Insights from 75,000 earthquakes induced in the Cooper Basin EGS

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Enhanced Geothermal System

Cooper Basin

(objective >100 MW\textsubscript{el})

- 6 deep wells in granite
- massive hydraulic stimulations
Enhanced Geothermal System Cooper Basin

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
<th>Cum# Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>H#1 stimulation</td>
<td>28,102</td>
</tr>
<tr>
<td>2005</td>
<td>H#2 stimulation, H#1 re-stimulation</td>
<td>45,525</td>
</tr>
<tr>
<td>2008</td>
<td>H#3 stimulation, H#1 - H#3 circulation</td>
<td>46,242</td>
</tr>
<tr>
<td>2010</td>
<td>Jol#1 stimulation</td>
<td>46,476</td>
</tr>
<tr>
<td>2012</td>
<td>H#4 stimulation</td>
<td>74,013</td>
</tr>
<tr>
<td>2015</td>
<td>Project abandoned</td>
<td>76,343</td>
</tr>
</tbody>
</table>
What remains?

→ One of the largest and best controlled data sets of injection induced seismicity
  ▪ seismicity continuously monitored since 2005
  ▪ magnitude range $M_L = -2$ to $M_L = 3.7$
  ▪ up to 24 local stations (surface seismometers, borehole geophones)
  ▪ complete record of hydraulic activities
  ▪ multi-well set up (cores, image logs, etc.) → ‘ground truth’
The ‘geothermal perspective’ prior to the Cooper Basin project

‘Hydraulic stimulations create complex, volumetric fracture networks as evidenced by spatial seismicity distributions’

Soulz-sous-Forêts
(Figure from Michelet & Töksöz, 2007. JGR.)
Habanero #1 stimulation

- > 28,000 induced events, $M_L$ 3.7
- planar reservoir structure
- apparent thickness ~200 m
- vertical hypocenter location error ($2\sigma$): 118 m
Habanero: A planar reservoir

- reservoir is dominated by a planar fault zone (thickness: meter scale or less)
- confirmed by subsequent wells (‘ground truth’)

Baisch et al., 2006. BSSA
Are other geothermal reservoirs really volumetric?

Re-processing of Soultz-sous-Forêts data sets

- ill constrained data excluded
- ‘planar reservoir hypothesis’ cannot be rejected

Baisch et al., 2010. IJRMMMS
Fault mechanisms

→ most FPS are consistent with slip driven by the regional stress field and occurring on the planar structure as outlined by hypocenters
→ plane dips ~10° (optimum orientation ~30°)

Why did this plane shear? Because no other orientations were available!
The role of natural fractures

- similar 'experiment' conducted at Jolokia, 10 km away from Habanero
- no pre-existing flowing fractures at Jolokia
- stimulation failed (14 days, 700 bar → 1 l/s)
→ stimulation does not work everywhere!

Jolokia stimulation

Baisch et al., 2015. BSSA
Spatio-temporal seismicity evolution: Constrains triggering mechanisms

H#4 stimulation, map view → systematic in space/time

Baisch et al., 2015. BSSA
Kaiser Effect:
Constrains triggering mechanisms

H#1 re-stimulation

Kaiser effect (stress memory): seismicity occurs at those locations, where previous stress criticality is exceeded
How stimulations change subsurface stresses

\[ \text{cumulative slip [mm]} \quad \text{modelled shear stresses} \]

\[ \rightarrow \text{large shear stress concentration at outer rim} \]

Baisch et al., 2015. BSSA
How stimulations change subsurface stresses

- Teleseismic earthquake triggered $M_L=3.x$ earthquake at the outer rim of previously stimulated reservoir (no hydraulic activities within 12 months)
- a sequence of 84 aftershocks followed
  → after-deformation is likely to also play a role during stimulation
Conclusions

- Cooper Basin experiments provide one of the largest and best controlled data sets of injection induced seismicity.
- Insights from these experiments improved our conceptual understanding of geothermal reservoirs and our understanding of the physical processes associated with induced seismicity.
Thank you!