho_s}{dt} + \dot{\varepsilon}_v \right)
\]

- Porosity evolution

\[
\frac{d n}{dt} = (\alpha - n) \left( \frac{1}{K_s} \frac{d_s p}{dt} - 3\alpha_s (\alpha - n) \frac{d_s T}{dt} - (1 - \alpha) \frac{d_s \varepsilon_v}{dt} \right)
\]
Finite element model and permeability-porosity relationship

FEM model: IC and BC

Model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rock mass</th>
<th>Fault</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_0$</td>
<td>0.01</td>
<td>0.05</td>
<td>-</td>
</tr>
<tr>
<td>$\rho_s$</td>
<td>2700</td>
<td>2700</td>
<td>kg m$^{-3}$</td>
</tr>
<tr>
<td>$\alpha_s$</td>
<td>$1 \times 10^{-5}$</td>
<td>$1 \times 10^{-5}$</td>
<td>K$^{-1}$</td>
</tr>
<tr>
<td>$c_s$</td>
<td>950</td>
<td>950</td>
<td>J kg$^{-1}$ K$^{-1}$</td>
</tr>
<tr>
<td>$\lambda_s$</td>
<td>3</td>
<td>3</td>
<td>W m$^{-1}$ K$^{-1}$</td>
</tr>
<tr>
<td>$E$</td>
<td>60</td>
<td>20</td>
<td>GPa</td>
</tr>
<tr>
<td>$\nu$</td>
<td>0.25</td>
<td>0.25</td>
<td>-</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.8</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>$\phi$</td>
<td>30.0</td>
<td>30.0</td>
<td>-</td>
</tr>
<tr>
<td>$\sigma_c$</td>
<td>200.0</td>
<td>0.0</td>
<td>MPa</td>
</tr>
</tbody>
</table>

Porosity evolution

\[
\frac{d_s n}{dt} = (\alpha - n) \left( \frac{1}{K_s} \frac{d_s p}{dt} - 3\alpha_s \frac{d_s T}{dt} + \frac{d_s \epsilon_v}{dt} \right)
\]
Model equations for THM processes in porous media

System of partial differential equations

**Energy conservation**

\[
(c\rho)_m \frac{dsT}{dt} - \nabla \cdot (\lambda_m \nabla T) + \rho_w c_w \mathbf{v} \cdot \nabla T = Q_T,
\]

\[
(c\rho)_m = n \rho_w c_w + (1-n) \rho_s c_s
\]

\[
\lambda_m = n \lambda_w I + (1-n) \lambda_s
\]

*Specific heat and thermal conductivity of porous medium*

**Mass conservation**

\[
\left(n \beta_w + \frac{\alpha - n}{K_s}\right) \frac{dsp}{dt} - \left[n \alpha_w + 3(n-1) \alpha_s\right] \frac{dsT}{dt} + \nabla \cdot \mathbf{v} + \alpha \mathbf{e}_v = Q_h
\]

\[
\mathbf{v} = -\frac{k}{\mu_w} (\nabla p - \rho_w \mathbf{g})
\]

*Darcy’s law*

**Momentum conservation**

\[
\frac{E}{2(1-2\nu)(1+\nu)} \nabla (\nabla \cdot \mathbf{u} - 3\alpha_s \Delta T) + \frac{E}{(1-2\nu)} \nabla^2 \mathbf{u} - \nabla \cdot (\alpha p \mathbf{I}) + [n \rho_w + (1-n) \rho_s] \mathbf{g} = 0
\]

\[
\mathbf{e} = \frac{1}{2} \left[ \nabla \mathbf{u} + (\nabla \mathbf{u})^T \right]
\]

*Strain tensor*

\[
\alpha = 1 - \frac{K}{K_s}
\]

*Biot’s coefficient*
Open source FEM solver: OpenGeoSys


Equations of state (EOS): IAPWS-IF97 on the free library freesteam http://freesteam.sourceforge.net/
Density-driven flow forms convective cells in the reservoir

Initial conditions

Pressure and temperature change follow different timescales

Geothermal doublet

After 25 years of injection:

a. Liquid front has reached the fault
b. Quenched area contracts
c. Fault shows preferential flow paths

Thermal-adveective process is slower than pore pressure diffusion
Cooling-induced stress controls fault stability

Coulomb Failure Stress (CFS)

\[ \Delta \text{CFS} = \frac{\tau_n}{\sigma_n} + \mu \sigma_n' \]

Where:
- \( \mu = 0.577 \)
- \( \sigma' = \sigma + \alpha p I \)

Increased instability

\[ \Delta \text{CFS} > 0 \]
Tensile failure can occur during cold water re-injection

Drucker-Prager failure

Where:

\[ q_{dp} = \frac{6 \sin \phi}{3 - \sin \phi} (-\sigma'_m) + \frac{6c' \cos \phi}{3 - \sin \phi} \]

\[ M_{DP} = \frac{q_{dp}}{q} \]

With:

\[ \sigma'_m = \text{tr} \left( \sigma' \right) / 3 \]

\[ s = \sigma' - I\sigma'_m \]

\[ q = \sqrt{3 \left( s : s \right) / 2} \]
Seismicity is enhanced by cooling and delayed in the fault

Rate of seismic production

Where:

\[
\dot{R} = \frac{R}{t_a} \left( \frac{\dot{\tau}_c}{\dot{\tau}_0} - R \right)
\]

With:

\[
\dot{\tau}_0 = 1 \times 10^{-3} \text{ MPa yr}^{-1}
\]
\[
\dot{\tau}_c = |\tau_n| + \mu \sigma_n'
\]
\[
t_a = A \sigma_n' / \dot{\tau}_0
\]

Seagall and Lu (2015) J Geoph Res
The size of the mobilized fault patch is controlled by cooling.

Fault-patch mobilization

\[ \mu_{fr} = \frac{\tau_n}{(-\sigma'_n)} \]
Conclusions, limitations and further research

Cooling controls seismicity in ESGS

Time in seismicity delay is due to advection

Fault location and re-injection temperature dominate the stability

Tensile fractures are likely to occur

Complex THM numerical analyses for reservoir management
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"The content of this presentation reflects only the authors’ view. The Innovation and Networks Executive Agency (INEA) is not responsible for any use that may be made of the information it contains."

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