Discussion on Induced Seismicity

Michael Manga & Antonio P. Rinaldi
On the maximum magnitude of induced event

PAW=Pawnee, $M_{\text{max}}=5.8$
BAS=Basel, $M_{\text{max}}=3.4$
CAR=Cardston, $M_{\text{max}}=3$
GFS=In-Situ experiment, aseismic

\[ \sum M_0 \leq 2G\Delta V \]
The case of Pohang, South Korea

Grigoli et al., 2018
The case of Pohang, South Korea

Two papers recently published on Science raised the questions on caon earthquake being induced/triggered by injection activity.

- The “European” paper – Grigoli et al.
  - Independent analysis of seismicity from regional network and InSAR ground uplift.
  - Complex source mechanism
  - Analysis of Coulomb Failure Stress shows that little changes can be attribute to recent (one year before) seismicity

- The “Korean” paper – Kim et al.
  - Analysis of aftershocks using local network
  - Correlate net injected volume with seismicity
The case of Pohang
InSAR modeling

Grigoli et al., 2018
The case of Pohang regional network seismicity

Grigoli et al., 2018
The case of Pohang Coulomb Failure Stress

Grigoli et al., 2018
The case of Pohang local network seismicity

Kim et al., 2018
The case of Pohang injection activity and seismicity

Kim et al., 2018
On the maximum magnitude of induced event

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$\sum M_0 \leq 2G\Delta V$

Pohang, $M_{max} = 5.4(5.5)$
St. Gallen Deep Geothermal System project timeline

2009  Feasibility study for geothermal project
2010  3-D seismic survey 270 km² (Heuberger et al., 2016)
2012  SED starts seismic monitoring

2013  Mar-Jul: Borehole drilling
      Jul: Stimulation of Malm inducing ML 3.5 earthquake
      Sep-Oct: Fishing for lost equipment and mud losses
      Oct: Production test (seismicity ceased)
      since Nov: shut-in of well

2014  May: Geothermal project suspended
The case of St. Gallen DGS
July 2013 – injection test

14 July
Injection test (175 m³)

Time
Catalog of located events - Diehl et al., 2017
Pressures and injection rates - Wolfgramm (GTN), 2014
The case of St. Gallen DGS
July 2013 – acid jobs

14 July
Injection test (175 m³)

17 July
Acid stimulations (290 m³)

Catalog of located events - Diehl et al., 2017
Pressures and injection rates - Wolfgramm (GTN), 2014
The case of St. Gallen DGS
July 2013 – gas kick and well control

**14 July**
Injection test (175 m³)

**17 July**
Acid stimulations (290 m³)

**19/20 July**
Gas kick and well control measures (700 m³)

Time
Catalog of located events - Diehl et al., 2017
Pressures and injection rates - Wolfgramm (GTN), 2014

12:00 gas kick
Gas Kick/Well control

www.seismo.ethz.ch
The case of St. Gallen DGS
July 2013 – gas kick and well control

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Injection test (175 m³)

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The case of St. Gallen DGS
July 2013 – gas kick and well control

### 14 July
- Injection test (175 m³)

### 17 July
- Acid stimulations (290 m³)

### 19/20 July
- Gas kick and well control measures (700 m³)

**Time**
- Catalog of located events - Diehl et al., 2017
- Pressures and injection rates - Wolfgramm (GTN), 2014

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12:00 gas kick
15:00 well control
05:30 ML 3.5 induced

06.07.2018
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The case of St. Gallen DGS
Spatial distribution of seismicity

Diehl et al., 2017
The case of St. Gallen DGS
Temporal evolution of seismicity

Catalog of located events - Diehl et al., 2017
Pressures - Wolfgramm (GTN), 2014

St. Gallen sequence
Full catalog

Stimulation period July 2013
The case St. Gallen DGS
The conceptual model

Injection test (14 July) induces minor seismicity and opens up fractures

Cross-section normal to fault plane

14 July
Injection test (175 m³)
Acid stimulations (17 July) induce further seismicity and increase fracture permeability so that gas can migrate upwards.

The case of St. Gallen DGS

The conceptual model

14 July
Injection test (175 m³)

17-19 July
Acid stimulations and gas kick
The case of St. Gallen DGS
The conceptual model

Well control measures (700 m³ injected) induces main sequence

14 July
Injection test

17-19 July
Acid stimulations and gas kick

20 July
Well control measures
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\( \star \) Pohang, \( M_{\text{max}} = 5.4(5.5) \)
\( \star \) St. Gallen, \( M_{\text{max}} = 3.5 \)