Enhanced remote earthquake triggering at fluid injection sites in the Midwestern US

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Groundwater Protection Council Meeting, St. Louis Missouri, Sept. 23, 2013
Outline

1. Introduction and motivation
2. The science of naturally triggered earthquakes
3. Using triggered earthquakes as a probe of induced sites
4. Outlook
Fluid-induced earthquakes on the rise

Ellsworth, 2013

Earthquake count (M≥3)

Midwest

Oklahoma

Shale Gas Development (fracking)

Number of earthquakes

Percentage of injection wells


Number of M3+ earthquakes

% of new injection wells

Courtesy of Katie Keranen
Large earthquakes near injection sites in 2011

- M3.9 Youngtown, OH
- M4.7 Guy, AR
- M5.7 Prague, OK
- M5.3 Trinidad, CO
- M4.5 Snyder, TX
Clear-cut anthropogenic swarms

- Close temporal correlation
- Close spatial correlation
- High injection pressures

Horton, 2012

Won-young Kim, 2013
Less clear-cut links

Oklahoma, Colorado, Texas:
- Long term injection at near-hydrostatic pressures.
- No M5 earthquakes during decades of pumping.
- Spatial correlation, but not temporal
Part II.
What can natural earthquake triggering tell us about anthropogenic earthquakes?
What is remote earthquake triggering?

**M = 7.9 Denali Fault earthquake triggered seismicity at Mammoth Mt., California**

- Broadband waveform showing denali
- Rayleigh waves

**High-pass filtered waveform showing locally triggered earthquakes**

**OMM spectrogram**

*Hill and Prejean, 2007*
Remote triggering recognized after Landers

1999 M7.1 Hector Mine and 1992 M7.3 Landers earthquakes

Gomberg et al., 2001
Other examples of remote triggering

Hill and Prejean, 2007
Remote triggering has global reach

triggered earthquakes in filtered seismograms 1000’s of km away from 15 big earthquakes

Velasco et al, 2008
Remote triggering is most prevalent at Volcanic and Geothermal sites

• Volcanic/Geothermal sites are reliably triggerable
• Volcanic/Geothermal sites have high fluid pressures and fluid-driven swarms

Sites of fluid-induced anthropogenic earthquakes should have remote triggering.

van der Elst and Brodsky, 2010
Why do we think fluids are involved in naturally triggered earthquakes?

1) observed more often at sites with fluids
2) seismic waves have other hydrologic effects:
   – mud eruptions
   – stream flow changes
   – well water level changes
   – geyser frequency changes
   – triggered inflation/deflation at volcanoes
The role of fluids in natural triggering: dynamic permeability enhancement (Fracture unclogging)

Aquifer permeability is enhanced by seismic waves

Elkhoury and Brodsky 2006
Fracture unclogging in the lab

Elkhoury, et al., 2011

![Image of fracture unclogging experiment](image)
Permeability enhancement and triggered earthquakes

- Pre-trigger
- ‘Clogged’ fracture

Diagram showing:
- Pore Pressure
- Distance
- Well

Diagram notes:
1. Pre-trigger
2. ‘Clogged’ fracture
Permeability enhancement and triggered earthquakes

1. Well
2. 'clogged' fracture
3. Diffusing pressure pulse
4. Potential triggered earthquakes

Pore Pressure vs. Distance

- pre-trigger
- post-trigger
Summary of remotely triggered earthquakes

- Set off by passing seismic waves of big distant earthquakes.
- A small proportion of earthquakes overall, but not uncommon.
- Mechanism is not well understood, but we know:
  1. Requires critical stresses.
  2. Is encouraged by high fluid pressure.
Part III:
Do we see remotely triggered earthquakes at injection sites?
The TA network: the right place at the right time
Detecting triggered earthquakes

- Typical seismic networks are not dense enough to catch small triggered earthquakes.
- Even with the TA, only detect down to M2.5.
- Typically we have only 1 station within 100 km (you need 4+ to locate an earthquake).

what can we do with one station?
The method: detecting little earthquakes with template matching

Earthquakes at Prague, OK
Matched-filter is a choosy earthquake detector.
Earthquakes with identical waveforms must come from the same swarm.
Earthquake time series
No where else in the midwest showed remote triggering

Common elements:
1. Long-term injection.
2. Relative seismic quiescence.
3. Large earthquakes looming.

Sites of triggered earthquakes
Summary

• Remote triggering is additional evidence of fluid-driven seismicity at injection sites.
• Remote triggering reveals critically stressed faults
• Proper monitoring of long-term injection sites may give warning of anthropogenic swarms.
What next?

USArray Status as of July 2013
Outlook

• If these triggered sequences happened today, we likely would have missed them.

• Even with the TA stations, a matched filter had to be used retrospectively.

• microseismicity (triggered or not) may be the best indicator of an ensuing swarm.

• better monitoring is needed to establish the patterns, and to identify them when they arise.
Do anthropogenic swarms consist mostly of small earthquakes?

- True for active frac operations, but not for long-term disposal.
- Size distribution is consistent with tectonic earthquakes ($b = 1$)
- For every 10 M3’s, you should expect 1 (or more) M4
Statistics of triggering

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<tr>
<th>Location</th>
<th>Catalog/Station*</th>
<th>Remote Trigger</th>
<th>Num. before†</th>
<th>Num. after†</th>
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