Dynamics of Fault Activation by Hydraulic Fracturing in western Canada

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Mechanisms for Inducing Earthquakes

- Direct fluid pressure effects of injection (pore-pressure diffusion)
- Changes in stress due to extraction or injection (poroelastic effects)
- Permeable reservoir/aquifer
- HF in proximity to a fault (pore pressure or stress)

Modified from Ellsworth, Science (2013)
Western Canada Sedimentary Basin

- Canada second only to USA in terms of development of shale gas and shale oil resources.
- Development focused primarily within the Western Canada Sedimentary Basin (WCSB).
- Seismicity observed throughout WCSB.
Induced seismicity related to hydraulic fracturing or waste water injection?

Summary of Seismicity Associated with Wells in the Western Canada Sedimentary Basin

<table>
<thead>
<tr>
<th></th>
<th>Disposal</th>
<th>HF</th>
<th>Tectonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of candidate wells (1985–2015)</td>
<td>1236</td>
<td>12,289</td>
<td>—</td>
</tr>
<tr>
<td>Number of wells associated with $M \geq 3$</td>
<td>17</td>
<td>39</td>
<td>—</td>
</tr>
<tr>
<td>Association % for wells ($M \geq 3$)</td>
<td>$\sim 1%$</td>
<td>$\sim 0.3%$</td>
<td>—</td>
</tr>
<tr>
<td>Number of $M \geq 3$ (1985–2009)</td>
<td>126*</td>
<td>13*</td>
<td>14</td>
</tr>
<tr>
<td>Number of $M \geq 3$ (2010–2015)</td>
<td>33*</td>
<td>65*</td>
<td>7</td>
</tr>
<tr>
<td>Association % for $M \geq 3$ (2010–2015)</td>
<td>31%</td>
<td>62%</td>
<td>7%</td>
</tr>
</tbody>
</table>

Atkinson et al., SRL (2016)
Societal Impacts

• No damage reported.

• BC O&G Commission received 15 individual complaints regarding felt seismicity.

“It sounded like a bang.”

“dishes rattled”

“It sounded like a cow walked into the side of the house.”

Source: BCOGC (personal communication)
Case Studies: Fox Creek Area, Alberta

- $M_w$ 3.9 event recorded in January 2015.
- Resulted in a “traffic light protocol” introduced for monitoring HF operations.

Bao and Eaton, Science (2016)
Traffic Light Protocols

Alberta, Canada

- $< 2.0 \, \text{ML}$: No action required
- $> 2.0 \, \text{ML}$: Inform the regulator, Invoke response plan
- $> 4.0 \, \text{ML}$: Cease operations, Inform the regulator

U.K.

- $< 0 \, \text{ML}$: No action required
- $> 0 \, \text{ML}$: Proceed with caution, Monitoring intensified
- $> 0.5 \, \text{ML}$: Cease operations
Case study 1: Crooked Lake, Alberta

- Winter 2015 Duvernay completions at 6 pads
- Seismicity strongly clustered near HF operations
- Cluster 1 seismically active for 3 months

Bao and Eaton, Science (2016)
Case study 1: Crooked Lake, Alberta

Comparison with injection data

Predicted Mmax (McGarr relation)

Event magnitudes

Injection pressure

Cumulative injected volume

Bao and Eaton, Science (2016)
Case study 1: Crooked Lake, Alberta

Comparison with injection data

Bao and Eaton, Science (2016)
Case study 1: Crooked Lake, Alberta

Comparison with injection data

Bao and Eaton, Science (2016)
Case study 1: Fault Activation

- Favourably oriented fault strands extending into crystalline basement.

- More persistent west strand: projects to location between two zipper-frac’d horizontal wells.

- Transient response of east strand: best explained by stress, not pore pressure.

Bao and Eaton, Science (2016)
Case study 1: Fault Activation

Bao and Eaton, Science (2016)

Schultz et al., JGR (2017)
Case study 2: Fault Orientation

- Potential activation of mis-oriented faults (strike direction $\sim S_{H_{\text{max}}}$)

Bao and Eaton (in prep)
Summary

1. In western Canada, induced seismicity is associated with ~0.3% of HF completions and ~1% of disposal wells.
   • 62% of M ≥3 earthquakes from 2010-2015 associated with HF completions.

2. Distinct signatures of fault reactivation.
   • stress triggering (transient).
   • fluid-pressurized faults (more persistent).

3. Potential activation of mis-oriented faults (strike direction ~ $S_{Hmax}$).
Research Agenda

- Identify critically-stressed faults.
- Understand how faults are activated (fluids vs stress)?
- Integrate reservoir models with fault activation models.

Data Availability (in Canada)

- Surface seismic monitoring close to HF operations in specific areas/reservoirs.
- Database of drilled wells and injection data.
  - 1 year lag between completion of HF operations and reporting to the regulator.
Acknowledgements

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