Earthquake-earthquake Triggering in Natural Swarms and Fluid-induced Seismicity

Kamran Karimi
Jörn Davidsen

Department of Physics & Astronomy

UNIVERSITY OF CALGARY
Fluid-Induced Seismicity

Natural Flows
- Magma flows in volcanic areas
- Rain-induced Seismicity

Human-made
- Shale gas fracking
- Water + sand + additives
- Fracturing
- Injection of wastewater
- Wastewater disposal

★ Natural Flows often lead to earthquake **swarms**
★ Are swarm-like features present in human-made fluid-driven earthquakes?
Temporal Evolution of *Aftershocks*: *Swarm*-like Features Have Been Observed.
Case Studies

We Analyzed three High Resolution Catalogs

★ **Induced** Seismicity
Oklahoma & southern Kansas

★ (suspected) **swarms**
the Yuha Desert

★ **natural swarms**
the Long Valley, Caldera

Schoenball & Ellsworth, *JGR* (2017)

Ross et al. *GRL* (2017)

Shelly et al. *JGR* (2016)
Case Studies

We Analyzed three High Resolution Catalogs

★ **Induced** Seismicity
Oklahoma & southern Kansas

★ **natural swarms**
the Long Valley, Caldera

★ **Aftershocks Properties:**
how do induced events compare with their natural analogs?
Infer Aftershocks: Declustering Method

Build A **Null** Model Of Uncorrelated Events: Poisson Process With Gutenburg-Richter Rate

\[ \lambda = c \times 10^{-bm_i} \]

Deviations From the Null Model Implies Aftershocks **Triggering**

\[ n_{ij} = \lambda \times |\vec{r}_i - \vec{r}_j|^{d_f} \times t_{ij} \]

\[ n_{ij}^* = \min\{n_{ij}\} \]

\( c \): Global Activity Rate

Fractal Dimension

\( d_f \approx 2 \)

Zaliapin et al. (2008), Zaliapin & Ben-Zion (2013), Gu et al. (2013)
Infer Aftershocks: Density Maps

Scaled **Time**

\[ t_j^* \equiv t_{i* j} 10^{-\frac{b}{2} m_i^*} \]

Scaled **Distance**

\[ r_j^* \equiv r_{i* j} 10^{-\frac{b}{2} m_i^*} \]

- **induced events** Oklahoma
- **suspected swarms** Yuha Desert
- **natural swarms** Caldera

Scaled **Time**

Scaled **Time**

Scaled **Time**
Infer Aftershocks: Triggering Cascade (Yuha Desert)
Spatial Density of Aftershocks

Induced Case: Oklahoma

\[ \rho(r) \propto r^{-\nu} \]

\[ r_{\text{rup}} \propto 10^\sigma \times m \]

\[ \sigma = 0.5 \]

Peak interpreted as rupture length
Spatial Density of Aftershocks
Suspected Swarms (Yuha Desert)

Peak interpreted as *rupture* length

\[ r_{rup} \propto 10^{\sigma \times m} \]
\[ \sigma = 0.4 \]

Power-law Decay

\[ \rho(r) \propto r^{-\nu} \]
\[ \nu = 1.7 \]
Spatial Density of Aftershocks
Natural Swarms (Caldera)

Peak interpreted as rupture length

\[ r_{\text{rup}} \propto 10^\sigma \times m \]
\[ \sigma = 0.36 \]

Power-law Decay

\[ \rho(r) \propto r^{-\nu} \]
\[ \nu = 2.9 \]
Aftershock Zones
Table of Exponents

<table>
<thead>
<tr>
<th>Location (Year)</th>
<th>Type</th>
<th>Linear Density $\rho(r) \propto r^{-\nu}$</th>
<th>Rupture Size $r_{rup} \propto 10^{\sigma m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oklahoma &amp; southern Kansas (2014–2017)</td>
<td>Fluid Induced (Man-made)</td>
<td>2.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Long Valley Caldera, California (2014)</td>
<td>Natural Swarm</td>
<td>2.9</td>
<td>0.36</td>
</tr>
<tr>
<td>Yuha Desert, California (2010)</td>
<td>Fluid Induced (Natural)</td>
<td>1.7</td>
<td>0.4</td>
</tr>
</tbody>
</table>

- Longer Ranged Trend (Typical of Tectonic Seismicity in California)
- Steep Decay Indicating the Dominant Role of Fluid Migration
- Explained by Non-local Transfer of Static (Coulomb Stress)
- Consistent with Diffusive Nature of the Swarm Propagation (Shelly et al. JGR 2016)
Aftershock Productivity

★Average Number of Aftershocks of an Earthquake Magnitude $m$

Productivity Exponent: $\alpha$

\[ N_{as} \propto 10^{\alpha m} \]

- **High Aftershock Productivity in Oklahoma**
- **Low Productivity Associated With Natural Earthquake Swarms (Hainzl & Ogata, 2005)**
Temporal Characteristics

Induced Case: **Oklahoma**

**Omori-Utsu relation**

\[
\lambda(t) = \frac{K}{(t + c)^p}
\]

\[
K \propto 10^{\alpha m}
\]

**Productivity Exponent**
Temporal Characteristics
Suspected Swarms (Yuha Desert)

Omori-Utsu relation

\[
\lambda(t) = \frac{K}{(t + c)^p}
\]

\[
K \propto 10^{\alpha m}
\]
Temporal Characteristics
Natural Swarms (Caldera)

Omori-Utsu relation

\[ \lambda(t) = \frac{K}{(t + c)^p} \]

\[ K \propto 10^{\alpha m} \]

Different Regimes

\[ p = 0.9, \quad p = 2.0 \]

\( \alpha \): Productivity Exponent
Triggering Topology

Zaliapin & Ben Zion, JGR (2013)

Burst-like:
- Large $N_{tc}$
- Small $d_f$

Swarm-like:
- Small $N_{tc}$
- Large $d_f$
Swarm-like Features Associated with Topology of Triggering Cascades in Caldera and (to a Lesser Extent) in Oklahoma
Take-home Messages

❖ Significant **event-event triggering** in both natural swarms & induced seismicity

❖ **Narrow** aftershock zones are not specific to induced seismicity but also occur in natural swarms

❖ Aftershock **productivity** might allow to distinguish between natural swarms and induced seismicity