Update on Injection-Induced Earthquakes

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Key Developments

• Ongoing swarm of earthquakes in Oklahoma likely associated with wastewater injection.

• Strong ground motions were recorded in East Texas, from an M4.1 quake associated with wastewater injection.

• Possible triggering of a Prague, OK, M5.6 earthquake by a M4.7 injection-induced quake.

• New focused, collaborative study of injections at the carbon sequestration facility in Decatur, Illinois.

• Continued Congressional and public interest but no additional funding and no changes in regulation.
Activities Entailing Fluid Injection at Depth

- Waste liquid disposal (chemicals and saline water)
- Enhancing oil and gas production (conventional)
- Tight shale gas and coal bed methane production (including disposal of wastewater)
- Geothermal production and Enhanced Geothermal Systems
- Carbon dioxide sequestration
How does fluid injection trigger earthquakes?

Increases in fluid pressure (P) at depth decrease the stress clamping the fault together, allowing the shear stress to dominate.

This phenomenon is well documented in laboratory experiments and has guided induced seismicity research for decades.

\[ \tau = c + \mu (\sigma_n - P) = \text{strength of plane} \]
Research Challenges and Questions - 1

• What factors control the seismic response to an injection activity?

• Is it possible to predict in advance whether a given injection well will induce earthquakes large enough to be of concern?

• Can a small-scale injection activity trigger a large earthquake?

• How do induced earthquakes affect the National Seismic Hazard Maps?
Research Challenges and Questions - 2

• Why do triggered earthquakes occur in some places and not others?

• How large an earthquake can be induced?

• How should injection practices be altered to minimize the risk of inducing damaging earthquakes?

• Once a significant earthquake occurs, what operational changes should be implemented?

• How do the answers to these questions relate to regulation and permitting?
Who wants to know?

• **Industry** (business risk, liability)
  - Oil and gas producers
  - Oilfield service providers
  - Waste disposal companies

• **Regulators** (decision-making)
  - Permitting agencies
  - Local land-use jurisdictions
  - Earthquake safety regulators

• **The public** (adequate regulation?)

• **Private facility owners**
  (risk mitigation)
  - Dams, hospitals, power, etc.
Fracking and Wastewater Injection

Hundreds of thousands of frac jobs

Only a handful of felt events

None as large as magnitude 4 (so far)

30,000 deep wastewater wells in U.S.

Many with volumes > $10^6$ m$^3$

Few with detected seismicity

Magnitudes as large as $M_w$ 5.6

adapted from geology.com
The seismicity observed and reported by NRCan in the Horn River Basin between April 2009 and December 2011 was induced by fault movement resulting from injection of fluids during hydraulic fracturing.

31 earthquakes; largest $M_w$ 3.6

“The seismicity observed and reported by NRCan in the Horn River Basin between April 2009 and December 2011 was induced by fault movement resulting from injection of fluids during hydraulic fracturing.”
A by-product of the fracking operation is “produced water” (natural brine and fracking flowback)
High rate of earthquakes in the midcontinent since 2001

Areas with anomalous numbers of earthquakes, 2009-2012
relative to the forecast of the 2008 National Seismic Hazard Map
P(N_{EQS}|NSHM) 2009-2013
Earthquakes in Oklahoma 2010-2011

A sharp increase in M3+ earthquakes in Oklahoma since 2009

Ellsworth, 2013
2011 Prague, Oklahoma Earthquake

$M_w 5.7$

No fatalities; a few injuries; significant economic damage
A moving target in Oklahoma
Disposal Well Shutdown After Swarm of Earthquakes in South-Central Oklahoma

A Love County disposal well was shutdown last week after a state seismologist suggested it might have triggered a swarm of damaging earthquakes that shook the area for weeks in September.
N. Oklahoma - Mississippi Lime Play

Oklahoma Geological Survey Catalog 1/1/2013 to 10/9/2013

SandRidge Energy
High water production well

Recent production from high-water saturation reservoirs in central Oklahoma

Water production per well in barrels during initial test

Keranen et al, 2013
High-volume disposal well

High volumes of produced water are disposed in nearby high-volume injection wells.

Keranen et al, 2013

Water injection per well per day

High-volume disposal well
Earthquakes are clustered in a region of high fluid redistribution in central Oklahoma. High water production well.
Earthquake Hazard and Seismicity
2009 - 2012

M ≥ 3
January 25, 2013 $M_w$ 3.9 Paradox Valley Earthquake

- 8 km from well
- Small magnitude activity within 1 year of start of injection
- $M_w$ 3.9 delayed 16 years after injection began
- Bureau of Reclamation reconsidering future of injection
Earthquakes Induced by Enhanced Oil Recovery
Cogdell Oil Field, West Texas

Active in late 1970s and early 1980s during water flooding

Resumption of seismicity in 2006 after \( \text{CO}_2 \) injection began

Largest event \( M_w \) 4.4

Seismicity detected during Passage of USArray

Earthquakes in **RED**
Injection wells in **Yellow**

Gan, W., and Frohlich, C, in press, Are recent earthquakes in the Cogdell oil field, Texas, triggered by \( \text{CO}_2 \) injection?. *Proc. Natl. Academy of Science.*
Earthquakes and Waste Water in the Barnett Shale

Detailed analysis using USArray Transportable Array showed seismicity to be associated with high-volume waste water injection wells.

Five Principal Earthquakes

- $M_w \ 3.9$ May 10, 2012
- $M_w \ 4.8$ May 17, 2012
- $M_w \ 4.1$ January 25, 2013
- $M_w \ 4.0$ September 2, 2013
- $M_w \ 4.1$ September 2, 2013

Investigating the 17 May 2012 M4.8 Earthquake near Timpson, East Texas

Timson Earthquakes
Earthquake Location Results from Temporary Networks

Cumulative Volumes

North: 1 million m³

South: 3 million m³
Timson  $M_w$ 4.1 January 25, 2013

ShakeMap Prediction

Observed Ground Motions

55% g

62% g

22 cm/s

Predicted values from GMPEs too small!
Earthquakes near Azle, TX, Nov-Dec. 2013

North Texas quakes prompt calls for inquiry into gas drilling as possible cause
“The proposed injection volumes of liquid CO\textsubscript{2} in large-scale sequestration projects are much larger than those associated with other energy technologies. There is no experience with fluid injection at these large scales and little data on seismicity associated with CO\textsubscript{2} pilot projects. If the reservoirs behave in a similar manner to oil and gas fields, these large net volumes may have the potential to impact the pore pressure over vast areas . . such large spatial areas may have potential to increase both the number and magnitude of seismic events.”
Background on Decatur CCS Project:

- Injection of 1000 tonnes/day CO₂ at Archer Daniels Midland ethanol production plant began in November 2011, into Mount Simon Sandstone at 2.1 km depth, resting directly on top of pre-Cambrian basement. Site is located in city of Decatur IL (population ~100,000).

- Permitting to increase injection to commercial scale (~3000 tonnes/day) is underway through U.S. EPA.

- The Illinois State Geological Survey manages the ongoing Illinois Basin - Decatur Project (IBDP) while ADM manages the Illinois Industrial Carbon Capture and Storage project (ICCS), which will add ~2000 tonnes/day capacity.

- Funding from DOE and industry collaborators: ADM and Schlumberger. Schlumberger already operates a 31-level borehole geophone array at this site, with plans for additional stations.

- USGS has set up an independent, 12-station seismic network at Decatur, with terms on data sharing and scientific cooperation at Decatur now being negotiated with the ISGS and ADM.
Three 500-ft-deep borehole + surface stations (DEC01, 02, 03) and nine surface stations
Field work end of Oct 2013: installed final station (DEC06), optimized entire network
Some Conclusions and Observations

• Fluid injection, but not fracking, is primarily responsible for the recent increase in midcontinent seismicity, through the well-understood effective stress mechanism.

• Although very few injection wells have seismicity associated with them, ancient faults have ruptured in triggered earthquakes with magnitudes up to $M_w$ 5.6.

• We currently have very limited predictive capability due to:
  • Uncertainty in the stress state and pore pressure
  • Rudimentary knowledge of flow paths
  • Poor knowledge of potentially capable faults
  • Poor detection and location capabilities of seismic networks
  • Difficulty in predicting how large an earthquake will grow

• Injection parameter data are typically inadequate for scientific study.
Update on Manmade Earthquakes

FAQ on earthquakes induced by fluid injection
http://www.usgs.gov/faq/?q=taxonomy/term/9833

Earthquake swarm continues in central Oklahoma

Shale, Hydraulic Fracturing and Induced Earthquakes (4/4/12)
http://gallery.usgs.gov/videos/533

Injection Induced Earthquakes (taped presentation, 12-2-13)
http://media.wr.usgs.gov/colloquium/WRC_02dec13.mp4

Injection Induced Earthquakes (review article, Science, 2013)
http://pubs.er.usgs.gov/publication/70048668

Modeling earthquake rate changes in Oklahoma and Arkansas: possible signatures of induced seismicity
http://pubs.er.usgs.gov/publication/70048493

Significant Induced Earthquakes in the Central and Eastern U.S. Since 2008