Induced seismicity: the creep route

Jean Schmittbuhl

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Outline

• **Induced seismicity:**
  – a forcing term compare to natural seismicity : test causality issues
  – shalower, possibly easier to monitor
  – In-situ conditions (large scale experiments)
  – Expected to add information on the knowledge of earthquake nucleation processes

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  – Overview of the mechanisms
  – Pore pressure increase: the case of Soultz-sous-Forêts
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Mechanisms for fluid induced earthquakes

Ellsworth, Science, 2013
The deep geothermal reservoir of Soultz-sous-Forêts (GEIE EMC) (1987- )

- Binary geothermal power plant (ORC)
  1.5 MWe net

- Reservoir: 200°C @5000m
- A complex pre-existing 3D network (granite) + a major fault zone (most of the seismicity) FZ-4770 in GPK3
- Abundant natural fluid (high salinity (~100g/l) – reservoir size?

Sausse et al, 2010
EGS stimulation and seismicity

• Target: Enhanced Geothermal System (EGS) – increase permeability of the reservoir from fluid stimulation

• A large number of induced seismicity (~10000 EQ/stimulation)

• A possible risk of felt EQ (if MI > 2)
  – 2000 : $M_{\text{max}}$ = 2.6
  – 2003 : $M_{\text{max}}$ = 2.9, 2.7
  – 2004 : $M_{\text{max}}$ = 2.0
  – 2005 : $M_{\text{max}}$ = 2.6

• A tool for reservoir imaging
GPK1 stimulation at Soultz-sous-Forêts

injection of 25 000 m³ during 16 days ~10000 located events

Bourouis and Bernard, 2007

Map view

<table>
<thead>
<tr>
<th>Depth interval (m)</th>
<th>Mean azimuth</th>
<th>Mean dip (deg)</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>2800–2900</td>
<td>N179°E</td>
<td>87</td>
<td>329</td>
</tr>
<tr>
<td>2900–3000</td>
<td>N165°E</td>
<td>67</td>
<td>402</td>
</tr>
<tr>
<td>3000–3200</td>
<td>N146°E</td>
<td>86</td>
<td>416</td>
</tr>
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Cornet et al, 2007
Fluid induced seismicity

GPK1 Stimulation (Sept-Oct 1993)

Onset of hydro shear

Onset of hydraulic fracturing

Vilarrasa et al, 2012

$\sigma_H : N170^\circ E$

Cornet et al., IJRMMSc, 2007
Fluid induced seismicity

GPK1 Stimulation (Sept-Oct 1993)

Onset Of Hydro-shear

Pressure diffusion:

\[ r = \sqrt{4\pi D t} \]

\[ \frac{\partial p}{\partial t} = \sum_{i=1}^{3} D_{ii} \frac{\partial^2 p}{\partial x_i^2} \]

\[ D = NK/\eta \]

\[ K = \begin{pmatrix} 0.7 \pm 0.2 & 0 & 0 \\ 0 & 1.9 \pm 0.3 & 0 \\ 0 & 0 & 5.2 \pm 2.6 \end{pmatrix} \times 10^{-17} \text{ m}^2 \]

Shapiro et al, GJI, 1999

Onset of hydraulic fracturing

Cargèse 2-6 Oct 2017
Earthquakes triggered by fluid extraction

SEGALL, Geology, 1989

- Poro-elastic effects related to fluid extraction
- Rate and state effects

Pressure reduction

Grasso & Wittlinger, BSSA, 1990; Grasso, 1992

Seismicity

Aseismic deformation

PE+R&S modeling

Segall and Lu, JGR, 2015
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Seismic/aseismic behavior

Scholz, 1998

EGS reservoirs at the aseismic/seismic transition
1993 Stimulation – Soultz-sous-Forêts

- Injected mechanical energy / radiated energy

\[ E_I = \int_{t_1}^{t_2} P(t) \times Q(t) \, dt \]

\[ \log_{10}(E_R) = 1.5 \times M_L + 4.8 \]

Rico et al, 2017
Before and after 1993 stimulation

Cornet et al., 1997

M~4.2 >> M~1.9 (observed)
More than fluid induced shear or hydraulic fracturing: fluid induced aseismic slip

Lessons from Soultz:
- A complex pre-existing 3D network (granite)
- A major fault zone (most of the seismicity) **FZ-4770**
- Shear and hydraulic fractures
- Evidences of aseismic slip in **GPK1 F-2925**
- From GPK2 casing deformation along FZ-4770
- From casing deformation in GPK4 (Jung et al, 2010)
Evidence of repeaters related to aseismic slip

1.5 mm/s
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- A tool for reservoir imaging
GPK2 stimulation: large scale Vp variation and aseismic slip

Calo et al, GJI, 2011
GPK2 stimulation: stress transfer from aseismic slip

7215 localized events (Mmax=2.5)
Stress inversion (715 events with M>1)

Schoenball et al, GRL, 2014
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The case of GRT1 (ECOGI)

Rittershoffen (< 10 km Soultz)

Stimulation of GRT1
(June/July 2013)

second crisis ~100h after shut-in (4d)
with a larger moment rate
Seismological network

Maurer et al., 2013
Template matching

2.5 seconds

4 hours

Lengliné et al, GJI, 2017
Temporal evolution

Temporal evolution of seismicity

682 identified and picked seismic events
557+0+125

1395 detected events with TM
1169+1+225

Kaiser effect
No seismicity for injection rate lower than previously applied

2nd crisis
High seismicity level 3.5 days after shut-in. No earthquake during this interval
Relocations

Lengliné et al, GJI, 2017
Fluid induced: pressure induced or not?

Pressure diffusion:

\[ r(t) = \sqrt{4\pi DT} \quad D=0.07 \text{m/s}^2 \]

\[ (D=0.05 \text{m/s}^2 \text{ in Soultz, 1993}) \]

No pressure diffusion:

\[ r(t) = \sqrt{\frac{\int_0^t Q(t') \, dt'}{\pi h}} \]
Stress transfer from aseismic slip (?)

Coulomb stress perturbation from a 1cm left-lateral aseismic slip
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Fluid injection-induced aseismic slip

2012 Brawley swarm
Brawley geothermal field (Imperial Valley)

Wei et al, EPSL, 2015
Fluid injection-induced aseismic slip

Guglielmi et al, Science, 2015
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### Soultz-sous-Forêts GEIE EMC

Hydraulic circulations in the lower reservoir (5 km)

<table>
<thead>
<tr>
<th></th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circul. days</td>
<td>160</td>
<td></td>
<td></td>
<td>80</td>
<td>240</td>
<td>330</td>
<td>160</td>
<td>50</td>
<td>140</td>
</tr>
<tr>
<td>Chem. Stim.</td>
<td></td>
<td>GPK4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pump</td>
<td>No sub pump</td>
<td></td>
<td></td>
<td>Failure</td>
<td></td>
<td></td>
<td>Failure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 wells</td>
<td></td>
<td></td>
<td></td>
<td>1P, 1R</td>
<td>1P, 1R</td>
<td></td>
<td>1P, 1R</td>
<td>1P, 1R</td>
<td>1P, 1R</td>
</tr>
<tr>
<td>3 wells</td>
<td>2P, 1R</td>
<td></td>
<td></td>
<td>2P, 1R</td>
<td>1P, 2R</td>
<td>1P, 2R</td>
<td>1P, 2R</td>
<td>1P, 2R</td>
<td>1P, 2R</td>
</tr>
<tr>
<td>4 wells</td>
<td></td>
<td></td>
<td></td>
<td>2P, 2R</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WHP R MPa</td>
<td>4 to 7</td>
<td>~7</td>
<td>~12</td>
<td>2 to 8</td>
<td>2 to 6</td>
<td>4 to 5</td>
<td>&lt;2</td>
<td>&lt;2</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Event</td>
<td>600</td>
<td>20</td>
<td>0 &amp; 80</td>
<td>243</td>
<td>206</td>
<td>411</td>
<td>5</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Mag Mx</td>
<td>2.3</td>
<td>1.9</td>
<td>- &amp; 1.5</td>
<td>1.4 - 1.7</td>
<td>1.7</td>
<td>2.3</td>
<td>1.7</td>
<td>-</td>
<td>0.3</td>
</tr>
<tr>
<td>Vol m3</td>
<td>205000</td>
<td>4500</td>
<td>4000</td>
<td>120000</td>
<td>200000</td>
<td>500000</td>
<td>300000</td>
<td>300000</td>
<td>150000</td>
</tr>
</tbody>
</table>

03/10/2017 R = reinjection

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2010 circulation test – Soultz-sous-Forêts

- 411 detected events, most intense activity when reinjection into GPK3 only
- Increase of activity at the end of the test, maybe due to the continuous rise of GPK3 injection pressure
- Remaining activity for 15 days after shut in
- 25 earthquakes of magnitude larger than 1 and 4 of magnitude larger than 2
  - a series of 3 occurred within a few days
  - the M=2.3 occurred 4 months after
- Not linked with significant hydraulic event
Sampling frequency 150 Hz
8 surface, short-period seismometers
Mostly vertical sensors

2009-2010 Circulation experiment

Water injected at 5 km depth
Starting 01/01/2009 - 11 months long
411 detected earthquakes
Automatic procedure $M \in [-0.3, 2.2]$

Manually reviewing all arrival times
Localisation (393 events)
Repeaters

Similar Events
Coherency > 90% at two stations
Frequency range [10-40] Hz
Windows of 1.7 s around P (256 pts long)

Four groups with at least one M>1 earthquake ([-0.3:2.3])
# of events (19 / 13 / 9 / 9)
Earthquake double difference relative relocation

Cross-correlation P-wave travel times delays

Projected on the inferred fracture plane

Uncertainties computed from likelihood computed around the best solution – 95% ellipse

Running window correlation to validate results S-P travel time delays

Less than 3 ms delay for all groups at all stations

Distance in the ray direction less than ~23 m
Variation of moment for events in repeaters

Singular Value Decomposition Method
[Rubinstein & Ellsworth, 2010]

Up to a factor x 300 of moment variation for one group

Corner frequency $f_c$ [10-20] Hz – uncertainties are quite important

Rupture radius of 54-108 m assuming a circular rupture patch

Consistent with the estimated rupture size considering a typical stress drop of 1MPa

Lengliné et al, JGR, 2014
Link with fluid injection: fluid induced?

Time history of the seismic slip on the 4 asperities

Lengliné et al, JGR, 2014
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  – **Pure creep induced seismicity: an experimental approach**
An experimental approach of creep induced seismicity without fluid

Optical monitoring « aseismometer »

Material: PMMA – subcritical Mode I fracture

AE monitoring « Seismometer »
Microscopic behavior

Pining/Depining

Local stick-slip motion

\( \langle v \rangle \sim 100 \, \mu m/s \)

Maloy et al, PRL, 2001
Slow slip events (optical events)

Local speed threshold:
\[ v > 10^*<V> \]

\[ M \approx E \cdot S \times \delta \]

Circles = events
Diameter of circles = \( \log_{10}(M) \)

Grob et al, PAGEOPH, 2009
Scaling of the fracture front

\[ \sigma(\delta) \propto \delta^{\zeta} \]

\( \zeta \equiv \) roughness exponent

Santucci et al, EPL, 2010
Macroscopic creep behavior

\[ \bar{a}(t - t_{\text{stop}}) - \bar{a}_0 = A \ln \left( \frac{t - t_{\text{stop}}}{t^*} + 1 \right) \]

\[ \bar{v} = \chi \exp \left[ -\alpha^2 (\bar{G}_c - \bar{G}) / k_B T \right] \]

Lengliné et al, PRE, 2011
BEM+fiber bundle modelling

A single fault approach

A continuous elastic bulk with long range interactions ($k_b = E*L$)

+ A discrete elastic/brittle interface with fibers ($k_i = N*k$)

Injection = imposed displacement

Stiffness ratio:

$$e = \frac{k_b}{k_i} = \frac{EL}{Nk}$$

N asperities (fibers)

$$x = aN^{1/2}$$

$$y = aN^{1/2}$$

[Stormo et al, GE, 2015; Frontiers in Physics, 2016]
Experimental / numerical comparison

Interfacial crack front

Stormo et al, FP, 2016

\( \zeta = 0.35 \)
Local velocity distribution

[Stormo et al, Frontiers in Physics, 2016]

\[ \eta_{\text{exp}} = 2.55 \quad \eta_{\text{stiff}} = 2.89 \quad \eta_{\text{soft}} = 2.54 \]
A loading perturbation – No fluid

No pore pressure change

A power law distribution over 3 orders of magnitude: a continuum of time scales

Lengliné et al, EPSL, 2012
Seismic events (acoustic emissions)

STA/LTA detection
(STA=20µs/LTA=100µs)
A creep induced seismicity

Consistent with energy partition:

\[ E_{\text{radiated}} \sim \frac{M_0}{20000} \]

Lengliné et al, EPSL, 2012
Schmittbuhl et al, GE, 2014
Low frequency signals

Jestin et al, 2017
Seismic/aseismic energy

Radiation efficiency

\[ \eta_R = \frac{E_R}{E_R + E_G} \]

Jestin et al, 2017
Induced seismicity

Fluid pressure
- High $P_f$
- Hydro-shear/hydro-frac fractures
- Low $P_f$
- Poro-elasticity
- Seismic slip
- Instable
- Asperities
- Enhanced permeability
- Observations?
- Exploration/Logs
- Pre-existing faults + stress field
- Fluid chemical properties
- Stimulation/circulation (?)