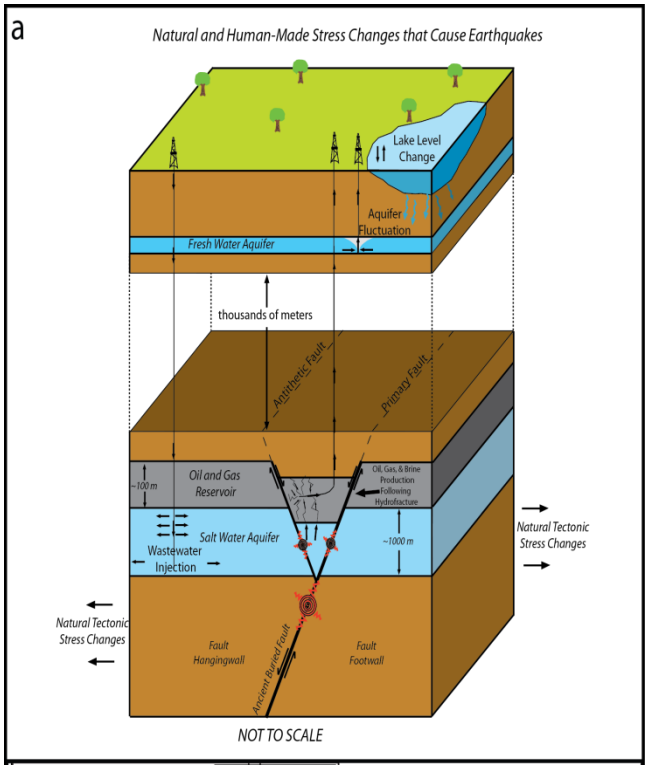
Overview of Induced Seismicity

William L. Ellsworth
U. S. Geological Survey



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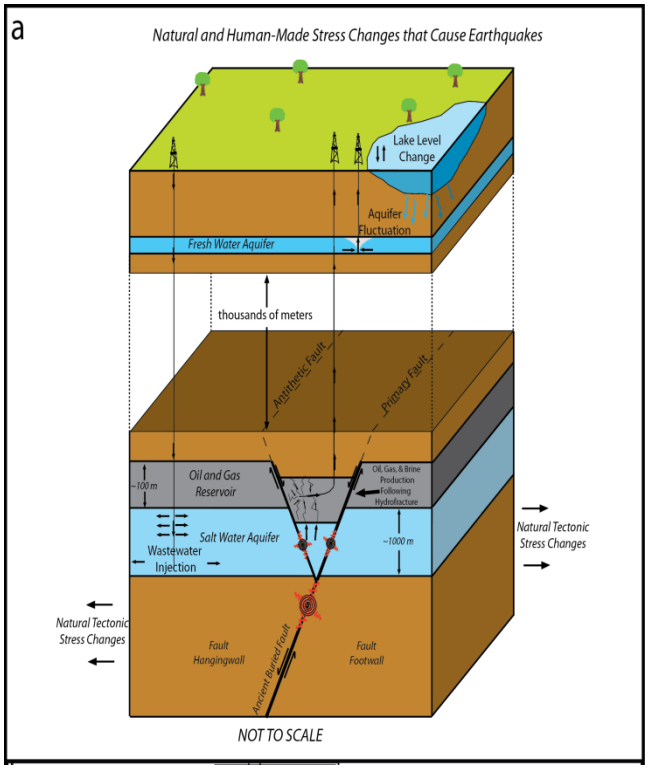
Outline

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



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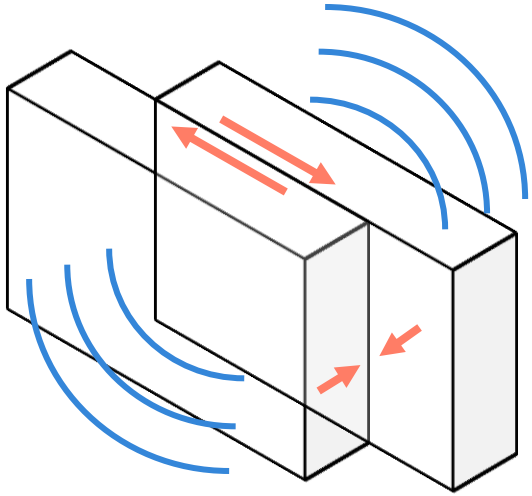
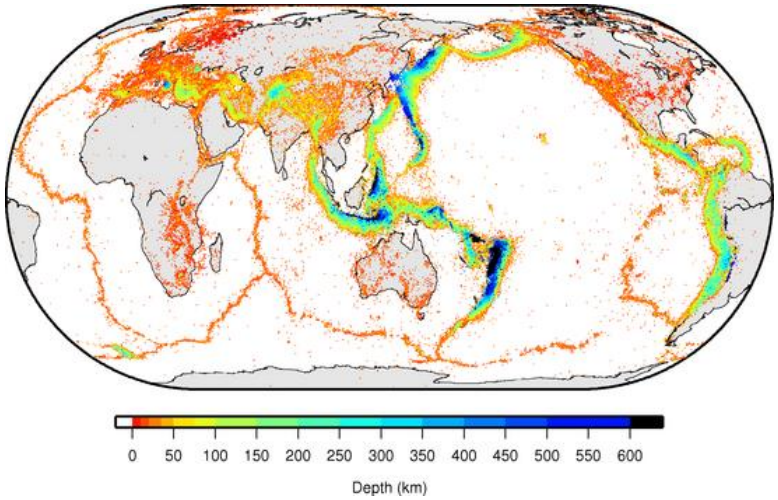
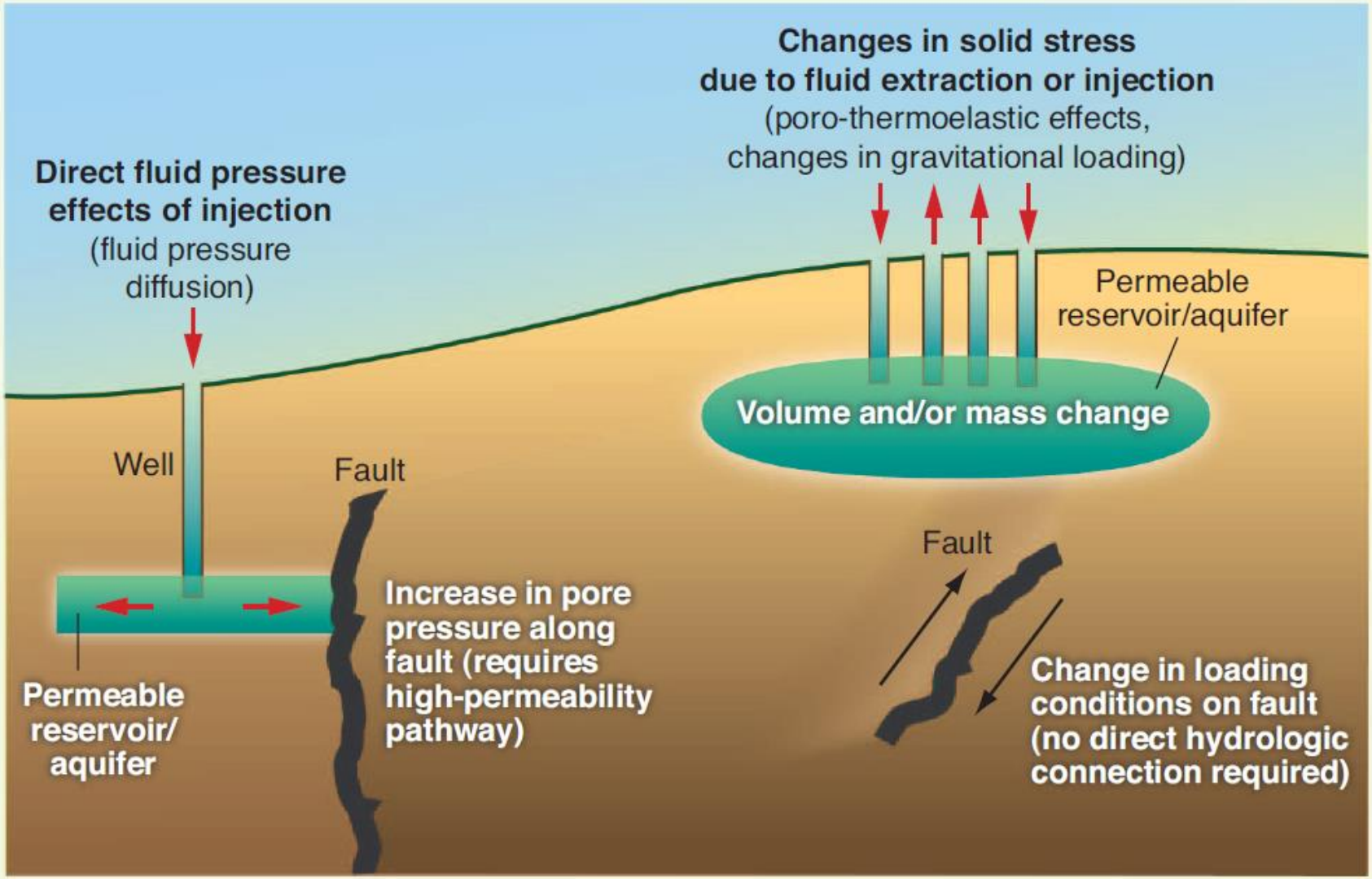
What Is an Earthquake?

- 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

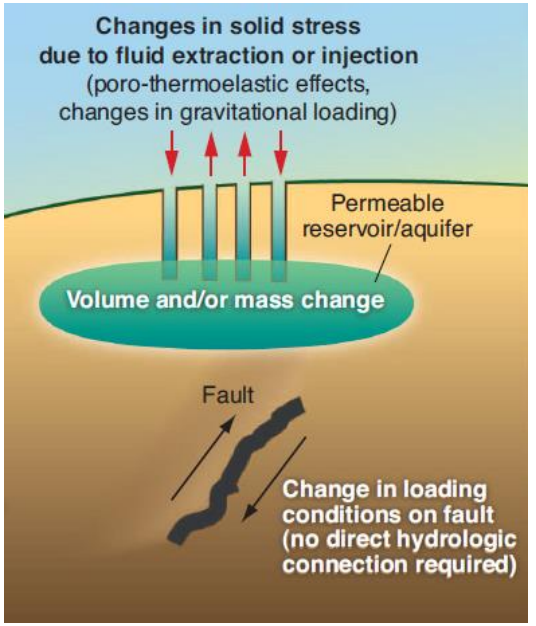
Inducing Earthquakes: Solid Stress Effect

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).

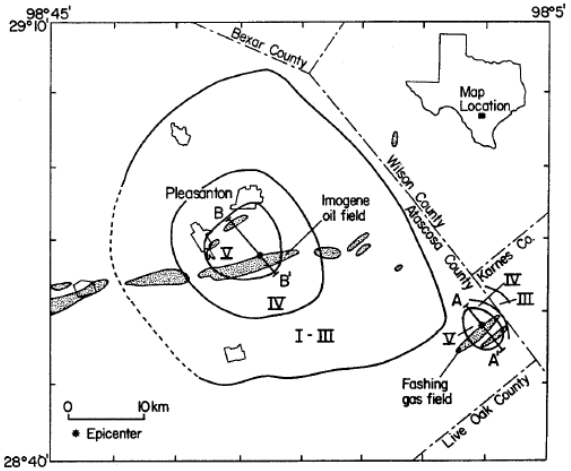
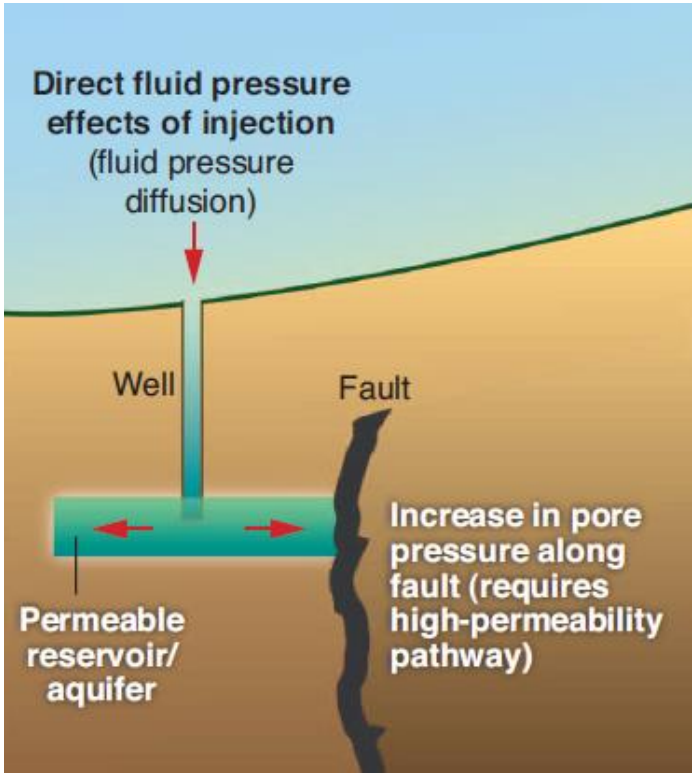


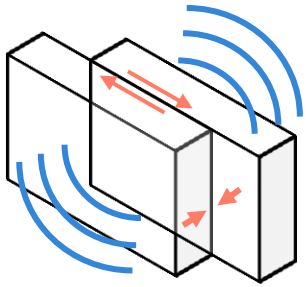
FIG. 1. Map of area in South Texas containing induced earthquakes. *Shaded* regions are more prominent oil and gas fields. Isoseismals for largest events are indicated in Modified Mercalli intensity scale. Locations of cross-sections in Figure 2 are indicated.

Inducing Earthquakes: Pore Pressure Effect



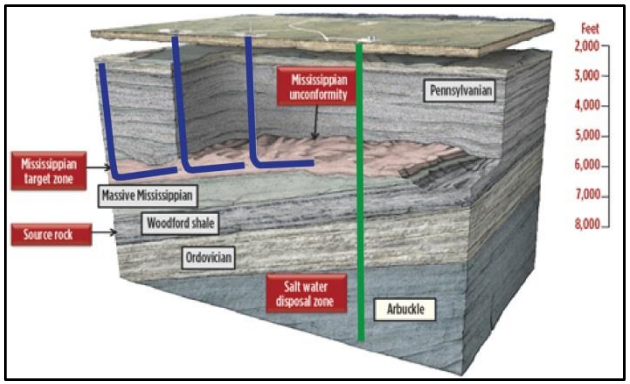
- Ancient faults can be reactivated by decreasing the effective normal stress

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



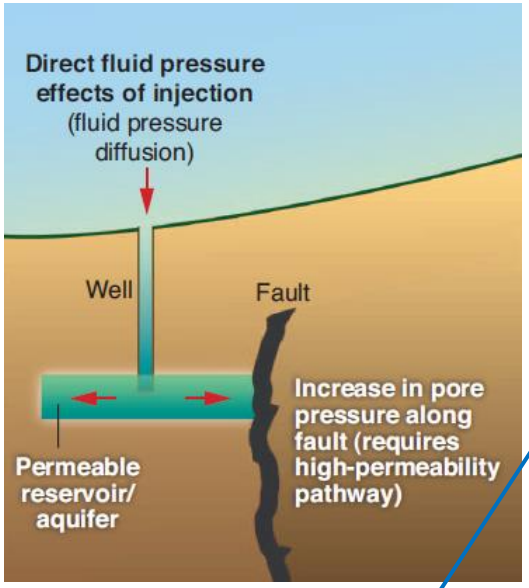
- Faults occur on a wide variety of scales and are found in virtually every geologic setting
- The Earth's crust is in a near critical failure state everywhere

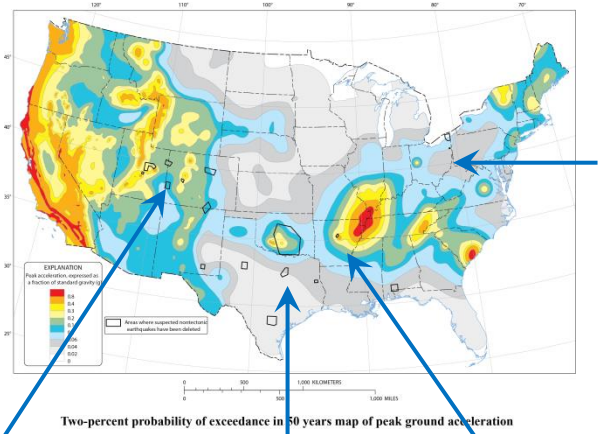
Fracking or Wastewater Disposal?



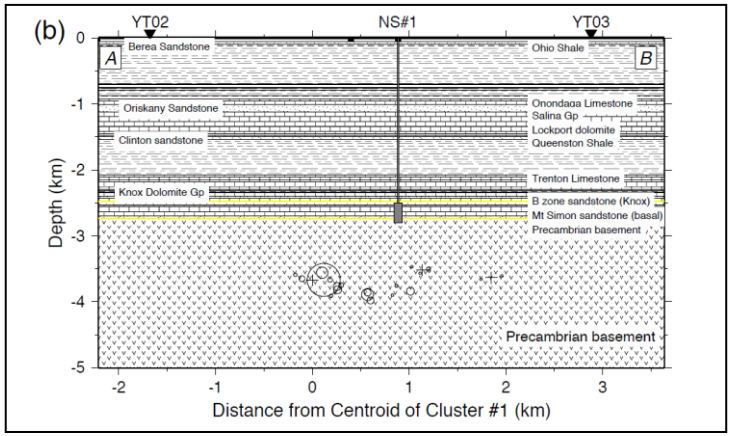
- Hundreds of thousands of frac jobs in the U.S.
- Only a handful of felt events.
- None as large as magnitude 3 have been documented in the U.S.
- M_w 4.4 in Canada

- 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 5.7
- Today's seismicity in north-central Oklahoma and southern Kansas in areas of massive wastewater injection



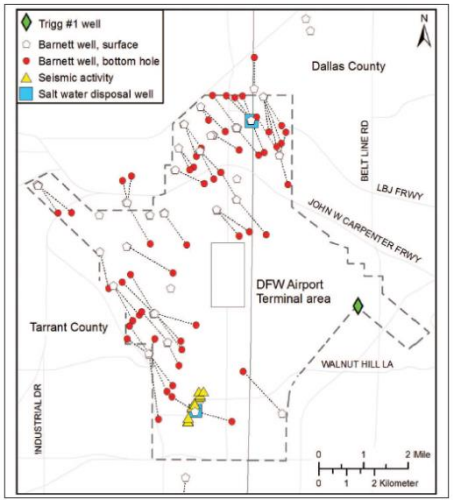


Youngstown, Ohio



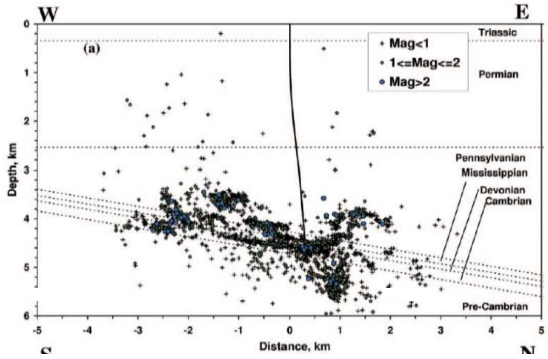
W.-Y. Kim, Induced seismicity associated with fluid injection into a deep well in Youngstown, Ohio. J. Geophys. Res. 10.1002/jgrb.50247 (2013)

DFW, Texas



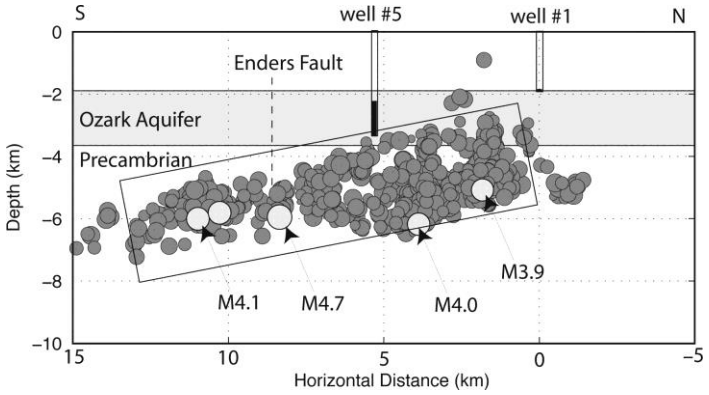
Frohlich, C., Hayward, C, Stump, B. and Potter, E., 2011, *The Dallas-Fort Worth Earthquake Sequence: October 2008 through May 2009*, Bull. Seismol Soc. Am, v. 101, 327-340.

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.

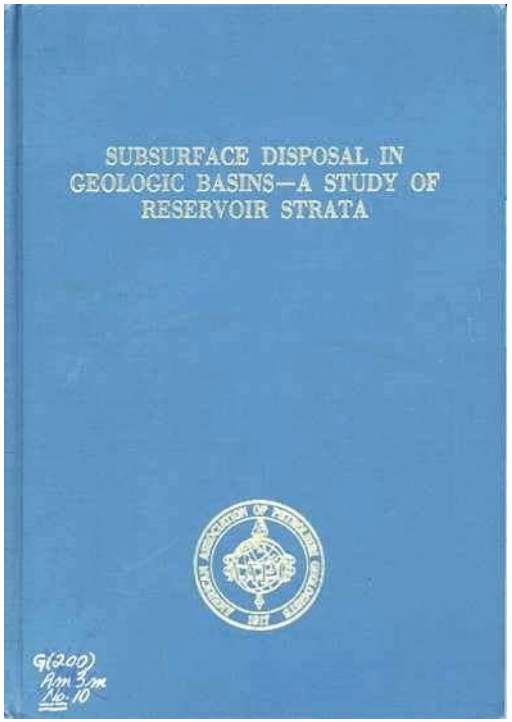
Guy, Arkansas



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.

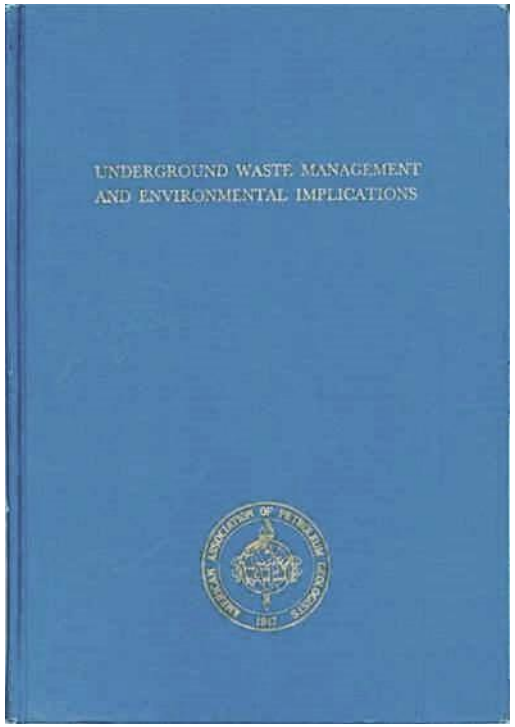
Human Induced Earthquakes
These are not new ideas

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)

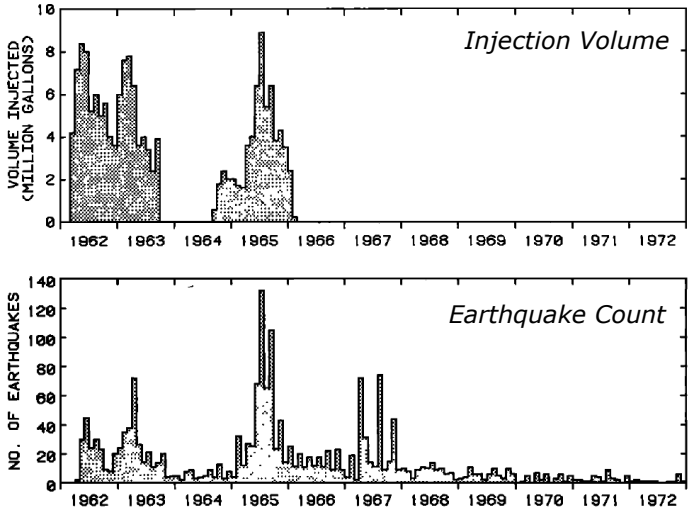


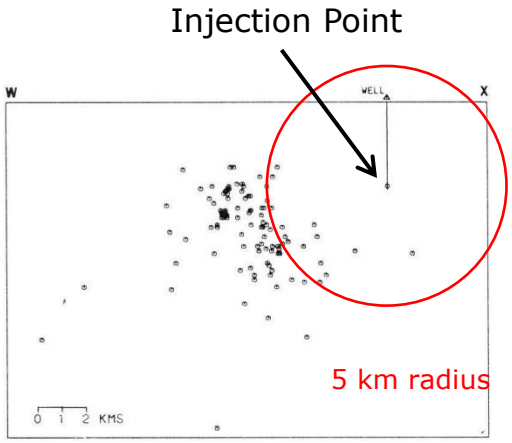
"The Denver earthquakes – and similar, less intensively studied cases in oilfields in western Colorado, Texas and Utah – have served a very good purpose in alerting us to this kind of long-term danger."

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.

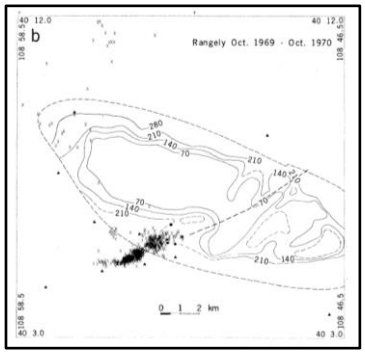




Cross Section of Earthquakes in 1967

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

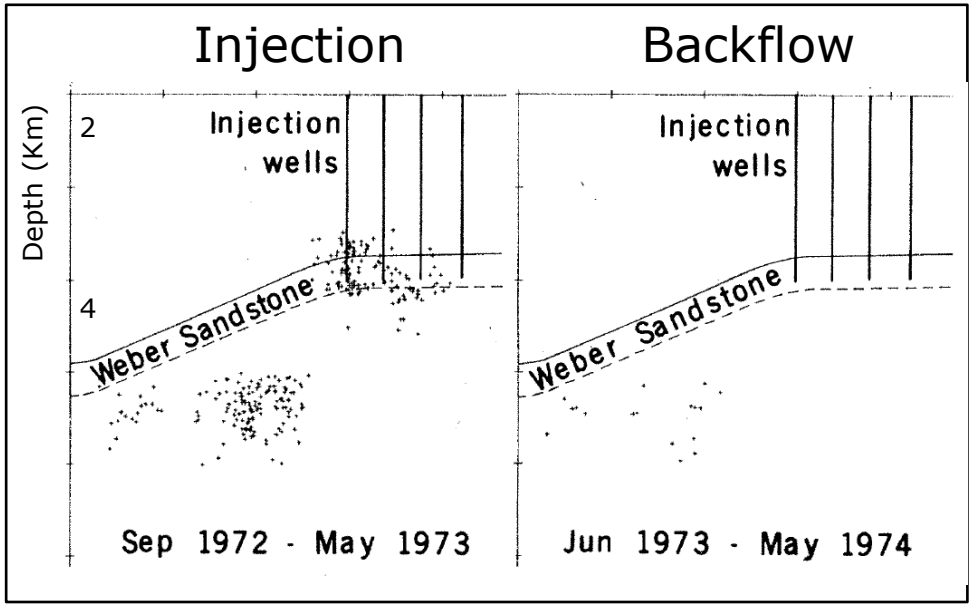


Verifying the Effective Stress Hypothesis at Rangely, Colorado

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.

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



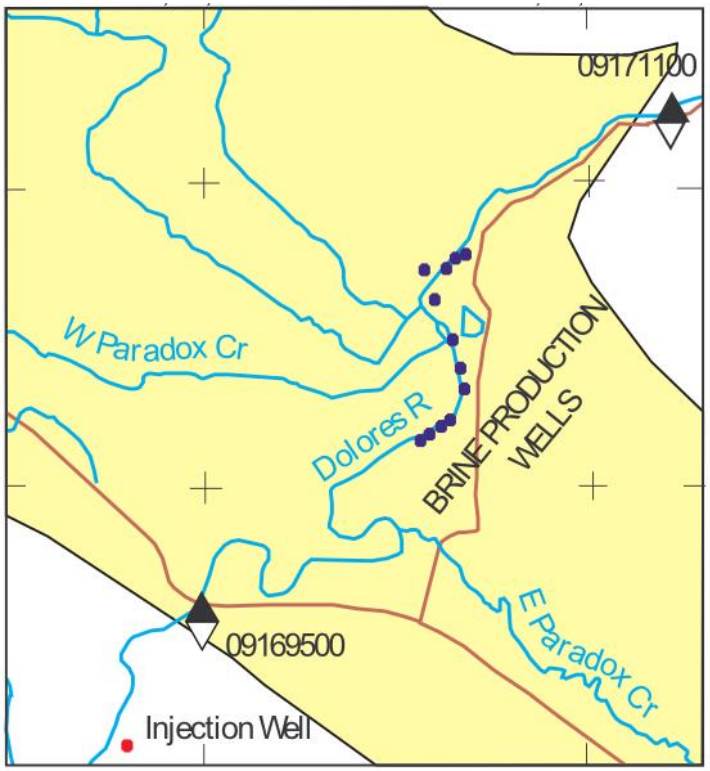
"The cessation of seismic activity within 1 day of the initiation of backflow in the experimental wells in May 1973 established the correlation between fluid pressure and earthquakes beyond a reasonable doubt."

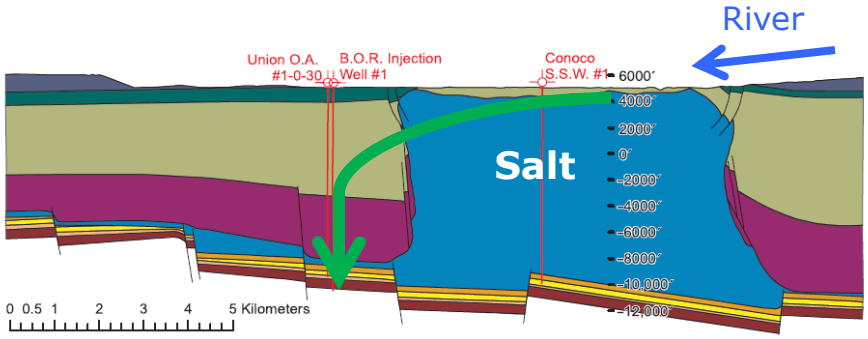
Raleigh, C.B., Healy, J.H. and Bredehoeft, J.T, 1976, *An Experiment in Earthquake Control at Rangely, Colorado; Science,* v. 191, p. 1230-1237.

U. S. Bureau of Reclamation Paradox Valley Project

Saltwater brine extracted from shallow water table below Dolores river is re-injected into limestone at 4.5 km depth

Purpose: Keep salt out of the Colorado River

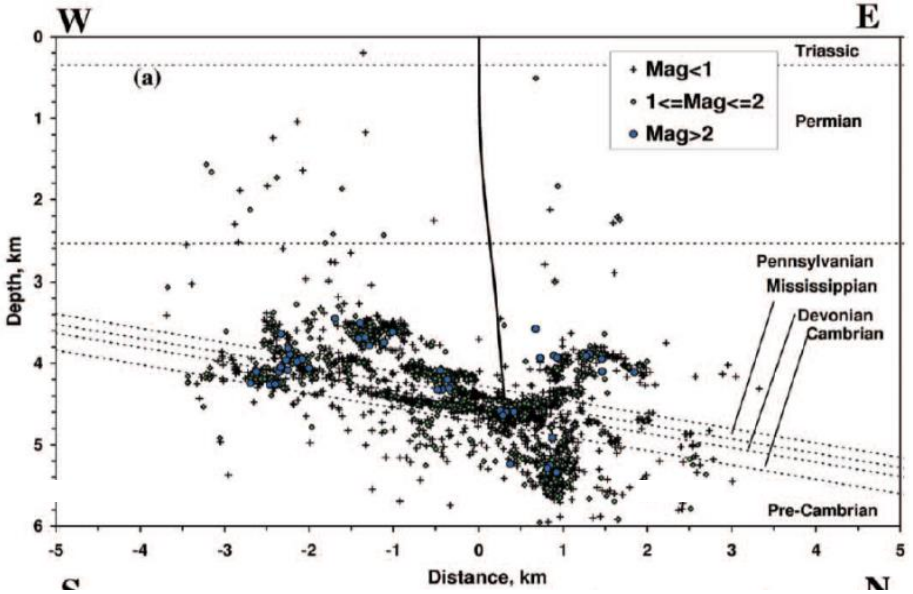




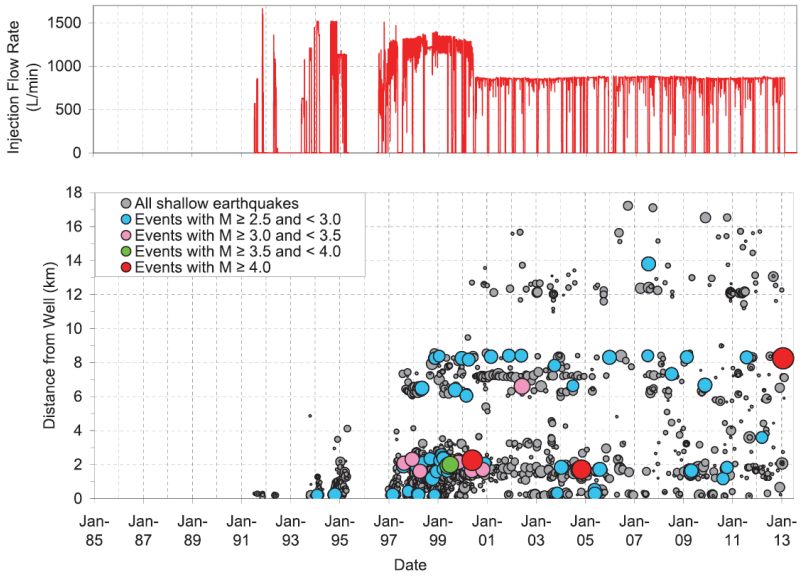
Block, L., et al., 2014, The 24 January 2013 M_L 4.4 Earthquake Near Paradox, Colorado and Its Relation to Deep Well Injection, *Seismological Res. Lett., v. 85, 609-624.*

Work of the U. S. Bureau of Reclamation Paradox Valley Unit

Injection Well



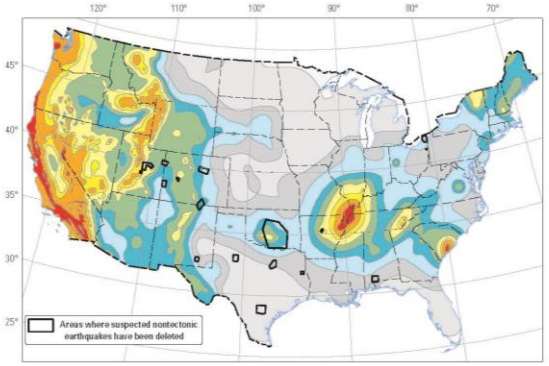
Pumping History and Seismicity



Ake, J., et al., 2005, Deep-Injection and Closely Monitored Induced Seismicity at Paradox Valley, Colorado. *Bull. Seismological Soc. Am*, v. 95, 664-683.

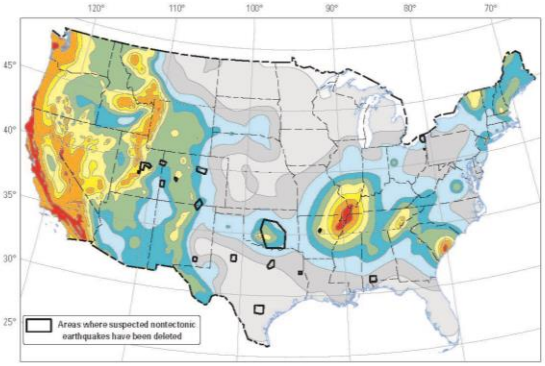
Block, L., et al., 2014, The 24 January 2013 M_L 4.4 Earthquake Near Paradox, Colorado and Its Relation to Deep Well Injection, *Seismological Res. Lett., v. 85, 609-624.*

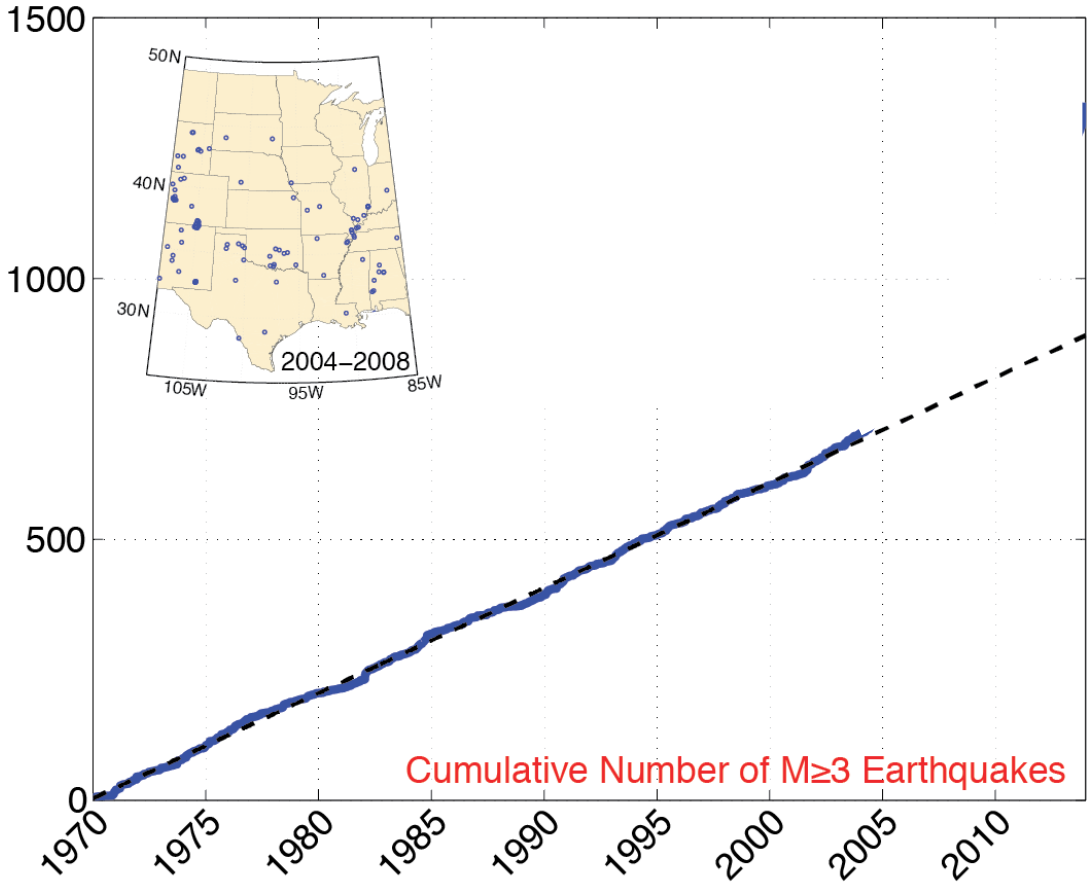
2014 National Seismic Hazard Map



- Underlies seismic design provisions of the build codes
  - Assumes time-independent rate of earthquake occurrence
  - 2% probability of exceedance in 50 years
- Based primarily on rate of small-magnitude earthquakes in the central and eastern U.S. where there are few active faults and deformation rates are near zero
- Areas with increased earthquake activity acknowledged but excluded in preparing the map

2008 Hazard Map used earthquake catalog data through 2006

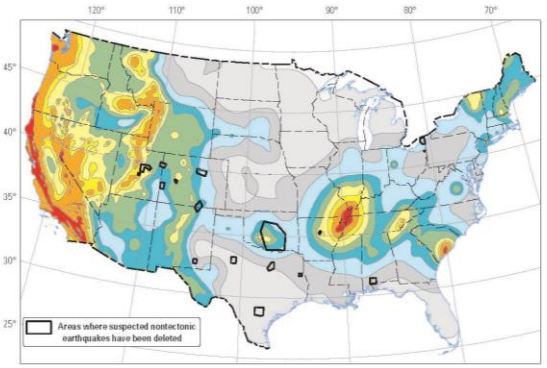


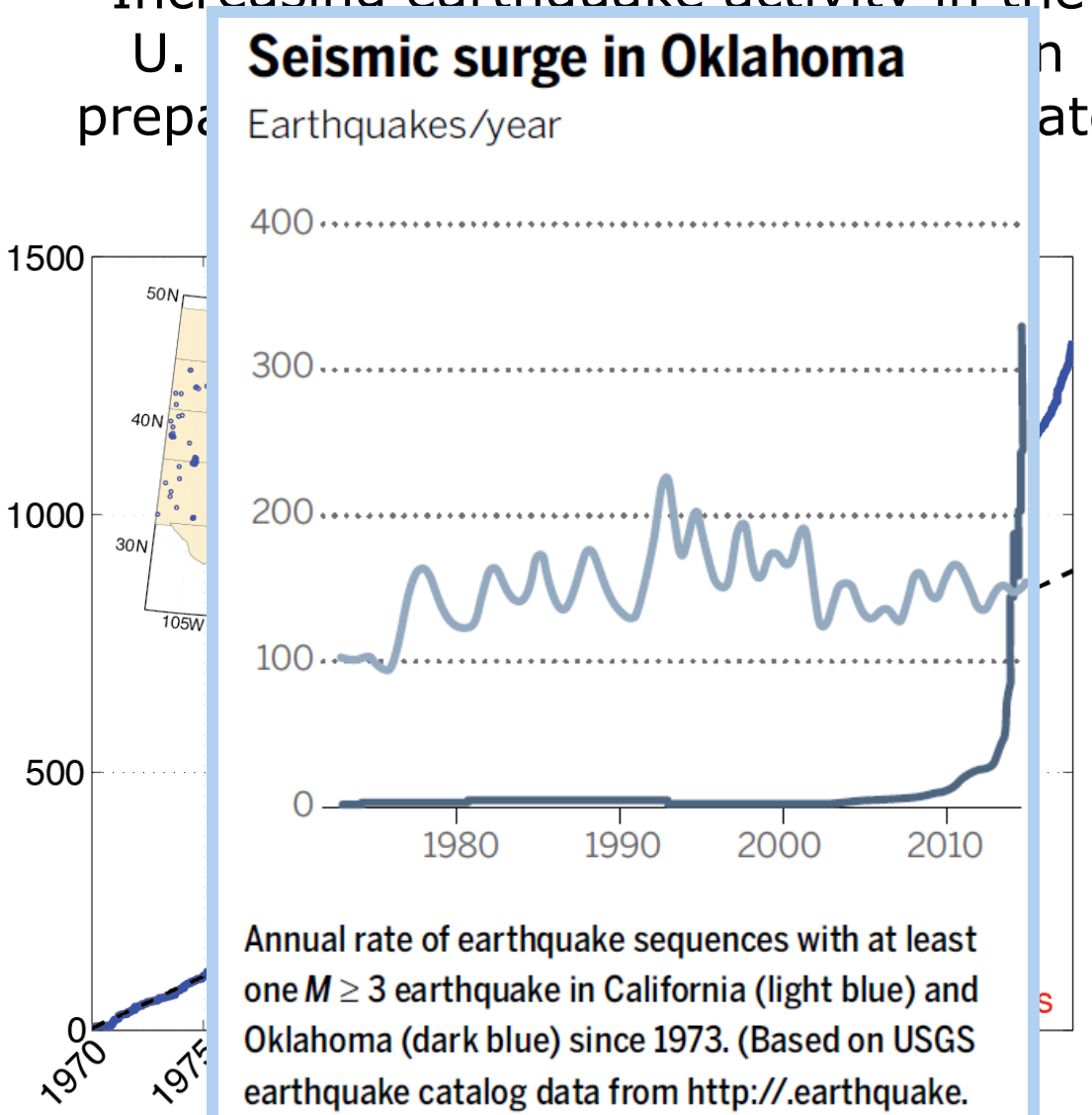


Earthquake rate modeled by a time-independent Poisson Process.

Selected areas of known or suspected induced seismicity removed from map.

Increasing earthquake activity in the U. n prepa ate





Seismic surge in Oklahoma

Earthquakes/year

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.)

Higher rate of earthquakes implies higher hazard.

But how much higher?

How long will the higher hazard last?

What types of hazard models do users want?

National Seismic Hazard Workshop on Induced Seismicity

Co-hosted by: Oklahoma Geological Survey and USGS
November 17th - 19th, 2014
Reed Center, Midwest City, Oklahoma

Consensus advice:
Develop a hazard model for the next year

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

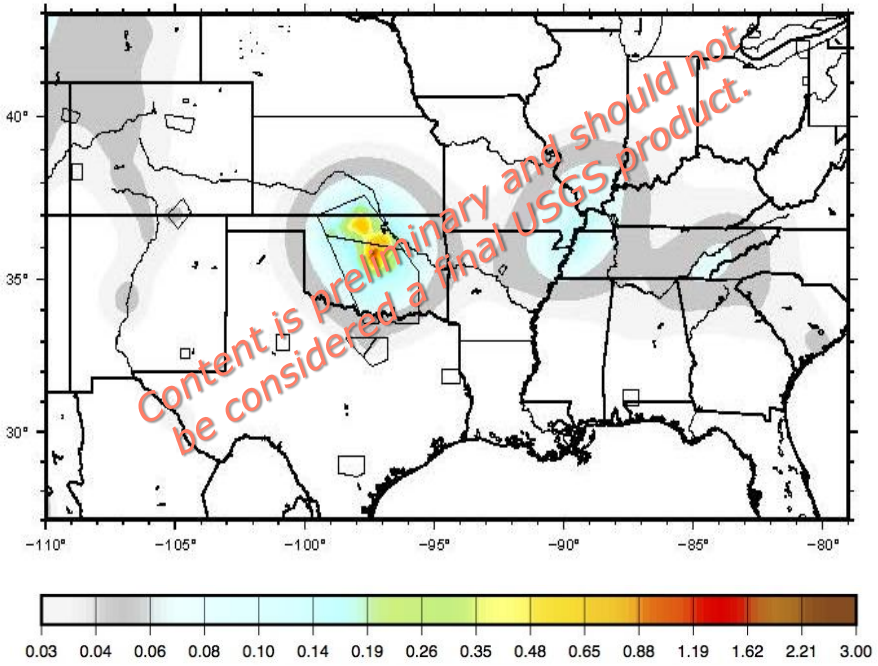
Mark D. Petersen, Charles S. Mueller, Morgan P. Moschetti, Susan M. Hoover, Justin L. Rubinstein, Andrea L. Llenos, William L. Ellsworth, Austin A. Holland, Art McGarr and John G. Anderson

Open-File Report 2015–1070

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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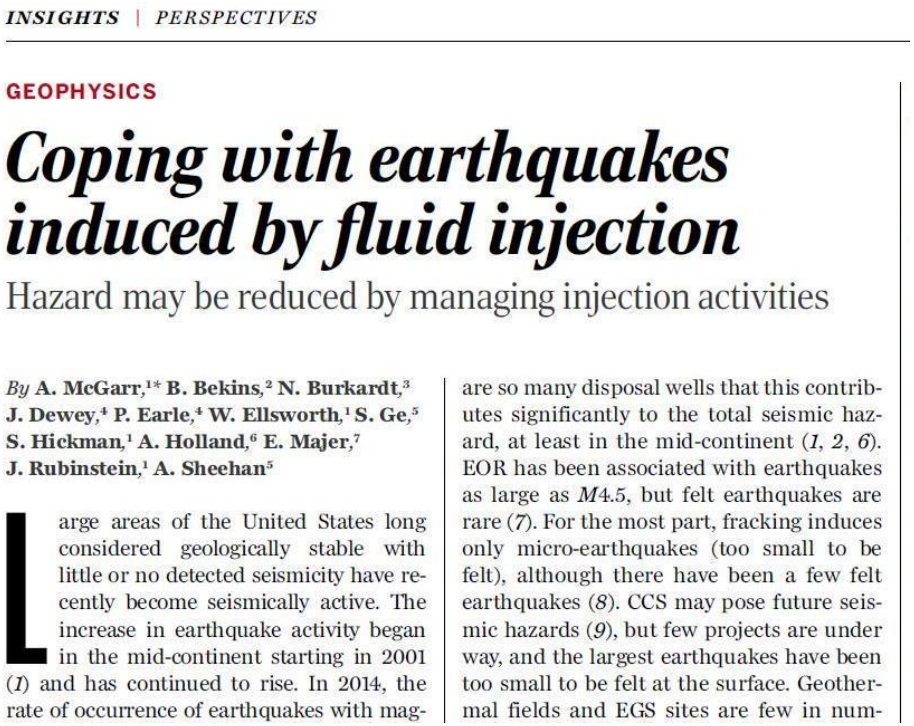
Research Agenda for Induced Seismicity

- 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



INSIGHTS | PERSPECTIVES

GEOPHYSICS

Coping with earthquakes induced by fluid injection

Hazard may be reduced by managing injection activities

By A. McGarr,[1]* B. Bekins,[2] N. Burkardt,[3] J. Dewey,[4] P. Earle,[4] W. Ellsworth,[1] S. Ge,[5] S. Hickman,[1] A. Holland,[6] E. Majer,[7] J. Rubinstein,[1] A. Sheehan[5]

Large areas of the United States long considered geologically stable with little or no detected seismicity have recently become seismically active. The increase in earthquake activity began in the mid-continent starting in 2001 (*1*) and has continued to rise. In 2014, the rate of occurrence of earthquakes with mag- are so many disposal wells that this contributes significantly to the total seismic hazard, at least in the mid-continent (*1*, *2*, *6*). EOR has been associated with earthquakes as large as *M*4.5, but felt earthquakes are rare (*7*). For the most part, fracking induces only micro-earthquakes (too small to be felt), although there have been a few felt earthquakes (*8*). CCS may pose future seismic hazards (*9*), but few projects are under way, and the largest earthquakes have been too small to be felt at the surface. Geothermal fields and EGS sites are few in num-

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/