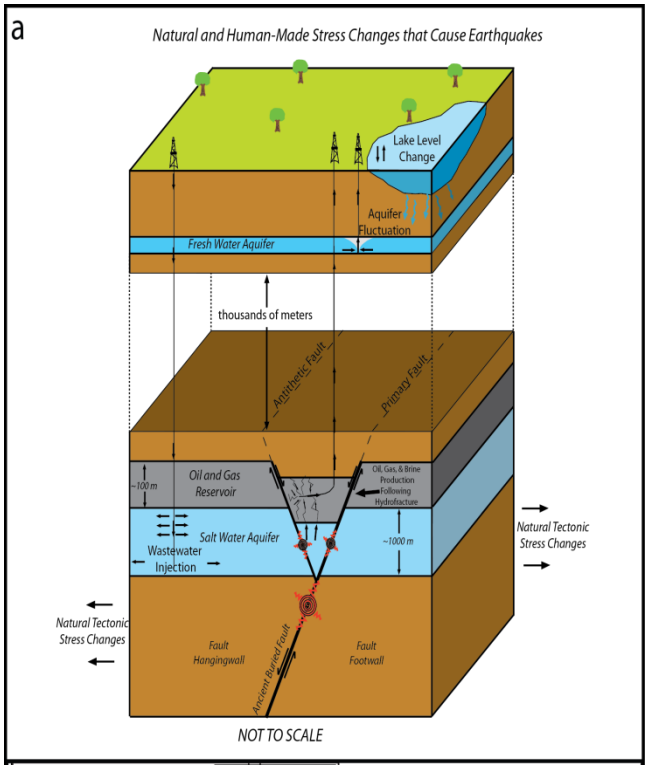
Overview of Induced Seismicity

William L. Ellsworth
U. S. Geological Survey



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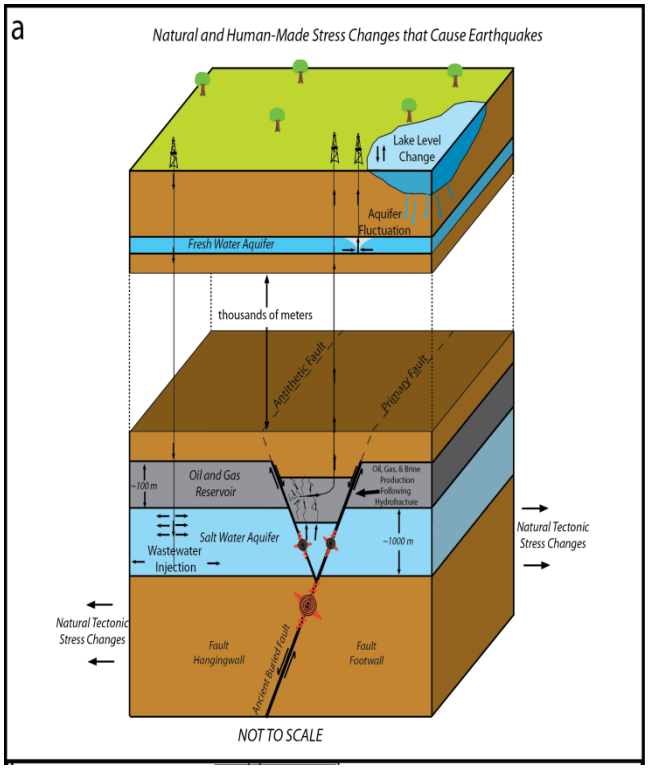
Outline

- Mechanics of Induced Earthquakes
- Hazard from Induced Earthquakes
- USGS Research Agenda



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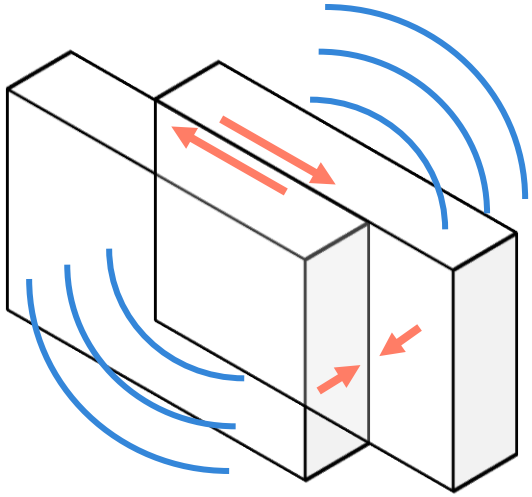
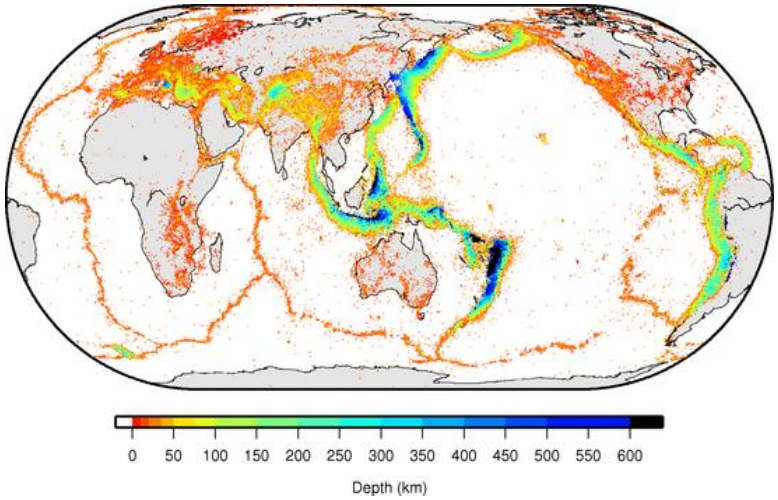
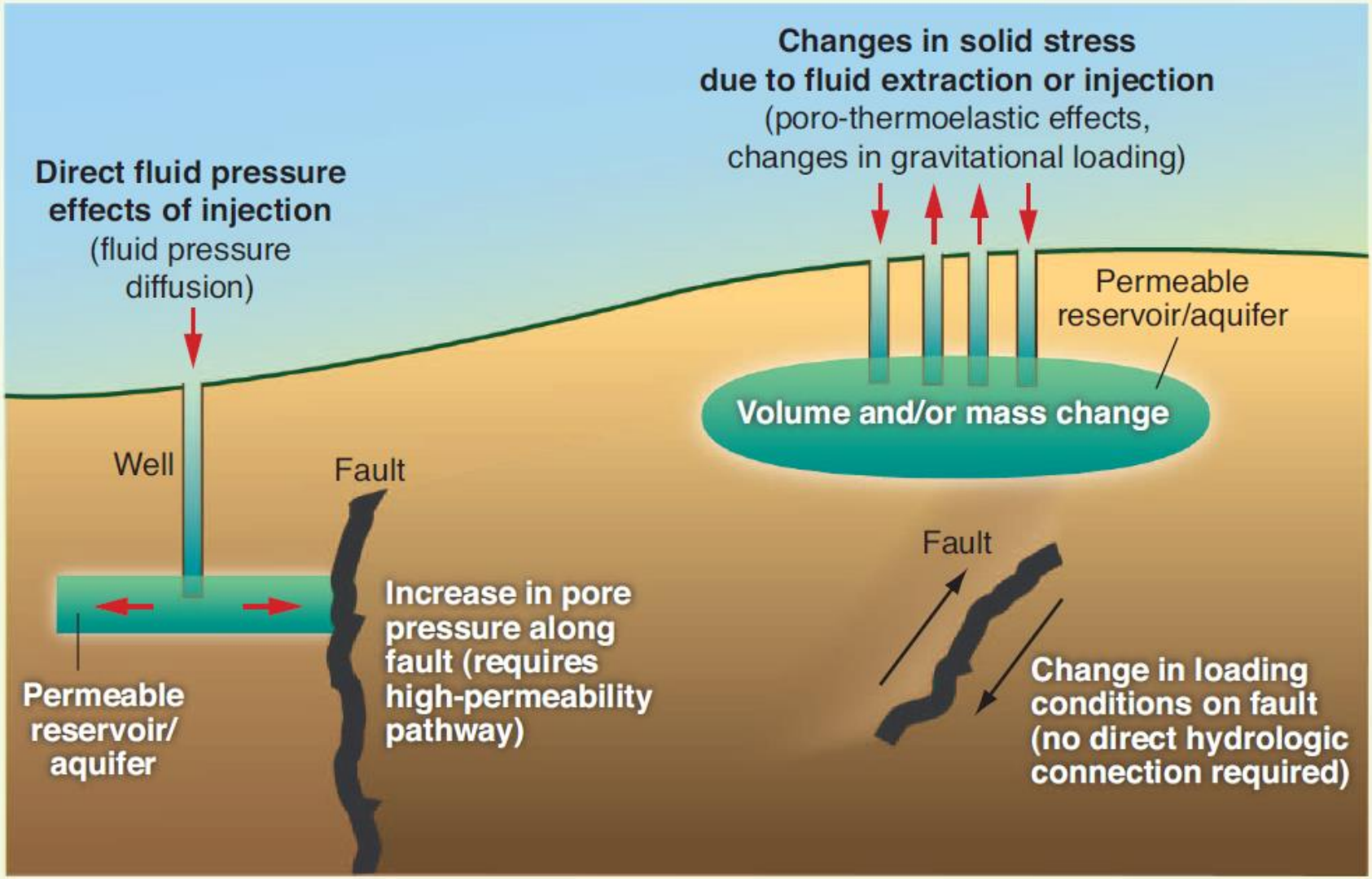
What Is an Earthquake?

- Shaking of the ground caused by the sudden slippage of a fault.
- Release of long-stored elastic energy by sudden slippage of a fault.
- An earthquake will begin when the stress exceeds the frictional strength of the fault.





Human Activity can Induced Earthquakes in Two Ways



W. L. Ellsworth, 2013, Injection-Induced Earthquakes, *Science* 341, 1225942 (2013). DOI: 10.1126/science.1225942

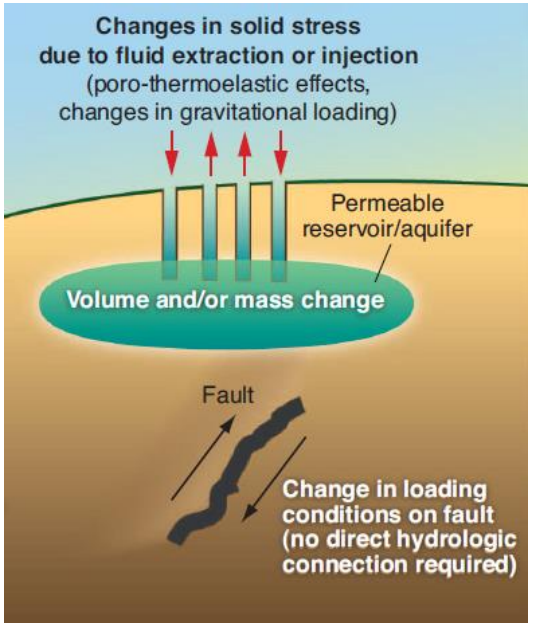
Inducing Earthquakes: Solid Stress Effect

Bulletin of the Seismological Society of America, Vol. 76, No. 4, pp. 939–948, August 1986

THE EVOLUTION OF SEISMIC BARRIERS AND ASPERITIES CAUSED BY THE DEPRESSURING OF FAULT PLANES IN OIL AND GAS FIELDS OF SOUTH TEXAS

BY WAYNE D. PENNINGTON*, SCOTT D. DAVIS, STEVEN M. CARLSON†, JAMES DUPREE‡, AND THOMAS E. EWING§

The earthquakes in the Fashing and Pleasanton areas of South Texas are due to the withdrawal of fluids from the Fashing gas field and the Imogene oil field.



Bulletin of the Seismological Society of America, Vol. 85, No. 6, pp. 1888–1895, December 1995

The 9 April 1993 Earthquake in South-Central Texas: Was It Induced by Fluid Withdrawal?

by Scott D. Davis, Paul A. Nyffenegger, and Cliff Frohlich

The available evidence strongly suggests that the Fashing, Pleasanton, and Falls City earthquakes were all triggered by hydrocarbon production (Pennington *et al.*, 1986; Olson and Frohlich, 1992).

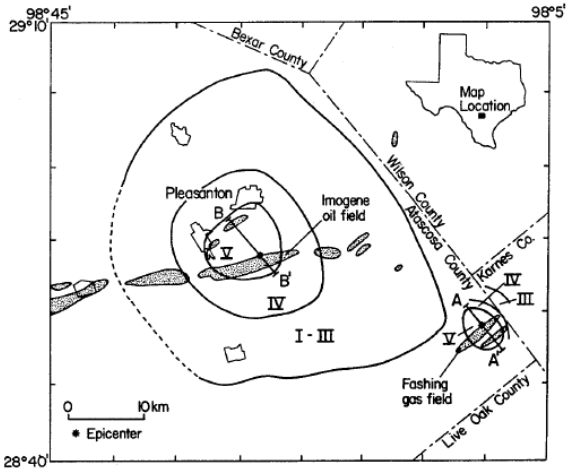
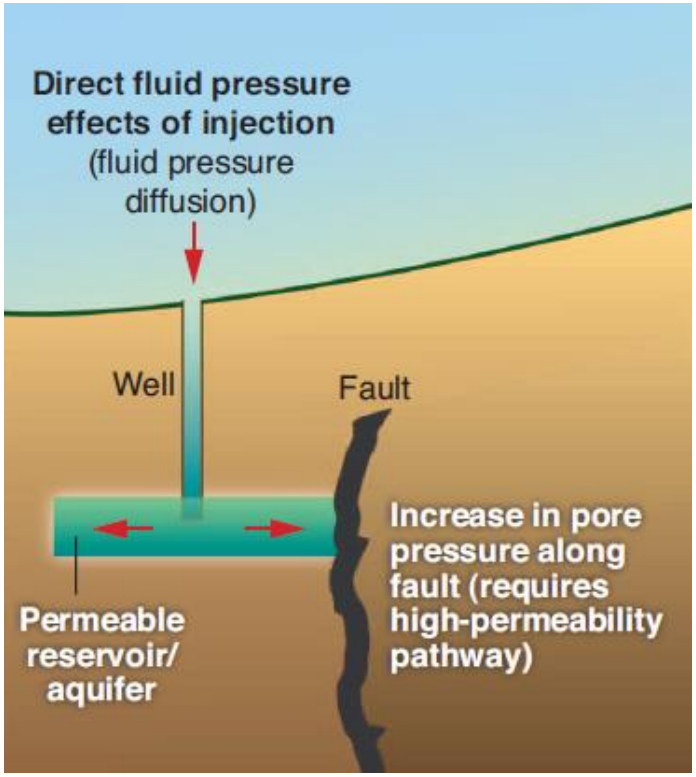


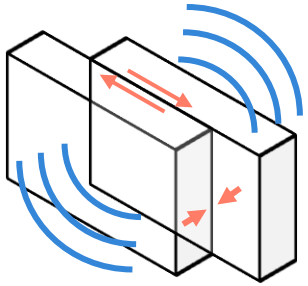
FIG. 1. Map of area in South Texas containing induced earthquakes. *Shaded* regions are more prominent oil and gas fields. Isoseismals for largest events are indicated in Modified Mercalli intensity scale. Locations of cross-sections in Figure 2 are indicated.

Inducing Earthquakes: Pore Pressure Effect

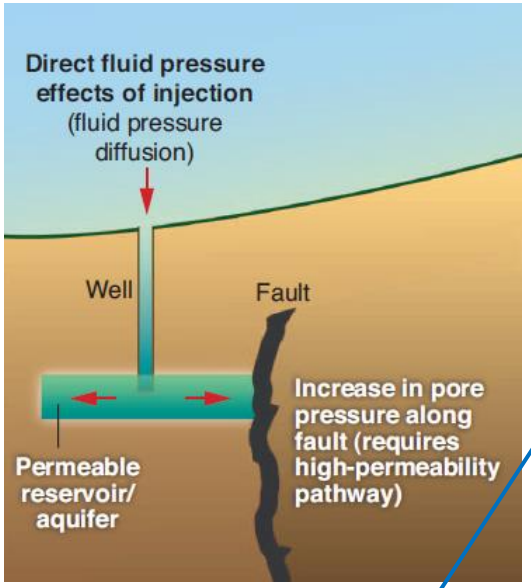


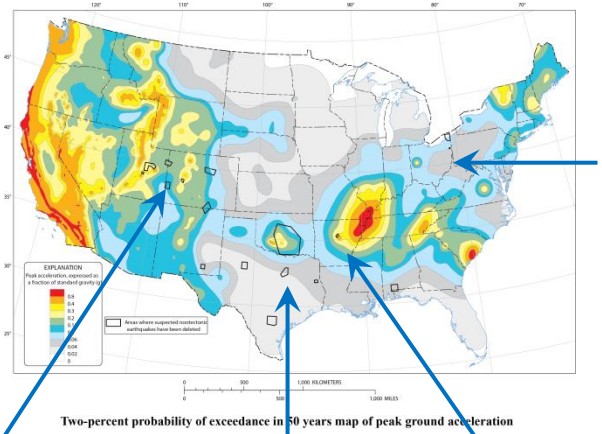
- Ancient faults can be reactivated by decreasing the effective normal stress

$$\tau_{crit} = \mu (\sigma_n - P)$$

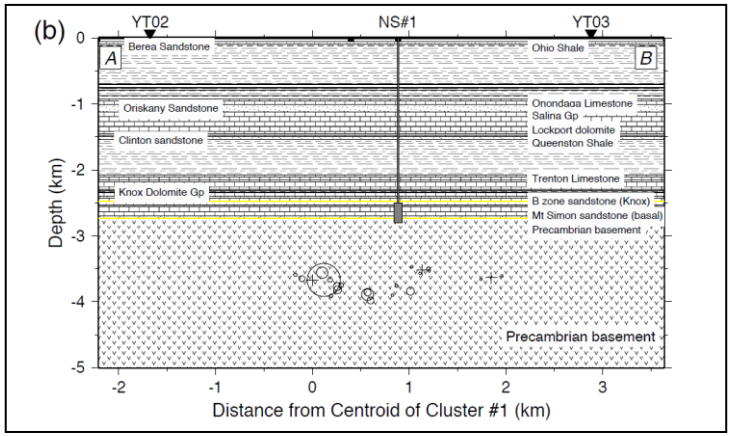


- Faults occur on a wide variety of scales and are found in virtually every geologic setting
- The Earth's crust is in a near critical failure state everywhere



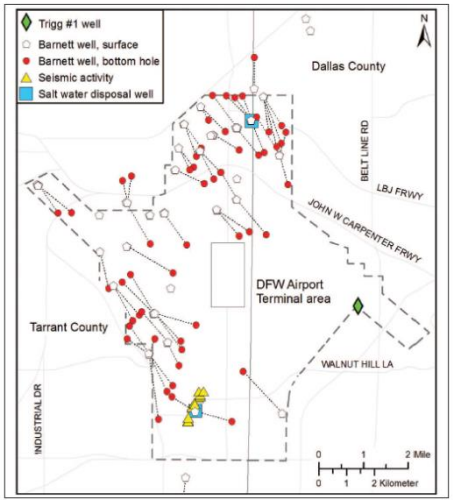


Youngstown, Ohio



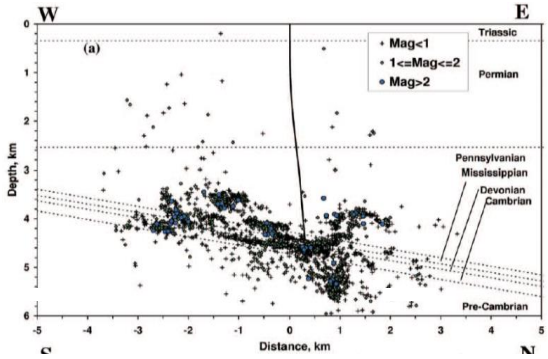
W.-Y. Kim, Induced seismicity associated with fluid injection into a deep well in Youngstown, Ohio. J. Geophys. Res. 10.1002/jgrb.50247 (2013)

DFW, Texas



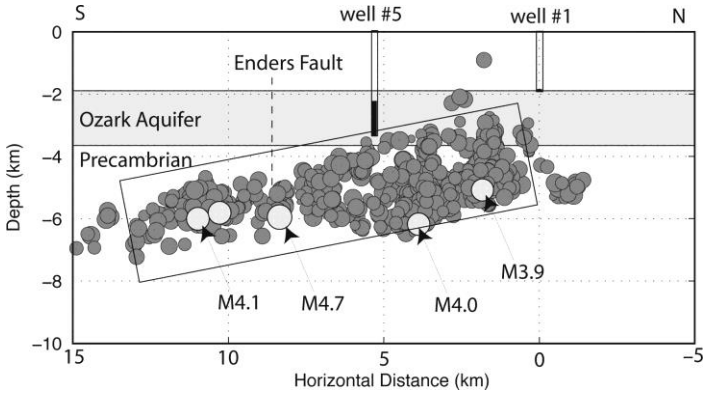
Frohlich, C., Hayward, C, Stump, B. and Potter, E., 2011, *The Dallas-Fort Worth Earthquake Sequence: October 2008 through May 2009*, Bull. Seismol Soc. Am, v. 101, 327-340.

Paradox Valley, Colorado



Ake, J., Mahrer, K., O'Connell, D., and Block, L., 2005, Deep-Injection and Closely Monitored Induced Seismicity at Paradox Valley, Colorado. *Bull. Seismol. Soc. Am*, v. 95, 664-683.

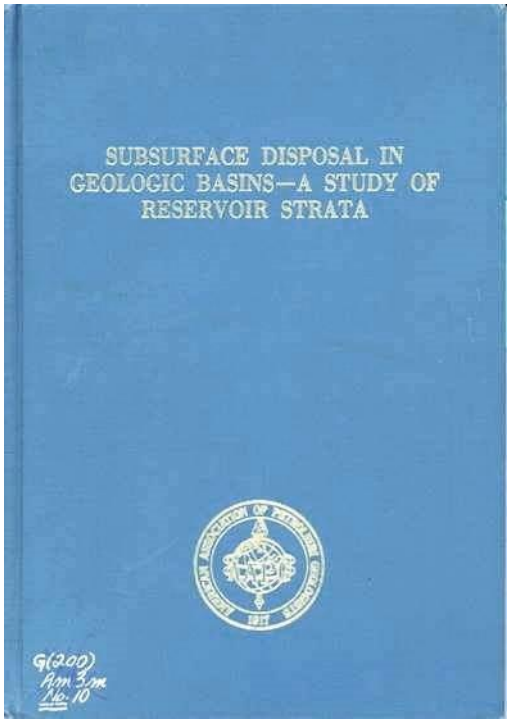
Guy, Arkansas



Horton, S., 2012, *Disposal of Hydrofracking Waste Fluid by Injection into Subsurface Aquifers Triggers Earthquake Swarm in Central Arkansas with Potential for Damaging Earthquake; Seismological Research Letters*, v. 83.

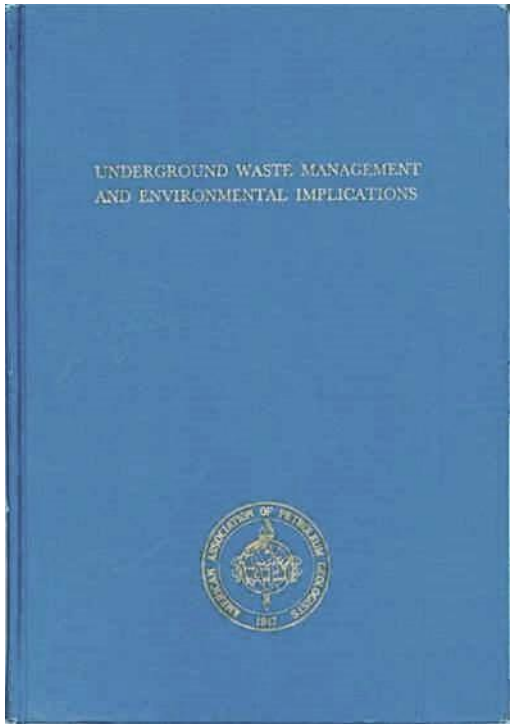
Human Induced Earthquakes
These are not new ideas

Subsurface Disposal in Geologic Basins – A study of Reservoir Strata
AAPG Monograph 10 (1968)



"the tremors … being the results of the release of stress when the pressures produced by injection of fluid overcome the friction on opposing rock surfaces."

Underground Waste Management and Environmental Implications
AAPG Monograph 18 (1976)

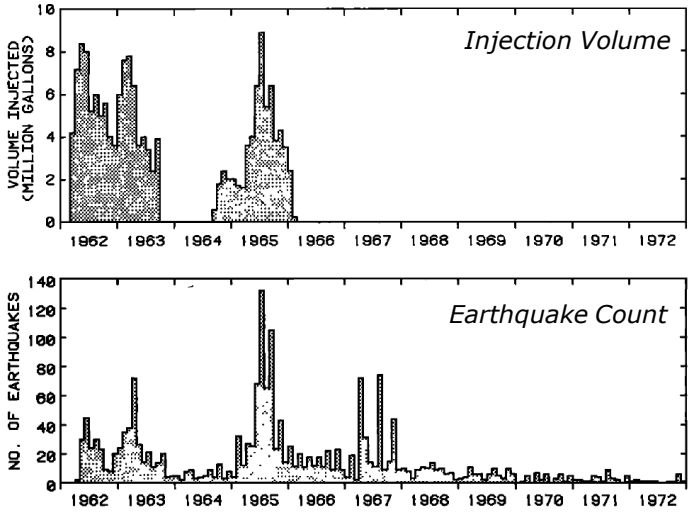


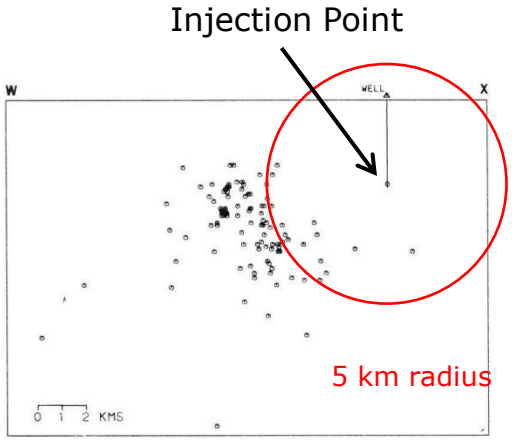
"The Denver earthquakes – and similar, less intensively studied cases in oilfields in western Colorado, Texas and Utah – have served a very good purpose in alerting us to this kind of long-term danger."

1960s Denver Earthquakes

"The disposal of waste fluids by injection into a deep well has triggered earthquakes near Denver, Colorado."

Healy, J.H., Rubey, W.W., Griggs, D.T. and Raleigh, C.B., 1968, *The Denver Earthquakes; Science,* v. 161, p. 1301-1310.

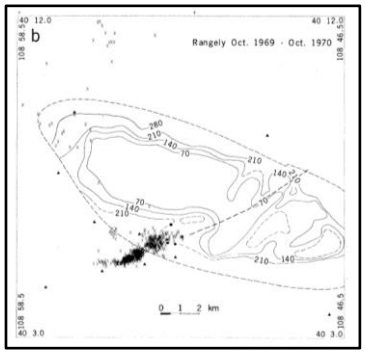




Cross Section of Earthquakes in 1967

Key Findings:

- Earthquakes induced by injection of chemical waste in a deep well
- Release of long-stored tectonic stress on ancient faults
- Earthquakes occurred more than 10 km from injection point
- Largest earthquake (Mw 4.8) occurred over one year after injection stopped
- Earthquakes continued into the 1980s

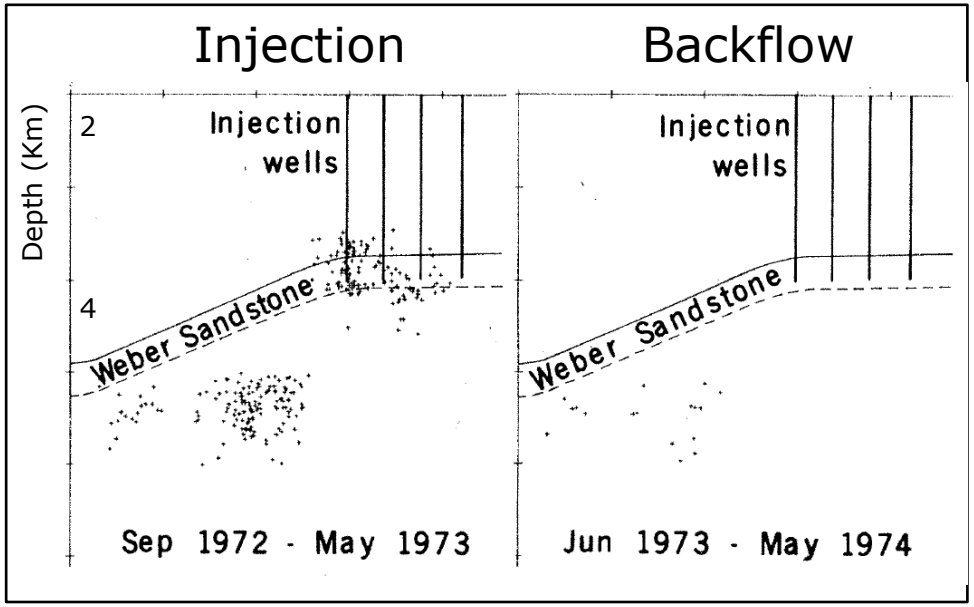


Verifying the Effective Stress Hypothesis at Rangely, Colorado

USGS experiment turned-on and off earthquakes in a Colorado oil field by varying injection pressure.

State of stress and pore pressure were measured, as was the frictional strength of the rocks.

$$\tau_{crit} = \mu (\sigma_n - P)$$

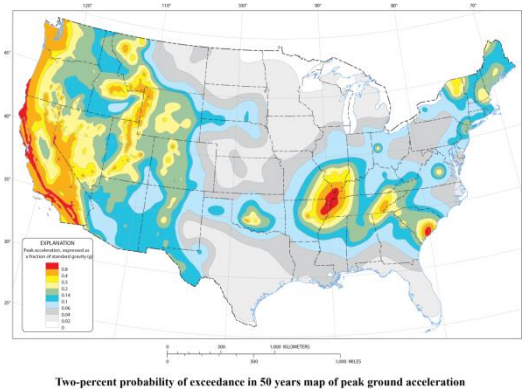


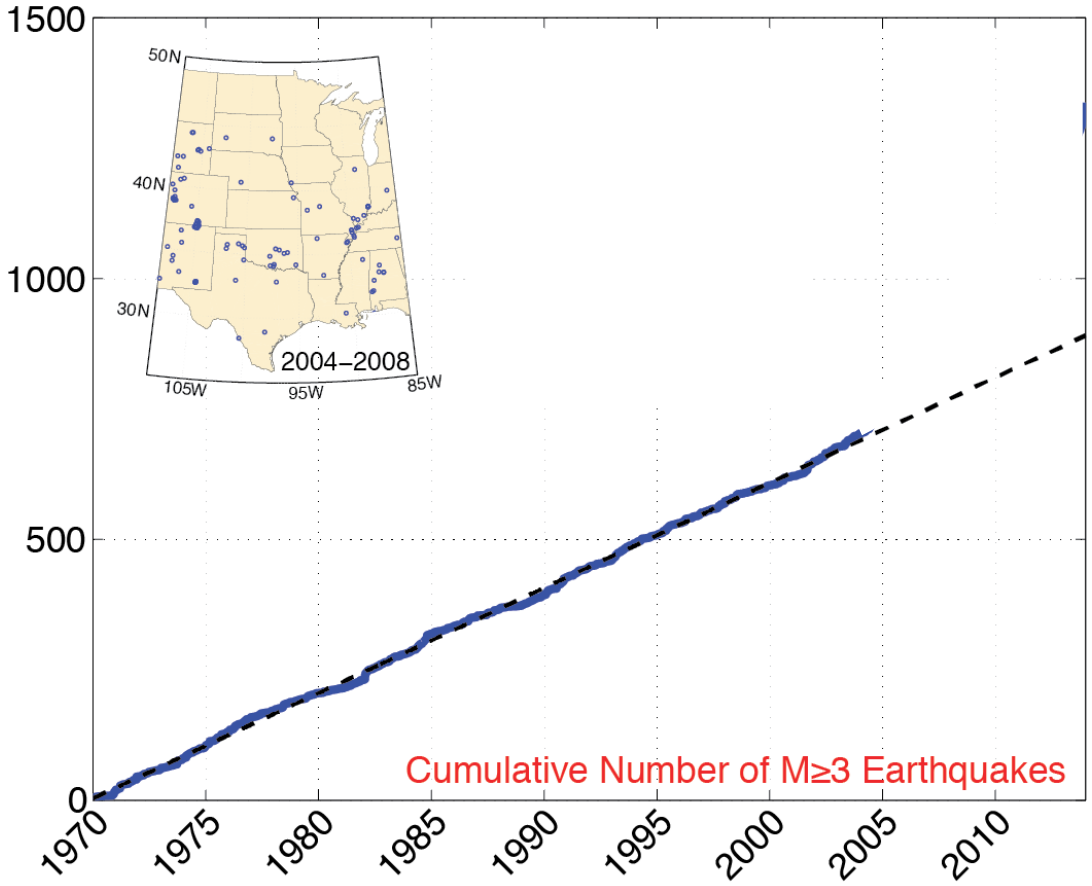
"The cessation of seismic activity within 1 day of the initiation of backflow in the experimental wells in May 1973 established the correlation between fluid pressure and earthquakes beyond a reasonable doubt."

Raleigh, C.B., Healy, J.H. and Bredehoeft, J.T, 1976, *An Experiment in Earthquake Control at Rangely, Colorado; Science,* v. 191, p. 1230-1237.

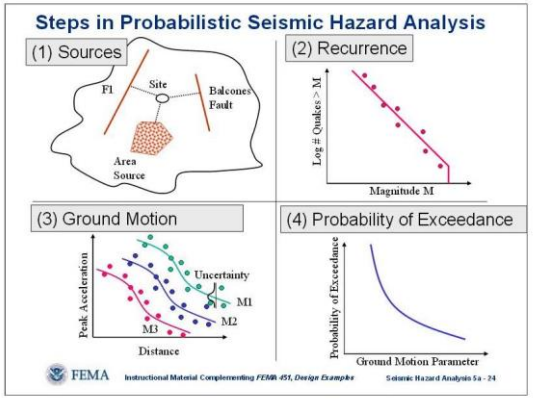
Hazard From Induced Earthquakes

Hazard model for the central and eastern U. S. primarily based on past seismicity

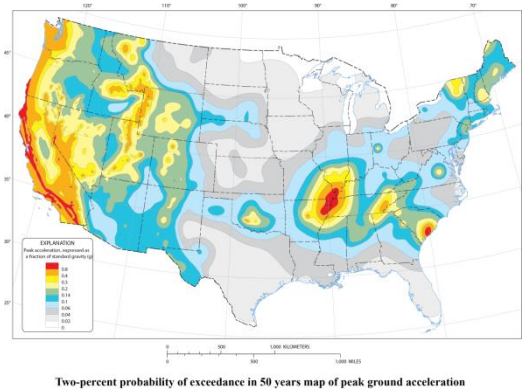




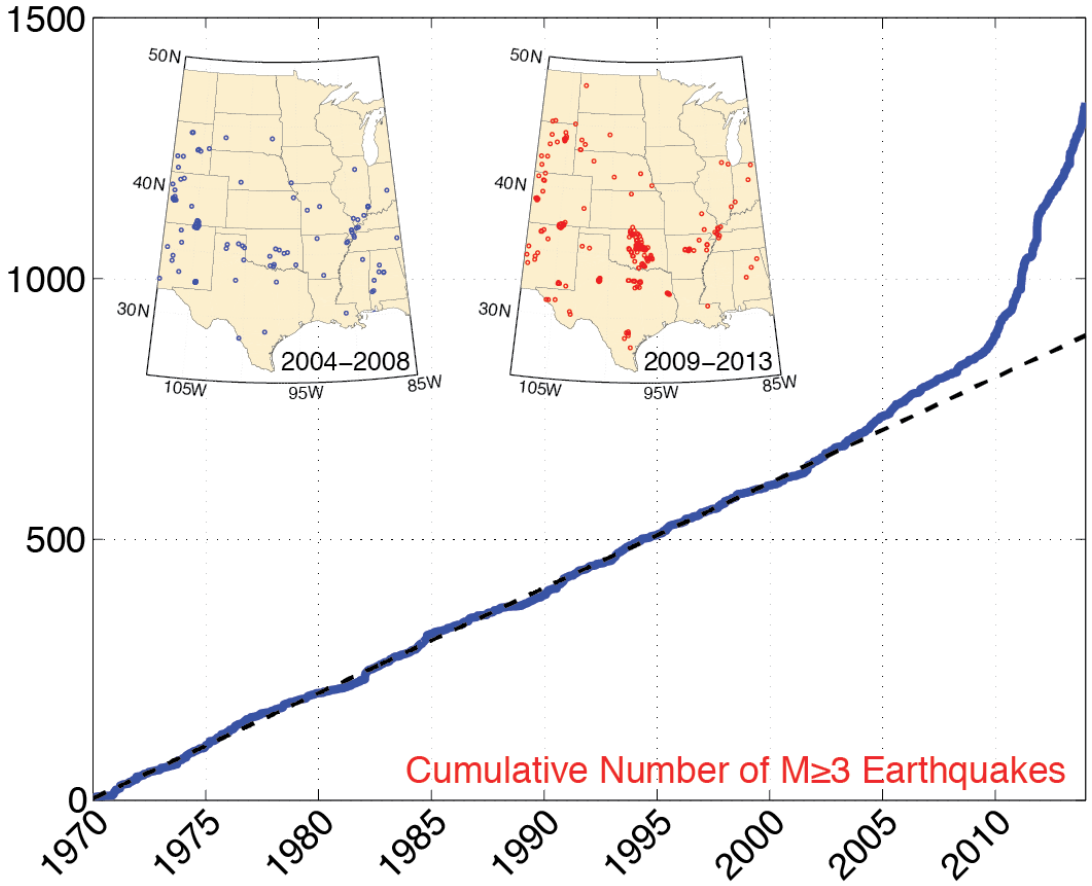
What rate of earthquakes should be expected in the future?



Hazard model for the central and eastern U. S. primarily based on past seismicity



Two-percent probability of exceedance in 50 years map of peak ground acceleration



Higher rate of earthquakes implies higher hazard.

But how much higher?

How long will the higher hazard last?

USGS and OGS drew attention to the unprecedented earthquake activity in Oklahoma in late 2013

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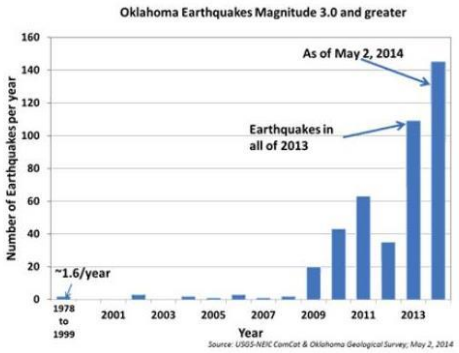
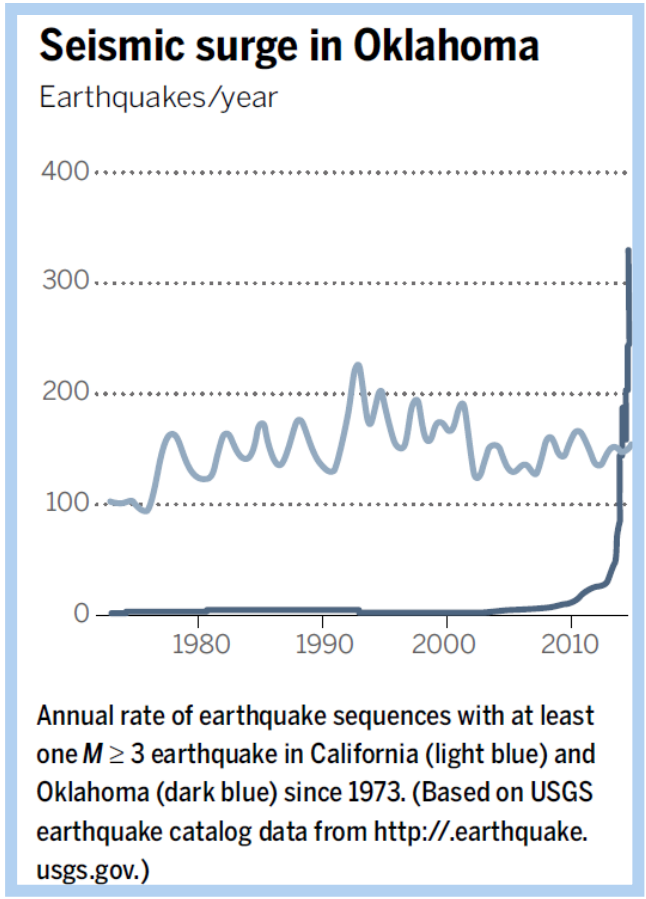
Record Number of Oklahoma Tremors Raises Possibility of Damaging Earthquakes

Updated USGS-Oklahoma Geological Survey Joint Statement on Oklahoma Earthquakes
Originally Released: 10/22/2013 1:07:59 PM; Updated May 2, 2014

The rate of earthquakes in Oklahoma has increased remarkably since October 2013 – by about 50 percent – significantly increasing the chance for a damaging magnitude 5.5 or greater quake in central Oklahoma. View map of Oklahoma seismicity. View animation of Oklahoma Seismicity.



A new U.S. Geological Survey and Oklahoma Geological Survey analysis found that 145 earthquakes of magnitude 3.0 or greater occurred in Oklahoma from January 2014 (through May 2; see accompanying graphic). The previous annual record, set in 2013, was 109 earthquakes, while the long-term average earthquake rate, from 1978 to 2008, was just two magnitude 3.0 or larger earthquakes per year. Important to people living in central and north-central Oklahoma is that the likelihood of future, damaging earthquakes has increased as a result of the increased number of small and moderate shocks.



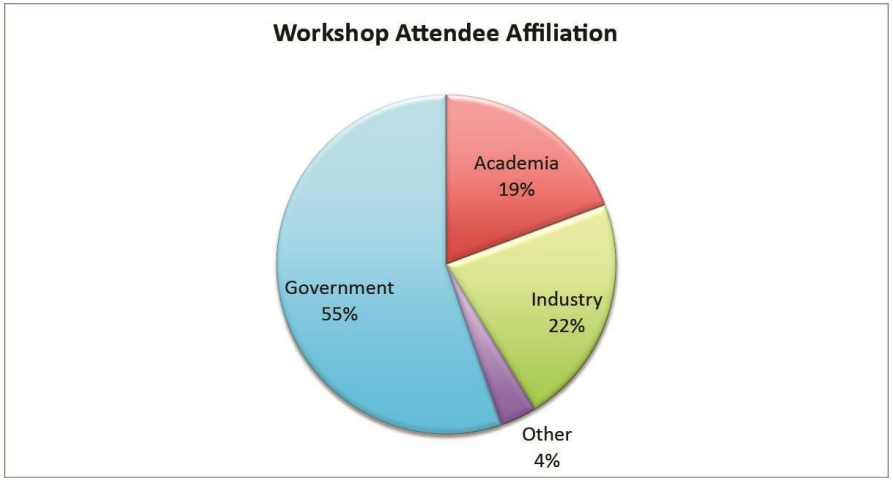
Annual rate of earthquake sequences with at least one $M \geq 3$ earthquake in California (light blue) and Oklahoma (dark blue) since 1973. (Based on USGS earthquake catalog data from http://.earthquake.usgs.gov.)

2014 saw a record number of earthquakes in Oklahoma, including twice as many earthquake sequences as in California

Workshop on Hazard from Induced Seismicity

November 18, 2014
Co-hosted by: Oklahoma Geological Survey and USGS
The Reed Center, Midwest City, Oklahoma

150 participants from industry, state and federal geological surveys, academia, regulatory agencies, state insurance and transportation agencies, etc.



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Incorporating Induced Seismicity in the 2014 United States National Seismic Hazard Models: Results of 2014 Workshop and Sensitivity Studies

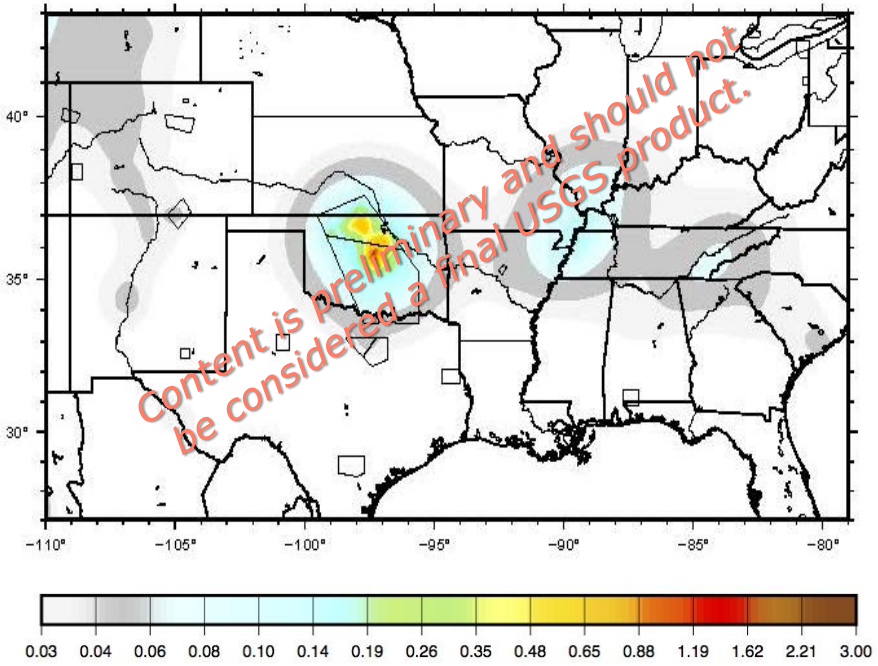
Mark D. Petersen, Charles S. Mueller, Morgan P. Moschetti, Susan M. Hoover, Justin L. Rubinstein, Andrea L. Llenos, William L. Ellsworth, Austin A. Holland, Art McGarr and John G. Anderson

Open-File Report 2014–XXXX

Preliminary Seismic Hazard Map for 2015

Example Map for 2015 Showing Hazard from Natural and Induced Earthquakes

Map shows shaking hazard for a 2-story structure that has 1 chance in 100 of being experienced or exceeded in the next 12 months. Shaking intensity expressed as the 5-hertz (0.2 second) spectral acceleration in units of g (acceleration of gravity).



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Research Agenda for Induced Seismicity

- Develop 1-year hazard map incorporating natural and man-made earthquakes.
- Improve communication of hazard to public, elected officials, regulators, industry.
- Continue to collect data to improve the accuracy of the hazard model, including the nature of the earthquakes and the ground shaking they produce.
- Continue research to develop a process-based understanding of induced earthquakes and the hazard they pose to society.

Thank You

Additional information on managing the hazard of injection-induced earthquakes:

McGarr, A., et al., 2015, Coping with Earthquakes Induced by Fluid Injection, *Science*, 20 February 2015, v. 347, p. 830-831, doi:10.1126/science.aaa0494

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Information on earthquakes and earthquake hazard available at http://earthquake.usgs.gov/