# Induced Seismicity from Fluid Injection and Draft Best Practices
# GWPC, UIC Conference
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The Oklahoma Geological Survey is a state agency for research and public service and is charged with investigating the state's land, water, mineral, and energy resources and disseminating the results of those investigations to promote the wise use of Oklahoma's natural resources consistent with sound environmental practices.

# Outline

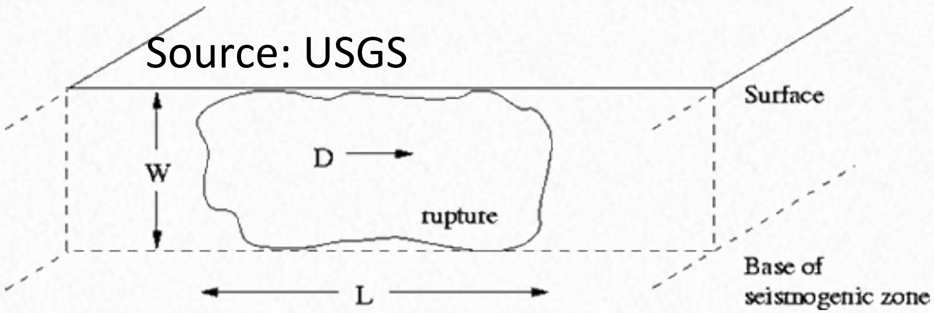
- Introduction to Triggered or Induced Seismicity
  - Resources
  - Brief background on earthquakes
- General Observations of Induced Seismicity Cases
- Draft OGS Best Practices for Fluid Injection
  - What data should we be collecting?

# Resources

- Ground Water Protection Council gwpc.org
  - A White Paper Summarizing a Special Session on Induced Seismicity (UIC Conference Jan. 2013)
  - White Paper II Summarizing a Special Session on Induced Seismicity (Annual Mtg. Sep. 2013)
- Induced Seismicity Potential in Energy Technologies (National Research Council)
- http://www.okgeosurvey1.gov/pages/research.php (Some generic and specific presentations)

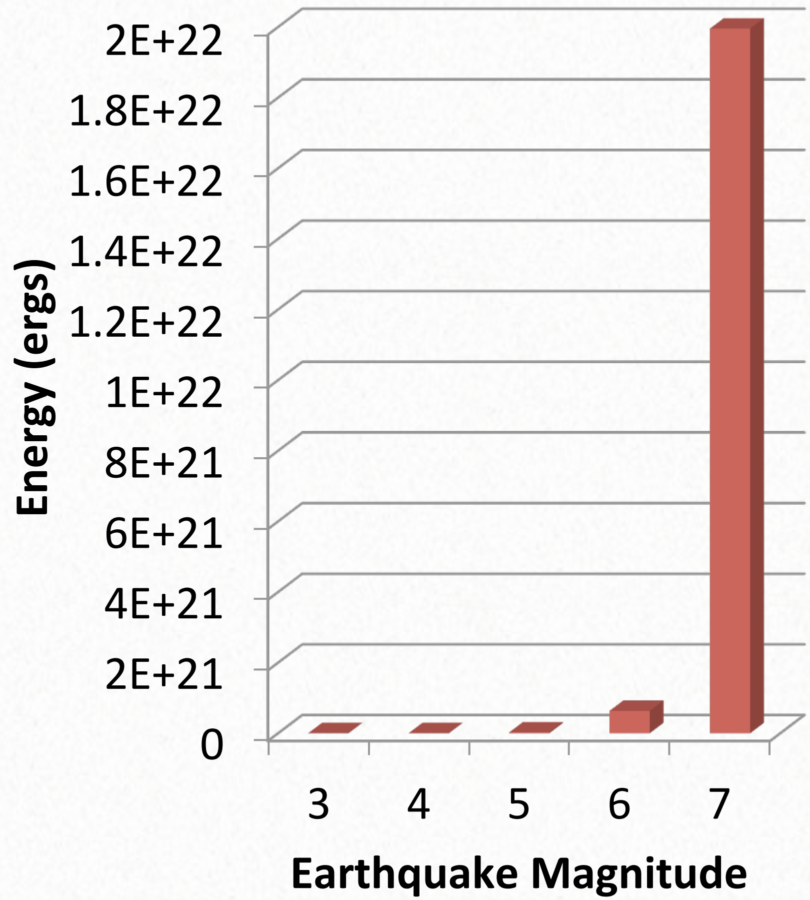
# Measuring an Earthquake: Magnitude

Source: USGS




$$M_o \propto WLD$$

- Magnitude is proportional to rupture area and slip on fault
  - Log measure of the energy released as seismic waves
  - 1 Magnitude unit is ~32 times more energy release
- Cannot be directly measured
- inferred from measurements at surface
- Magnitude estimates contain uncertainty



# Earthquake Recurrence Statistics

$$\log_{10} N = a - bM$$

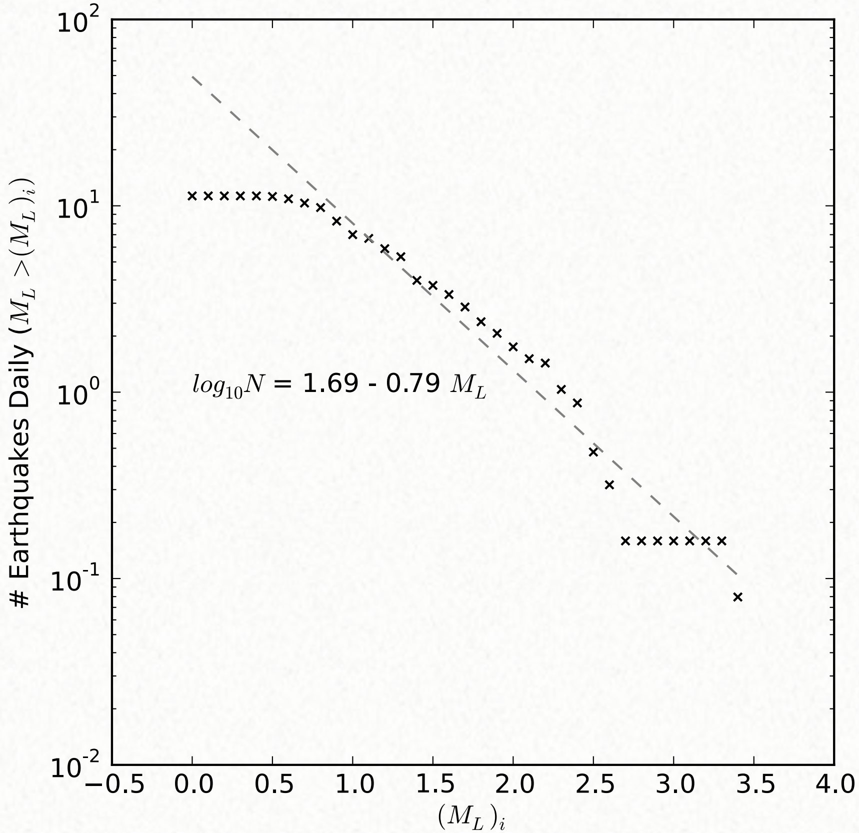
**Gutenberg-Richter Law**

N -- number of earthquakes,

M -- associated magnitude,

a -- level of earthquake occurrence (DC offset),

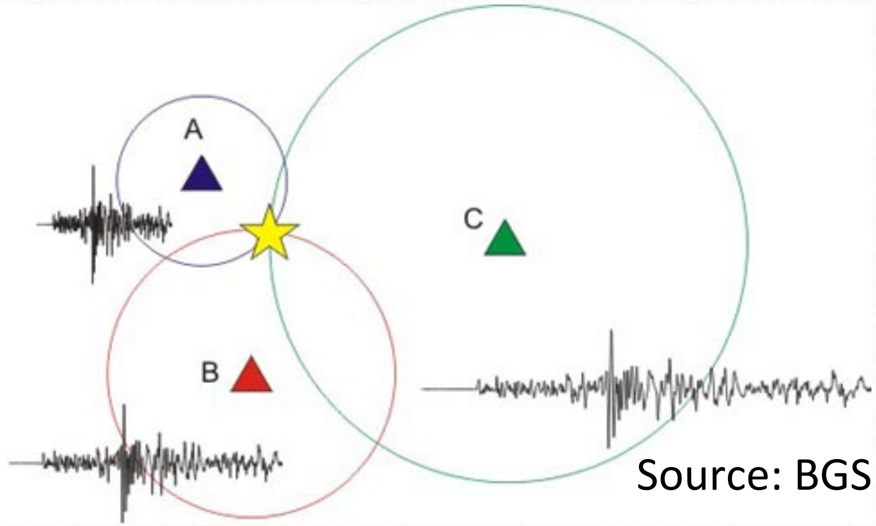
b -- relationship of number of earthquakes by magnitude




- empirically determined; b-values ~ 1 around the world
- For every magnitude 5 in a region there are ~10 magnitude 4 earthquakes
- Where relationship rolls off it indicates your detection threshold
- A represents a rate of earthquake occurrence over time
- Other models as well ETAS

# Earthquake Locations

- Earthquake locations contain uncertainty
  - Some more than others
- Factors controlling location accuracy
  - Station very near earthquake (depth)
  - How many stations are close to earthquake
  - Understanding of velocity distributions within the Earth



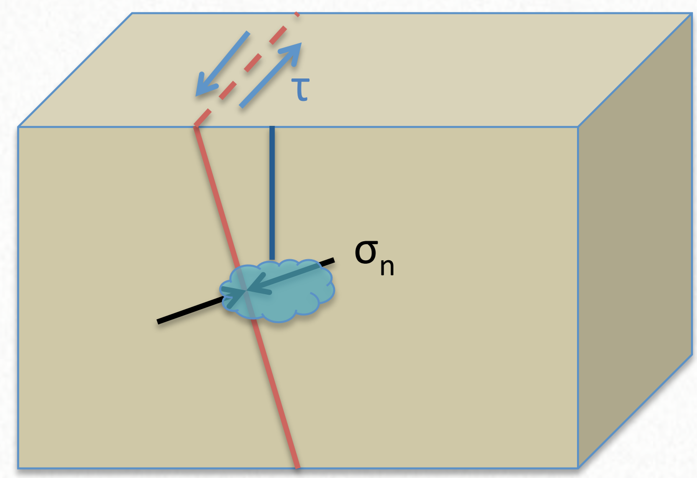

Source: BGS

Oklahoma has a good regional network (may not be adequate to assess specific cases of IS)

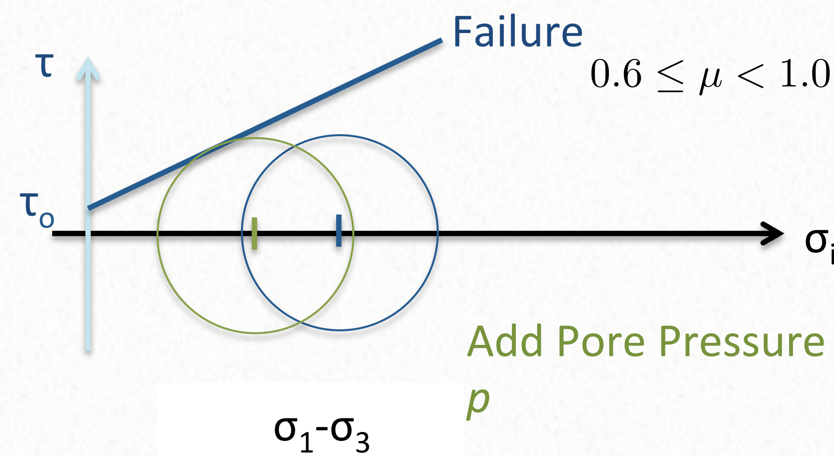
- Horizontal uncertainties are about 8 km with uncertainties .1 to 15 km
- Vertical uncertainties .1 to unconstrained

# Induced Seismicity from Fluid Injection, Diffusion of Pore-Pressure

- Increased pore pressure from fluid injection effectively reduces friction on fault
  - Or in Mohr-Coulomb space moves the circle towards failure

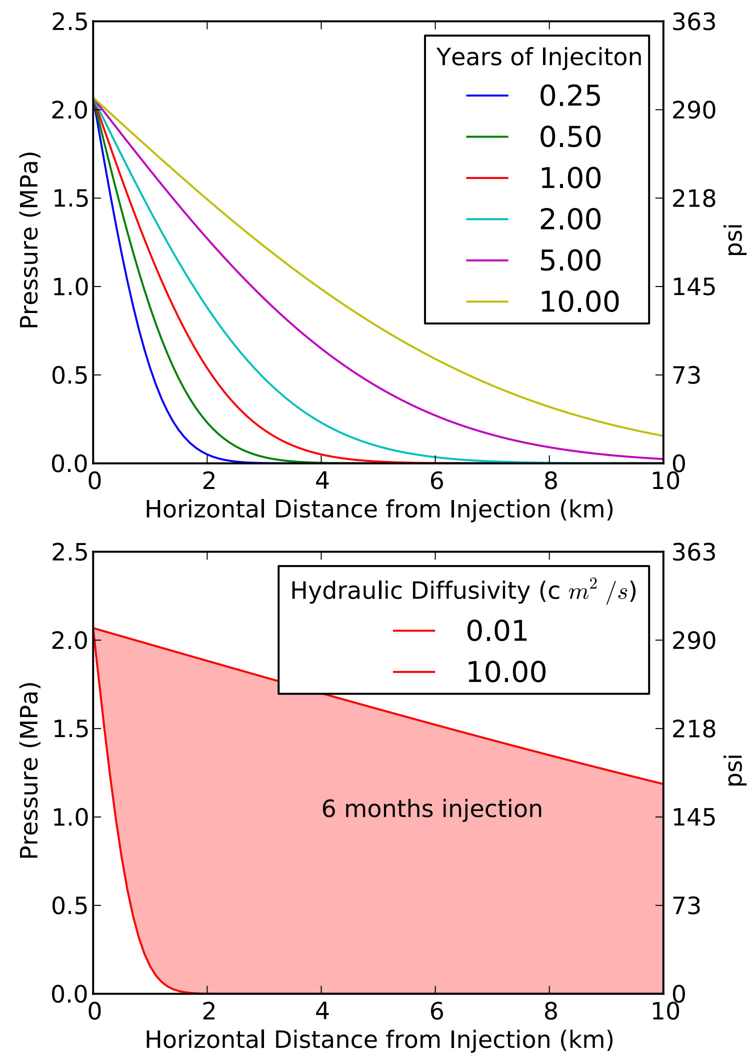



$$\tau_{crit} = \tau_o + \mu(\sigma_n - p)$$



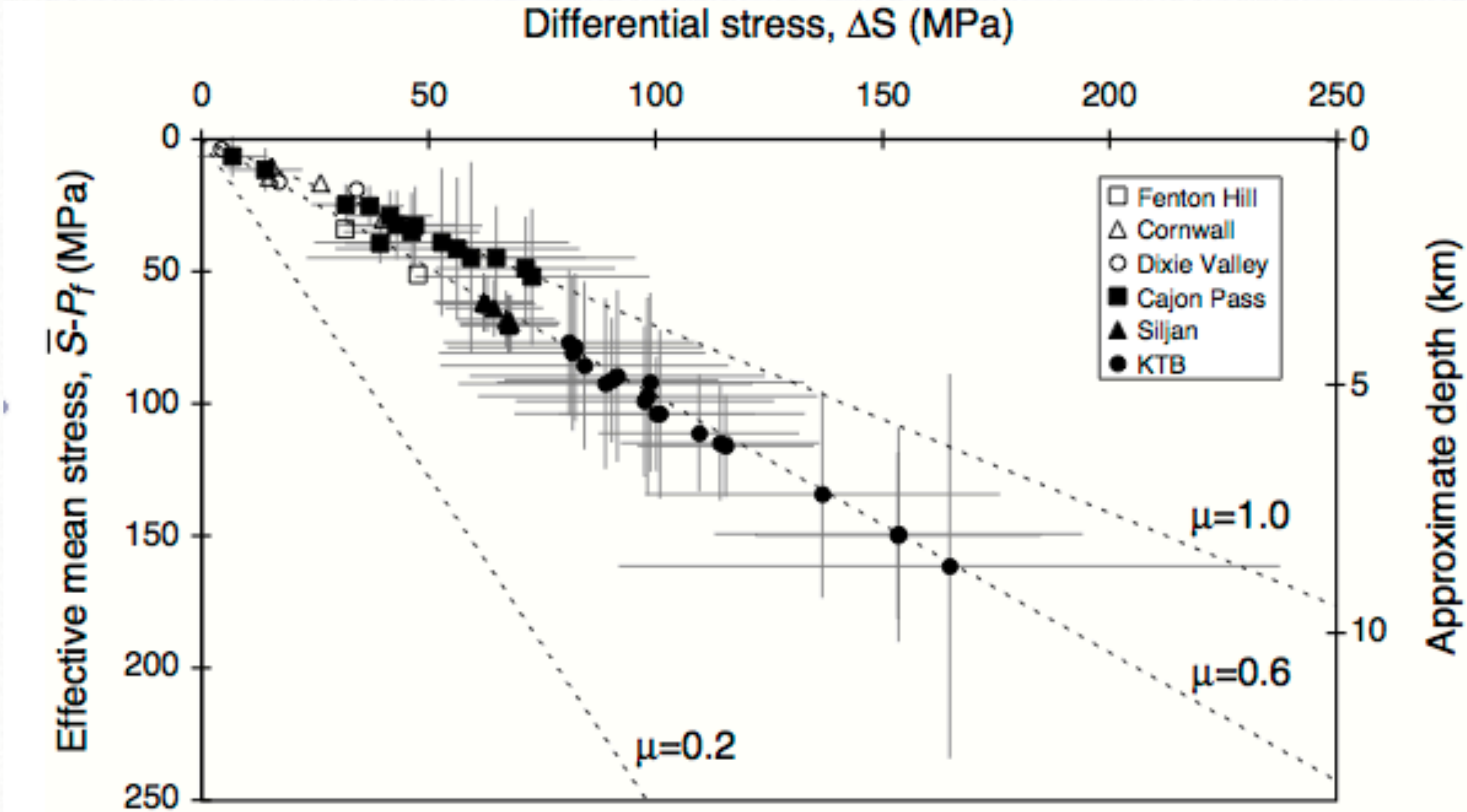
# Pressure Diffuses Within the Earth

- Pressure increase is not due to actual fluid flow
- Pressure increases over time
- Can be much more rapid
- Because water is fairly incompressible it is similar to an elastic response although slower
- Proportional to permeability



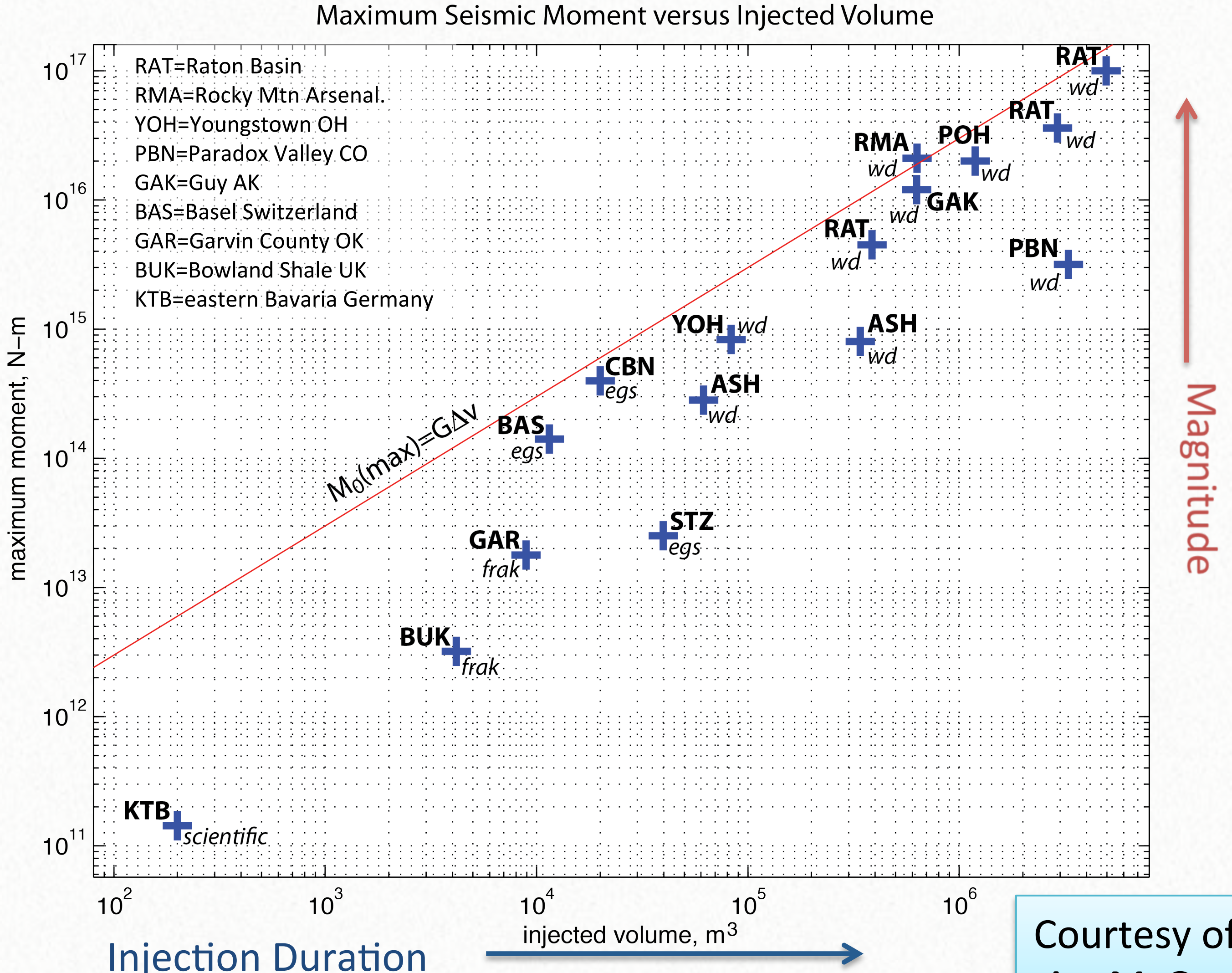

Talwani et al. (2007) J. Geophys Res.

# Most of the Earth's brittle crust is near failure




Townend & Zoback (2000) Geology; Zoback et al. (2002) International Geol. Rev.

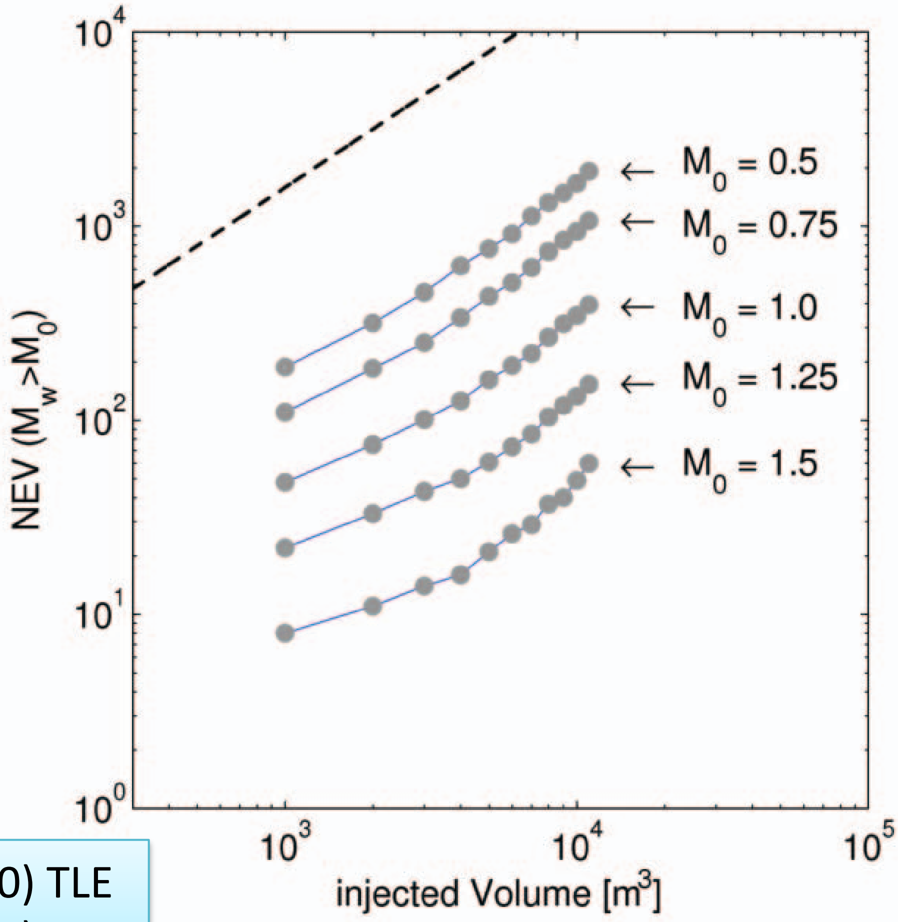
# Earthquake magnitude may scale with injected volume




Courtesy of:
Art McGarr (USGS)

# Magnitude evolution with injected volume

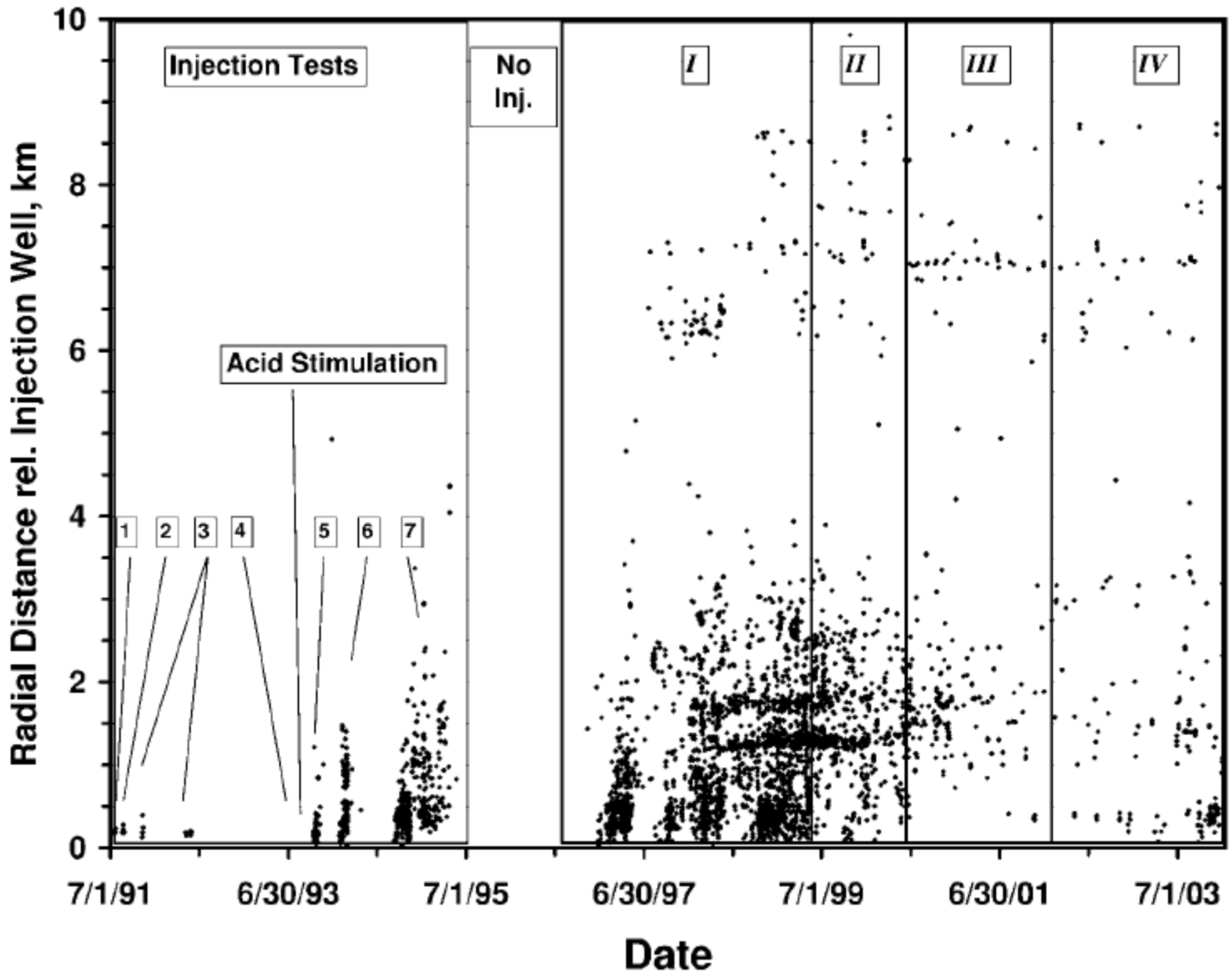
- Number of larger induced earthquakes may increase with continued injection
- This has been observed in a number of induced seismicity cases




Shapiro et al. (2010) TLE
Shapiro et al. (2007) GRL

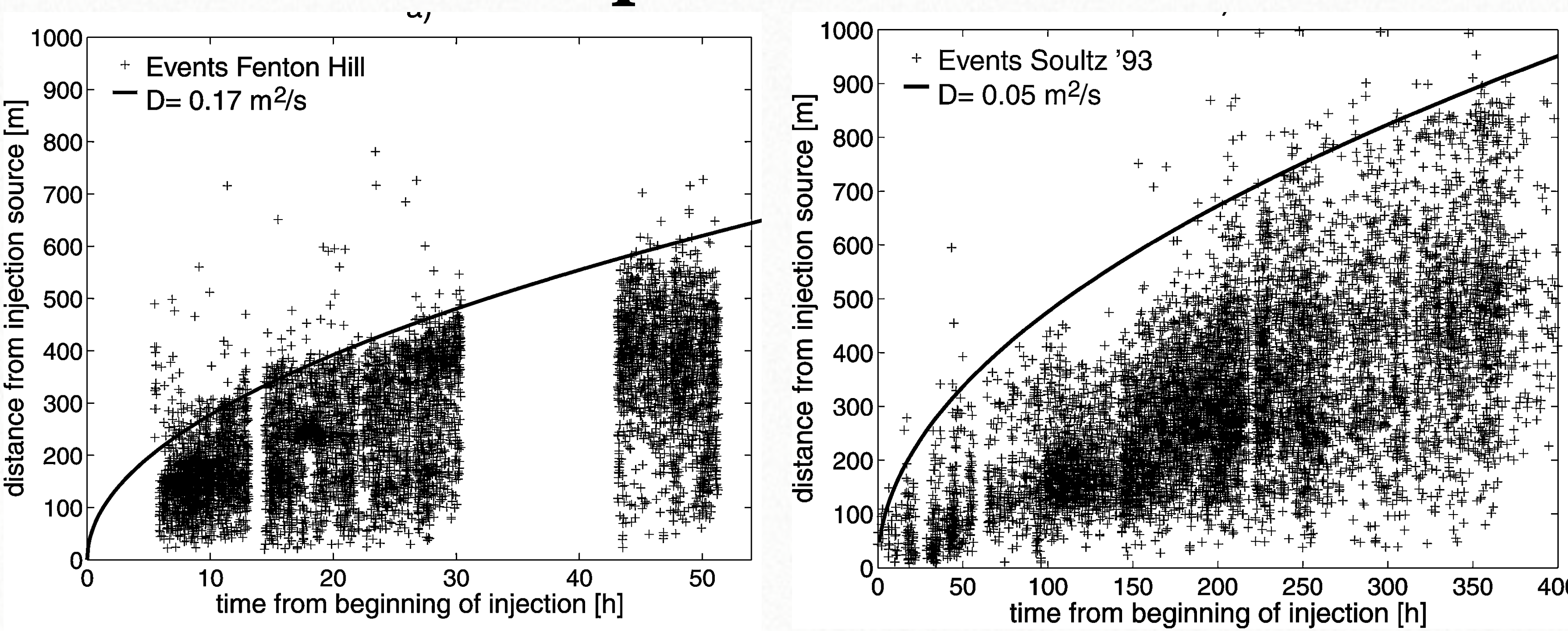
# Earthquakes may start close to the well and migrate away

- Pressure diffusion is often modeled using this observation
- Most of the earthquakes still tend to occur very near the injection interval




Paradox Valley, Ake et al. (2005)

# Pore Pressure Diffusion Model for Earthquake Locations

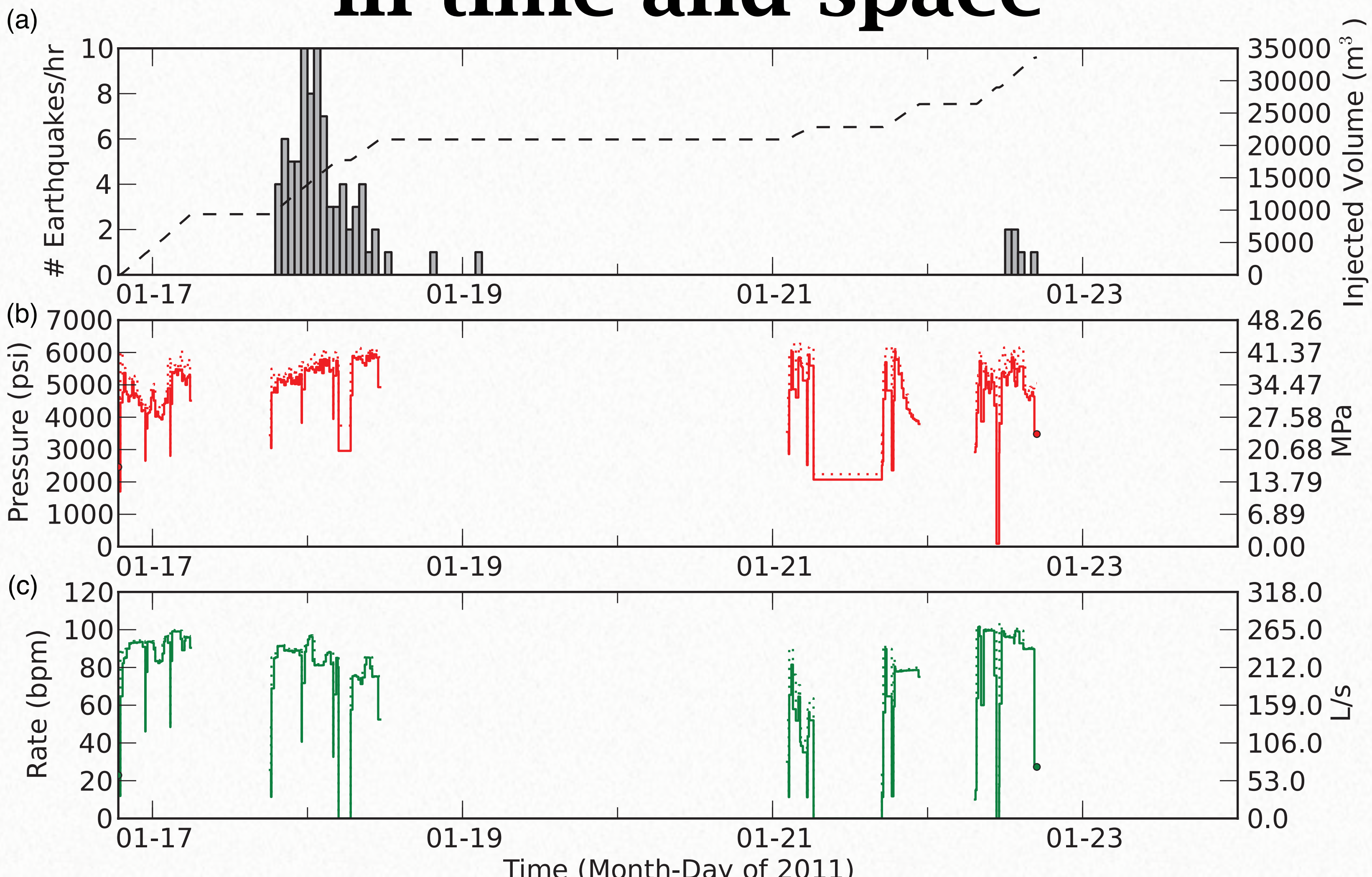



Earthquakes may continue and even get larger after injection ceases

- e.g. Rocky Mountain Arsenal Hsieh & Bredehoeft (1981) JGR

Shapiro et al. (2003) Geophysics

# IS often identified by correlations in time and space




Holland, Bull. Seismol. Soc. Amer. (2013)

# Temporal correlations are common amongst classic cases of IS

Rangely, Raleigh et al. (1976)

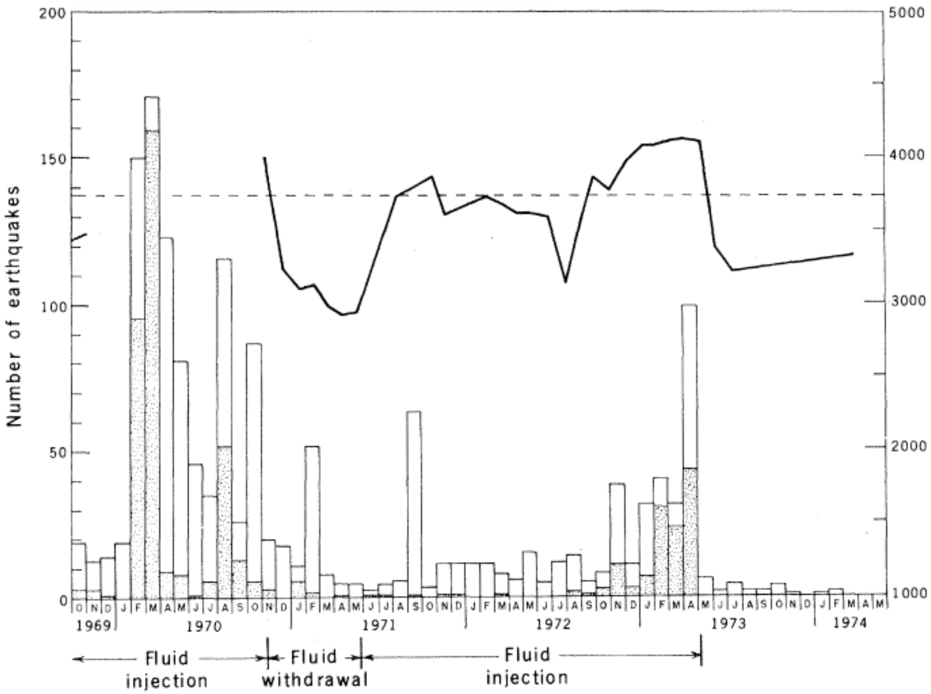
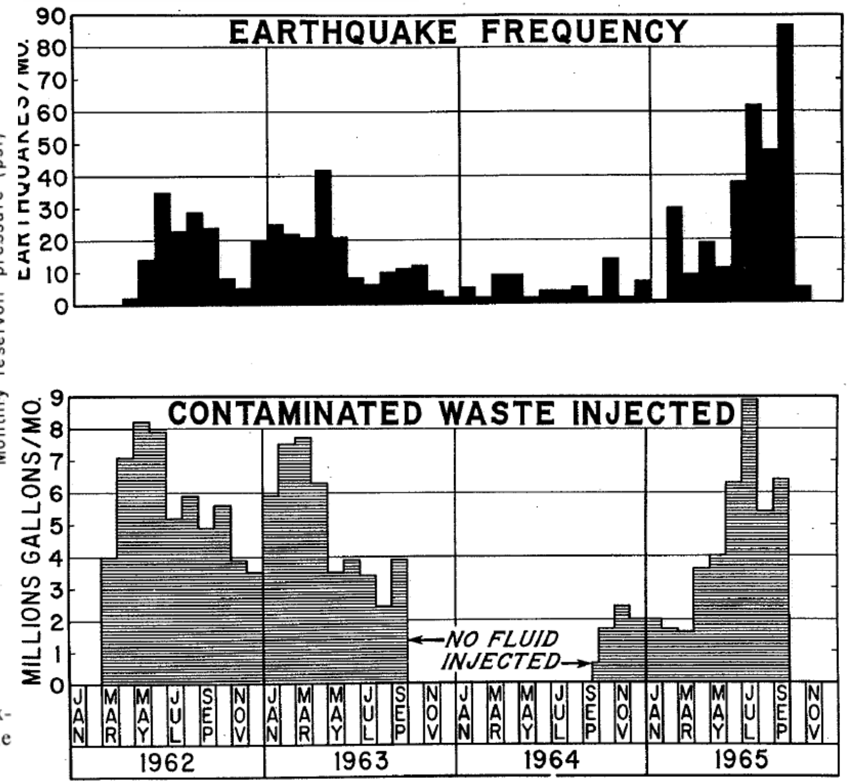



Fig. 7. Frequency of earthquakes at Rangely. Stippled bars indicate earthquakes within 1 km of experimental wells. The clear areas indicate all others. Pressure history in well Fee 69 is shown by the heavy line; predicted critical pressure is shown by the dashed line.

RMA, Healy et al. (1968)



# Well known risk factors for induced seismicity

- Proximity to known faults
  - Especially those favorably oriented within the existing stress field
  - Past seismicity indicates critical stresses and generally favorably oriented faults
- Existing state of stress and pore pressure in the reservoir
- Injection volumes and pressures
  - High volumes increase the potential for large earthquakes
  - High pressures increase the likelihood of having induced seismicity even if it is tiny
    - e.g. microseismic from hydraulic fracturing
- These observations and more guide the development of best practices

# Introduction to OGS Draft Best Practices

- It is for operators or regulators to decide what level of risk is acceptable.
- Within an established risk level, non-specific terms such as “frequent” and “near” can be more precisely defined.
- These recommendations are general and based on current understanding of the causes of induced seismicity.
- Currently finalizing draft due out this fall for comment

Best practice items will be denoted as:

- **1. Don’t finish your round of golf in a lighting storm.**

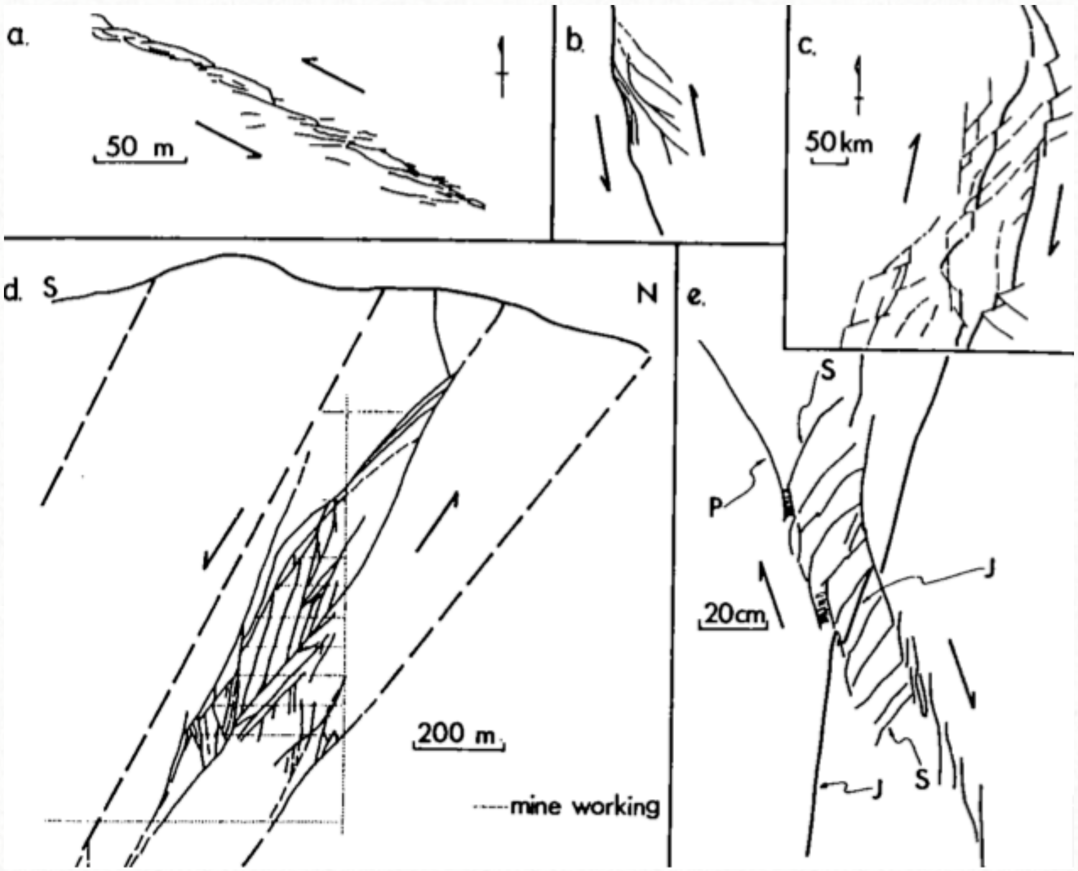
# Proximity to faults

- **1. Fluid injection near known faults should be avoided**
  – Faults and asperities (fault roughness) within faults act as stress concentrators, fault branches also act as stress concentrators
  – Faults can act as both permeability barriers as well as high permeability zones (highly dependent on fault properties)
  – Highly permeable zones can channel the diffusion of pore pressure significantly large distances
  – Fluid pressure may build near an injection well (does not require injection under pressure, hydraulic head)
- **2. Fluid injection wells should be sited further from faults that are favorably oriented within either the regional or local stress field**

Zoback (April 2012) Earth magazine, and many others

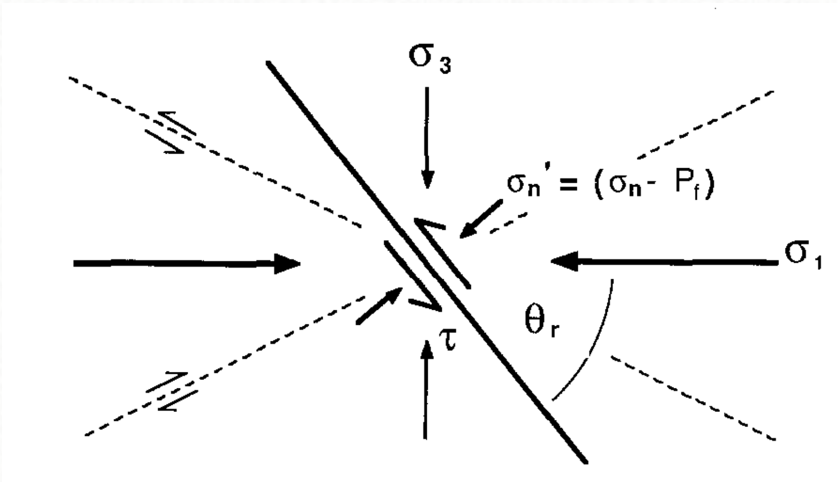
# Are all faults created equal?

- Large faults may lead to large earthquakes
- Faults at all sizes show great complexity at all subsequent scales
- Makes identifying all optimally oriented faults problematic



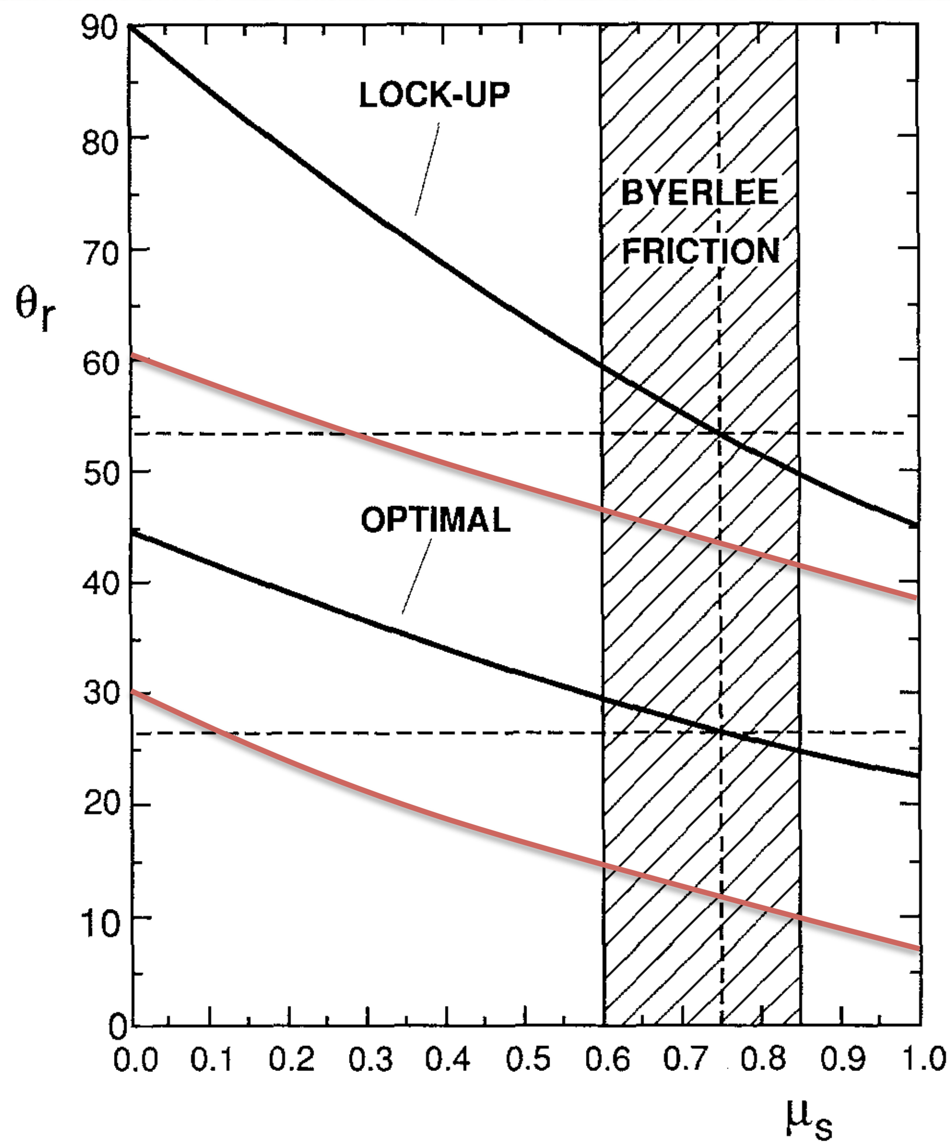

Scholz (1990)

# Optimal Fault Orientations




Sibson (1990) Bull. Seismol. Soc. Am.

- Red lines indicate the range of possible orientations aligned within the regional stress field.
- Fault slip outside of this region is unlikely but possible with very dramatic increases in pore pressure.



# Monitoring of injection and formation pressure response to injection

- **3. Injection pressure and volume should be monitored and recorded frequently during the operation of the well.**
  - Monthly injection information will likely not accurately represent the injection history of the well
  - Inadequate for detailed reservoir modeling
- **4. Formation pressure should be monitored as often as practical. However, at a minimum, regular shut in, pressure fall-off tests should be conducted to measure formation pressure.**
  - This monitoring may help identify when and how fluid injection is altering properties within the formation
- Has the potential to improve performance of an injection well
- May help to identify or discount potential induced seismicity

# Injection into or near basement

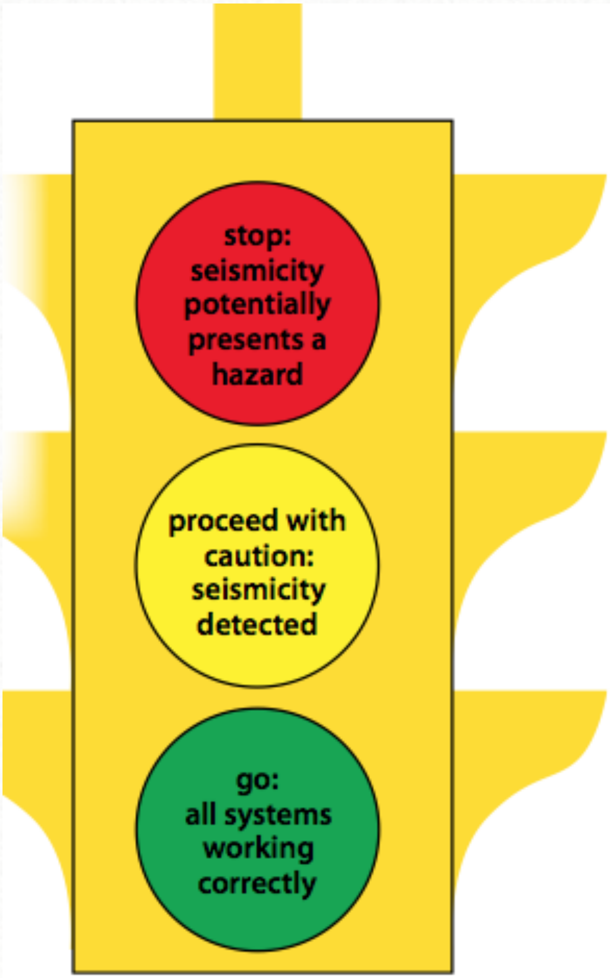
- **5. Injection into crystalline basement should be avoided.**
  - Permeability in crystalline basement is generally low
  - Fluid and pore pressure may concentrate in networks of existing natural fractures and faults where permeability is the greatest
  - Permeability barriers or spatial inhomogeneity can lead to increased stress

# Additional Monitoring in Higher Risk Environments

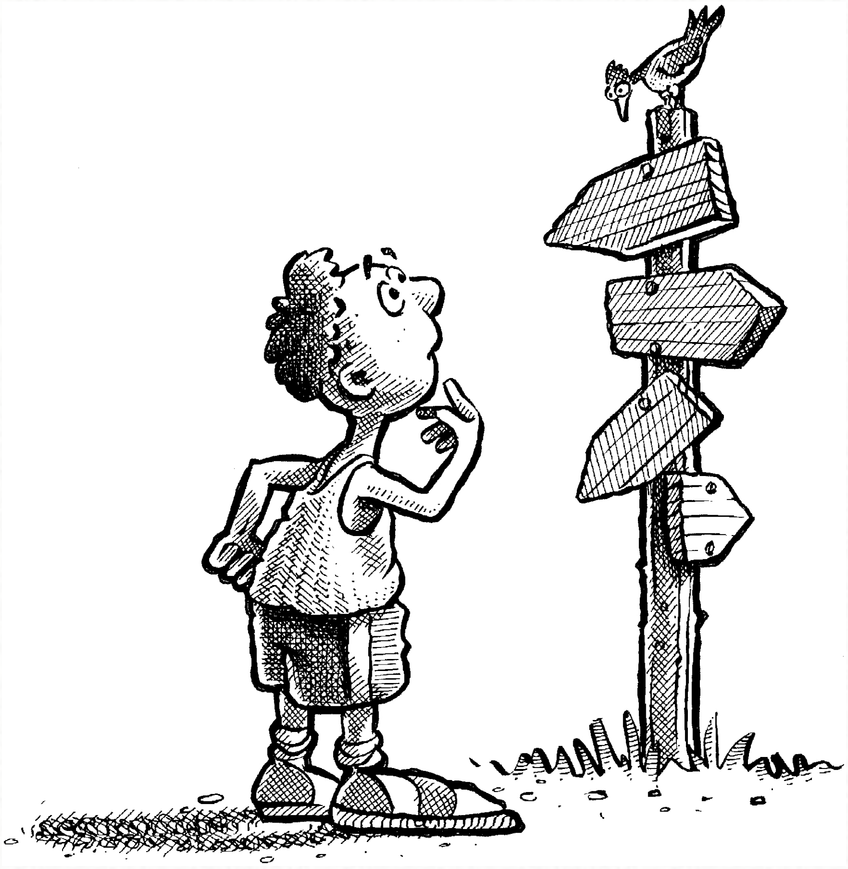
- **7. The siting of new injection wells in higher risk environments should be approached with caution.**
  - More frequent monitoring of injected volume, injection pressure, and formation pressure is recommended, as well as additional earthquake monitoring.
- **8. In cases where fluid injection is occurring in higher risk environments, additional geotechnical information may help to provide further constraints on injection limits.**
  - Mini-fracs and image logs can provide the orientation and magnitude of stresses as well as the orientation of natural fractures and can help to address the potential for triggered seismicity.

# Response to Potentially Induced Seismicity

- **9. The operator should have a plan in place to recognize and respond in a timely manner to unexpected seismicity or changes in injection pressure or volume.**
- Modifications to injection parameters
- Additional monitoring
- Identify prior to operations what levels of seismicity will generate actions within a response plan




Zoback (April 2012) Earth magazine



# Questions or Comments?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# Induced Seismicity from Fluid Injection and Draft Best Practices

Induced seismicity from fluid injection has become a greater concern over the past few years with a significant number of new possible cases and growing public and political concern. These observations and a number of potential cases of induced seismicity in Oklahoma have caused the Oklahoma Geological Survey to develop a draft set of best practices regarding fluid injection induced seismicity. These best practices are generally designed to be quite broad and allow those implementing the best practices to define these generic terms for a given level of risk. The best practices are based off of observations from previous well-documented cases of induced seismicity and the physics behind induced seismicity. The causes of induced seismicity are generally well known and include either the diffusion of pore pressure or altering the stresses within the subsurface. These stress changes or pore pressure changes interact with naturally occurring stressed faults or fractures to trigger earthquakes. We will look at the proposed best practices in regards to relative risk and observations from published literature. Well-known risk factors for injection induced seismicity include proximity to known faults, especially those already critically stressed, existing state of stress and pore pressure within the reservoir, and high injection pressures or volumes.