West Coast Regional Carbon Sequestration Partnership
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WESTCARB Regional Partnership

Understanding and Managing the Potential for Induced Seismicity in CO_2 Storage Projects

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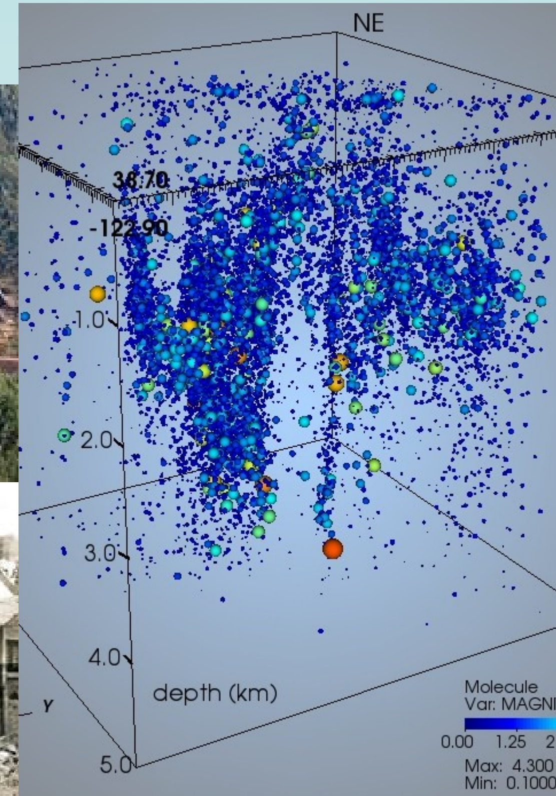
Outline

- Introduction
- Some observations, general characteristics of induced seismicity
- Managing the risks of induced seismicity
- Some remaining questions
- Summary

Induced Seismicity is Common in Subsurface Activities

- Seismicity has been associated with reservoir impoundment, mining, fluid injection
- Characteristically many more small events than large ones; once in awhile a large one has occurred.
- Seismicity not all bad – useful for imaging subsurface

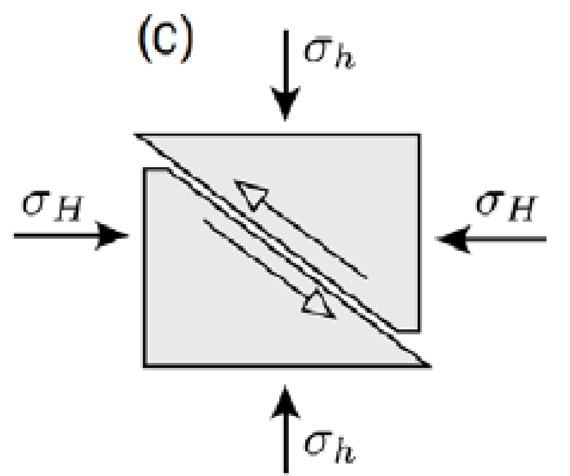
Koyna reservoir dam, India, (above) and damage from 1967 M6.5 earthquake (below) (www.indianetzone.com and www.timescontent.com)



Seismicity at Geysers geothermal area (courtesy E Majer, LBNL)

Causal Mechanisms

- Earthquakes (fault slip) occur when the shear stress along a fault is greater than the strength of the fault.
- Induced or triggered earthquakes occur when human activity causes changes in stresses within the Earth that are sufficient to produce slip.
- This can result from:
  - An increase in shear stress along the fault
  - A decrease in strength of the fault
  - Decrease the normal stress across the fault
  - Increase the pore pressure within the fault
  - Decrease in cohesion on fault
  - Thermal stresses

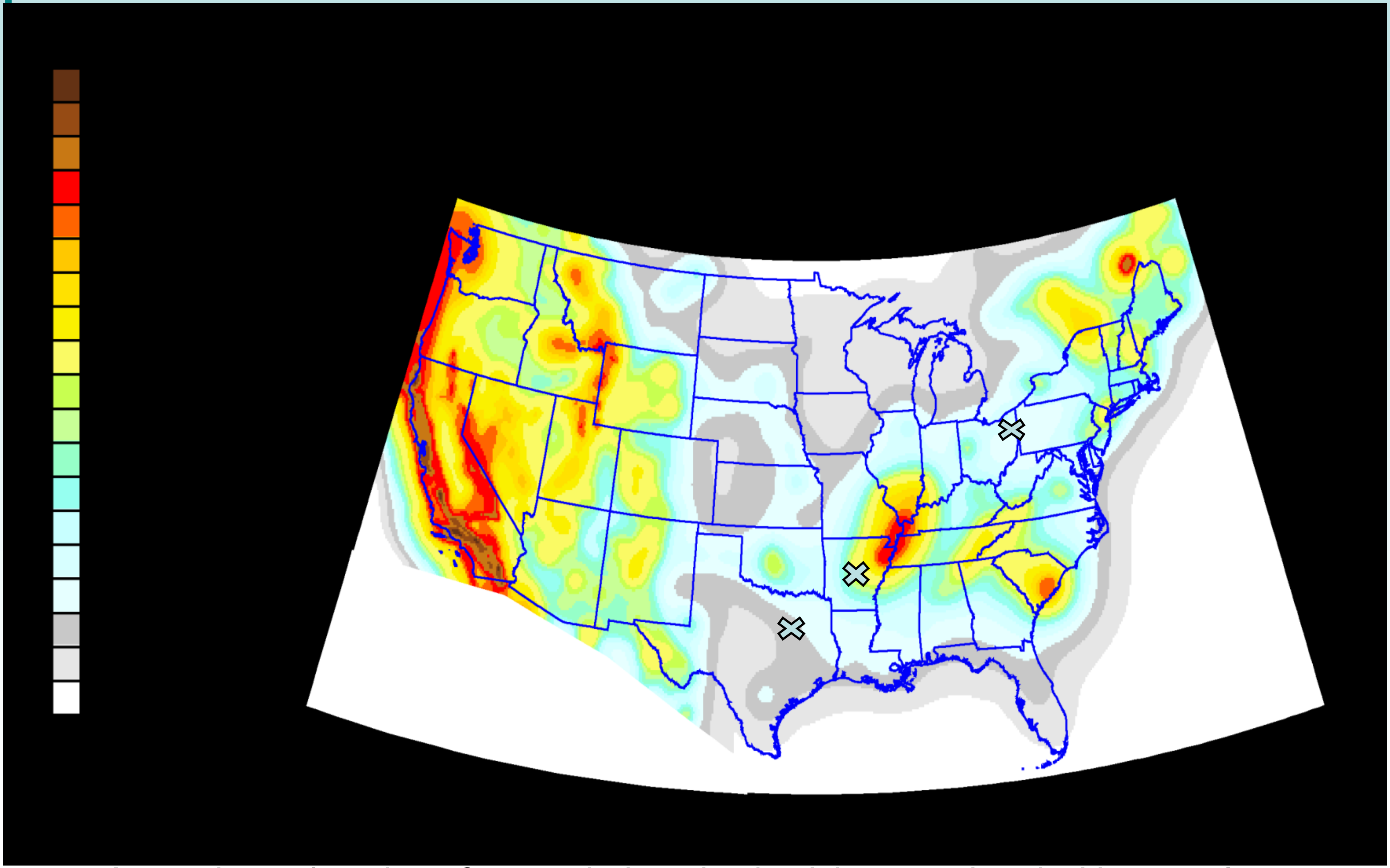


Historical Data: "Felt-Earthquakes" "Likely" Related to Energy Technologies in US

Energy technology	Number of Projects	Number of Felt Induced Events	Maximum Magnitude of Felt Events	Number of Events M≥4.0[d]	Net Reservoir Pressure Change	Mechanism for Induced Seismicity	Location of M≥2.0 Events
Vapor-dominated geothermal	1	300-400 per year since 2005	4.6	1 to 3 per year	Attempt to maintain balance	Temperature change between injectate and reservoir	CA (The Geysers)
Liquid-dominated geothermal	23	10-40 per year	4.1[b]	Possibly one	Attempt to maintain balance	Pore pressure increase	CA
Enhanced geothermal systems	~8 pilot projects	2-10 per year	2.6	0	Attempt to maintain balance	Pore pressure increase and cooling	CA, NV
Secondary oil and gas recovery (waterflooding)	~108,000 (wells)	One or more events at 18 sites across the country	4.9	3	Attempt to maintain balance	Pore pressure increase	AL, CA, CO, MS, OK, TX
Tertiary oil and gas recovery (EOR)	~13,000	None known	None known	0	Attempt to maintain balance	Pore pressure increase (likely mechanism)	None known
Hydraulic fracturing for shale gas production	35,000 wells total	1	2.8	0	Initial positive; then withdraw	Pore pressure increase	OK
Hydrocarbon withdrawal	~6,000 fields	20 sites	6.5	5	Withdrawal	Pore pressure decrease	CA, IL, NB, OK, TX
Waste water disposal wells	~30,000	8	4.8[c]	7	Addition	Pore pressure increase	AR, CO, OH
Carbon capture and storage, small scale	1	None known	None known	0	Addition	Pore pressure increase	IL
Carbon capture and storage, large scale	0	None	None	0	Addition	Pore pressure increase	None yet in operation

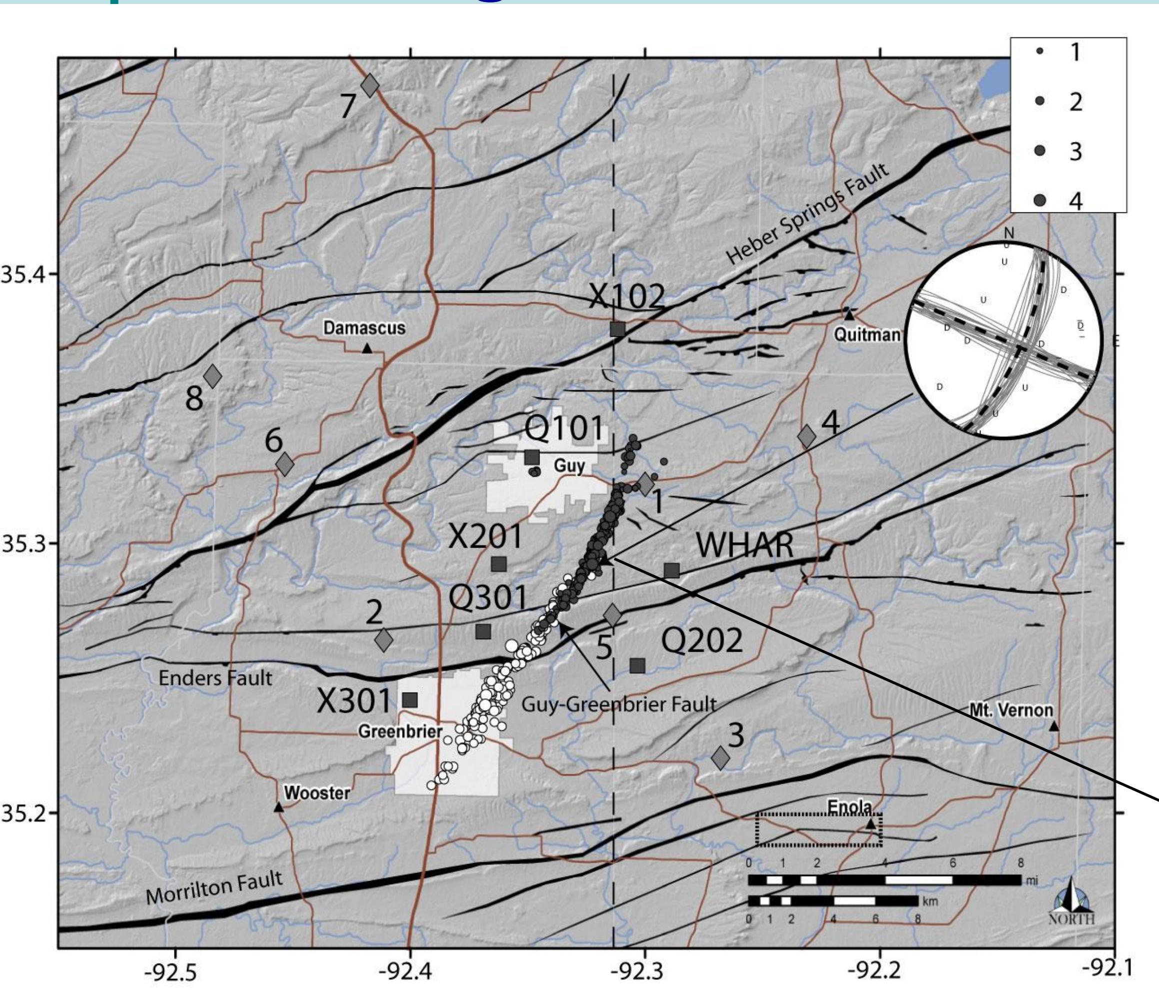
(Source: NRC report on induced seismicity)

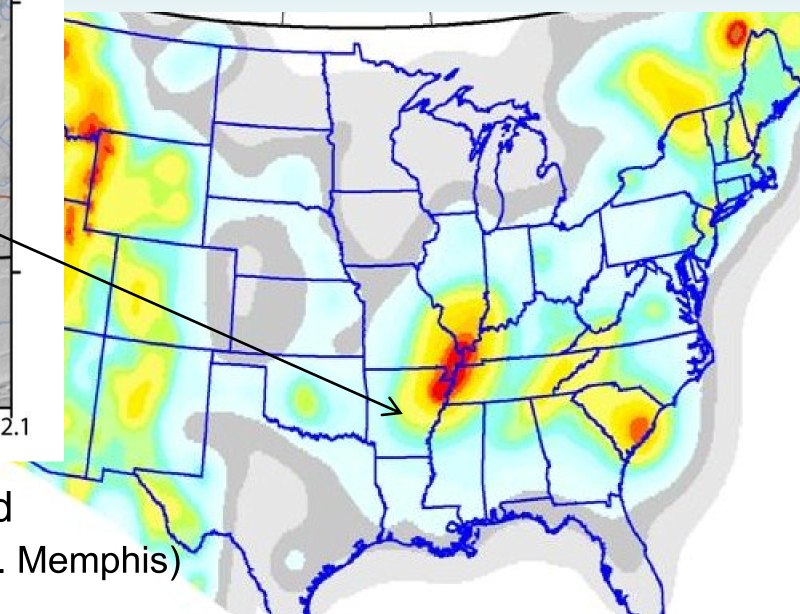
Induced Seismicity Not Always in Tectonically Active Areas



Approximate location of recent induced seismicity associated with natural gas development activities

Induced Seismicity Commonly Occurs on Pre-existing Faults





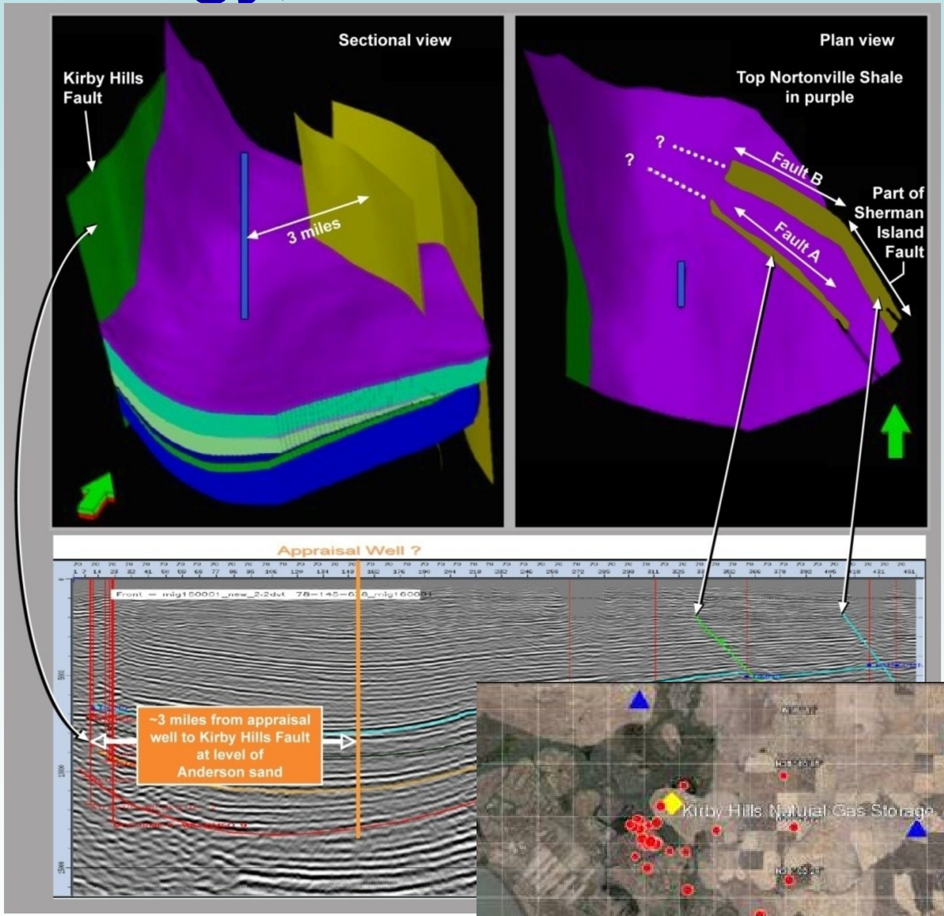
Induced seismicity on Guy-Greenbrier fault, due to fluid Injection activities (maximum event M4.7). (S. Horton, U. Memphis)

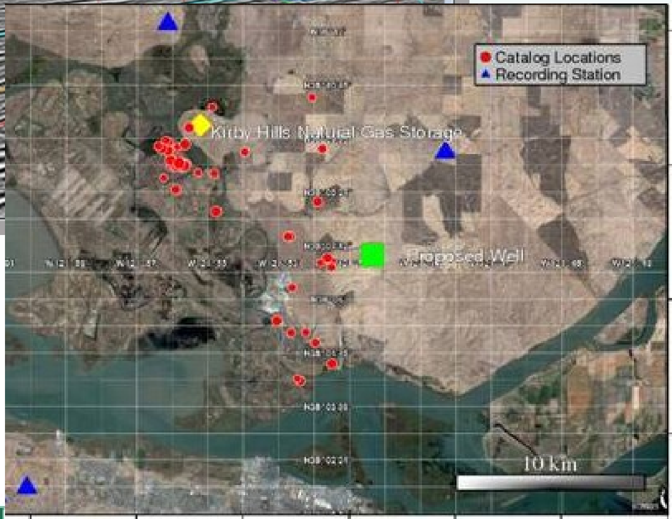
The Potential for Induced Seismicity Can Be Managed Using Best Practice Approaches

- Site selection and characterization
- Risk assessment
- Managing reservoir pressures during operation
- Monitoring
- Public outreach
- Event response procedures

Site Characterization Provides Essential Data on Geology, Hydrology, etc

- Develop 3-D geologic model
  - Identify faults
- Determine in-situ stress state
- Determine in-situ fluid pressures; regional hydrologic boundary conditions
- Review historical seismicity – magnitude, location, frequency
- Perform social characterization

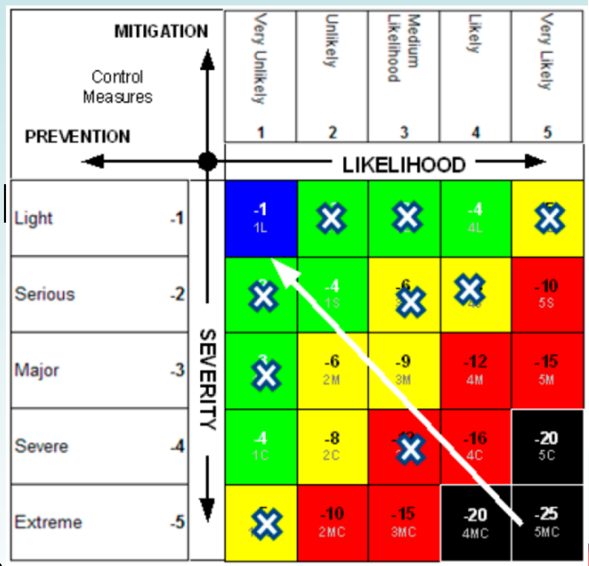




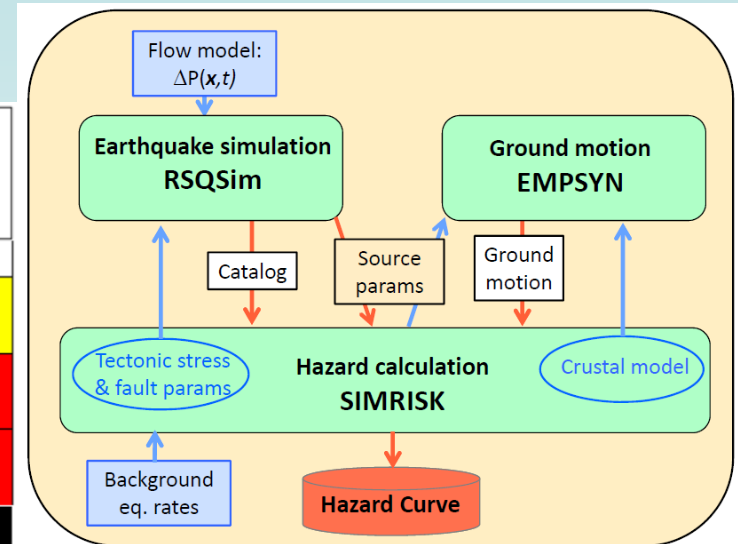
Geologic model and historical seismicity in vicinity of WESTCARB proposed pilot CO_2 injection test in northern California

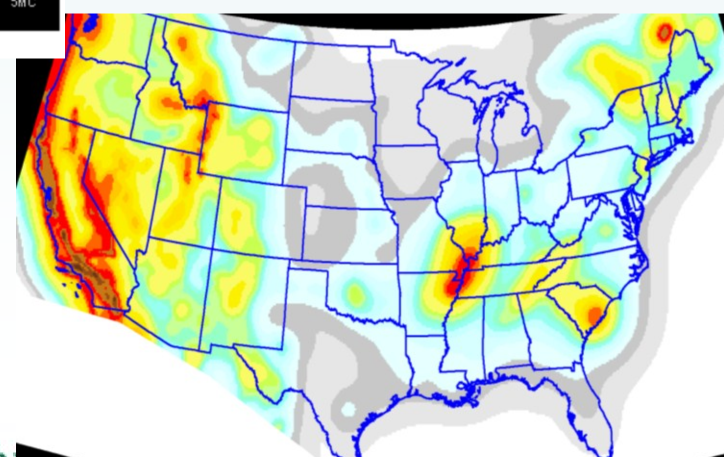
Identify and Analyze Risks, Develop and Implement Risk Response

- Project risk assessment includes induced seismicity along with other potential risks
- Review, consider update of natural seismic hazard assessment of site
- Consider induced seismicity probabilistic hazard analysis



White arrow indicates decreasing risk

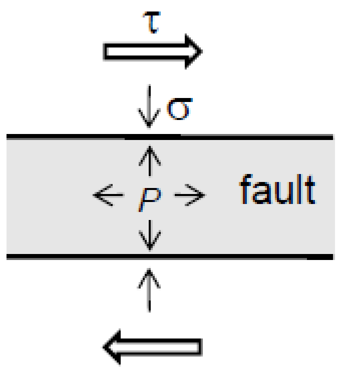


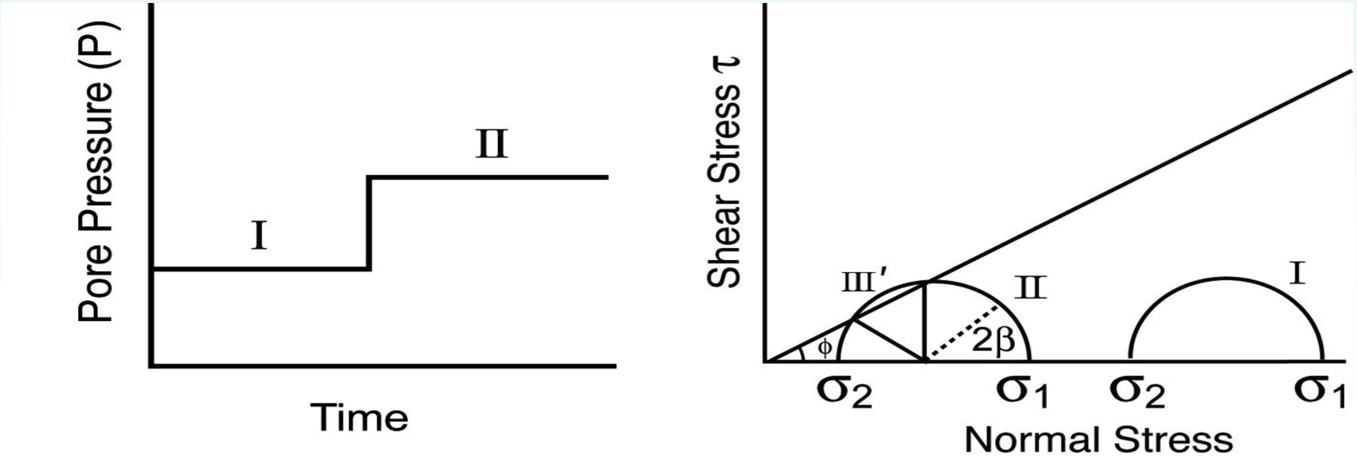


Managing Reservoir Pressures: Determine Max Allowable Pressure on Faults

- “Coulomb criterion”: faults slip when frictional resistance (allowable shear stress) is exceeded
- Input data: in-situ stress state and coefficient of friction, μ, of fault
- Determine *P*, the maximum allowable fluid pressure on fault

$$\tau_s = \mu(\sigma - P)$$

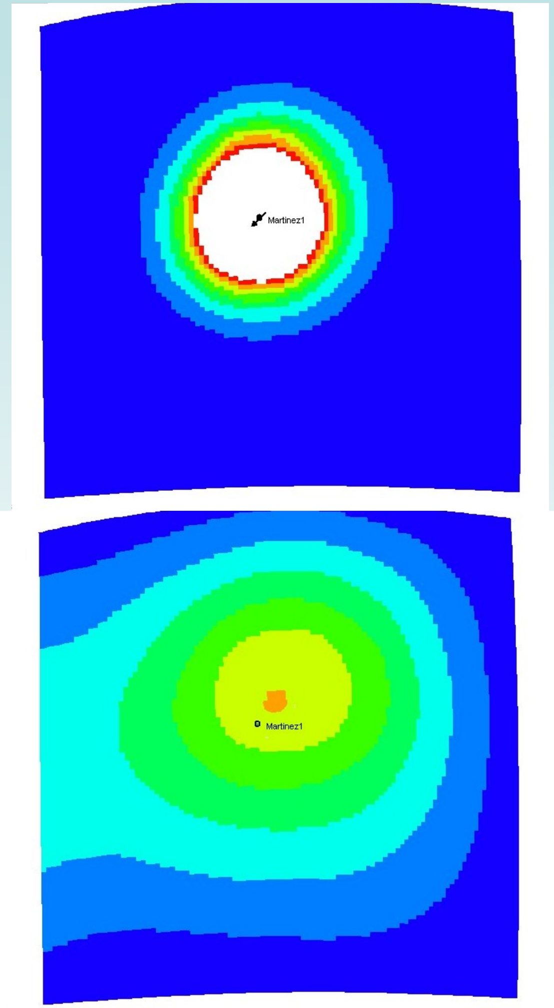




Use of “Mohr circles” to evaluate potential for fault slip

Managing Reservoir Pressures: Design of Injection Operations

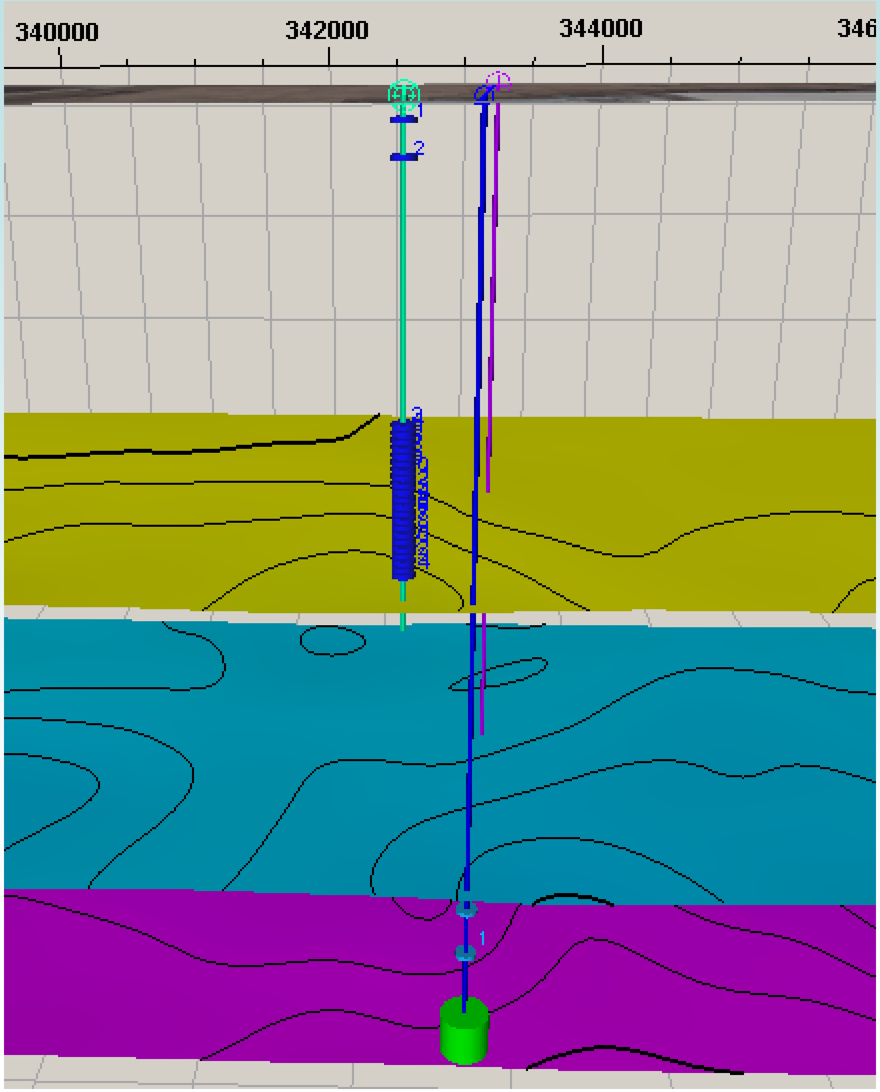
- Model reservoir pressures – operational period and post-injection
  - Incorporate actual hydrologic boundary conditions
- Consider pressure limits in location and number of injection wells
  - Site injection wells far from faults
- For depleted oil and gas reservoirs, consider setting original reservoir pressure as a limit
- Consider brine extraction for pressure management



Pressure increase around an injection well (blue is zero); top- end of injection; bottom-150 days later; fault on left

Monitoring for Induced Seismicity

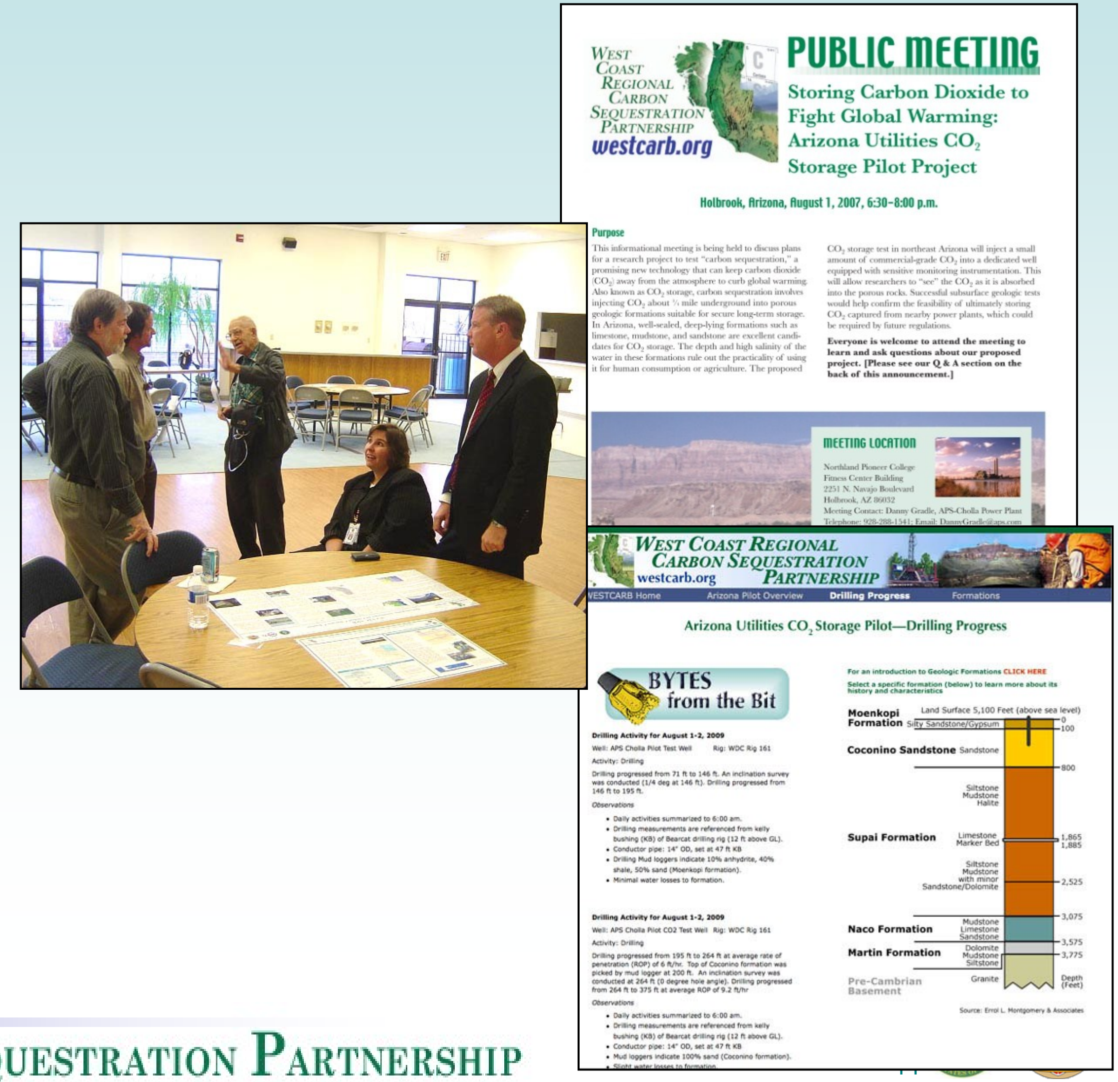
- Reservoir pore pressures
  - Direct measurements
  - Indirect: surface displacements, seismic
- Microseismic measurements
  - Permanent sensors; integrate with regional network
  - Integrated with overall seismic monitoring scheme
  - One year or 6 month baseline
- Monitoring need follow from risk assessment – technical risks and social attitudes



Schematic of wells and wellbore monitoring at Decatur RCSP project

Incorporating Induced Seismicity into Public Outreach Programs

- Characterize local attitudes toward seismicity
- Incorporate discussion of seismicity, natural and induced, into project outreach plan
  - Account for technical risk and local attitudes
- Consider making seismic data available to public in "real time"
- Plan ahead for complaints

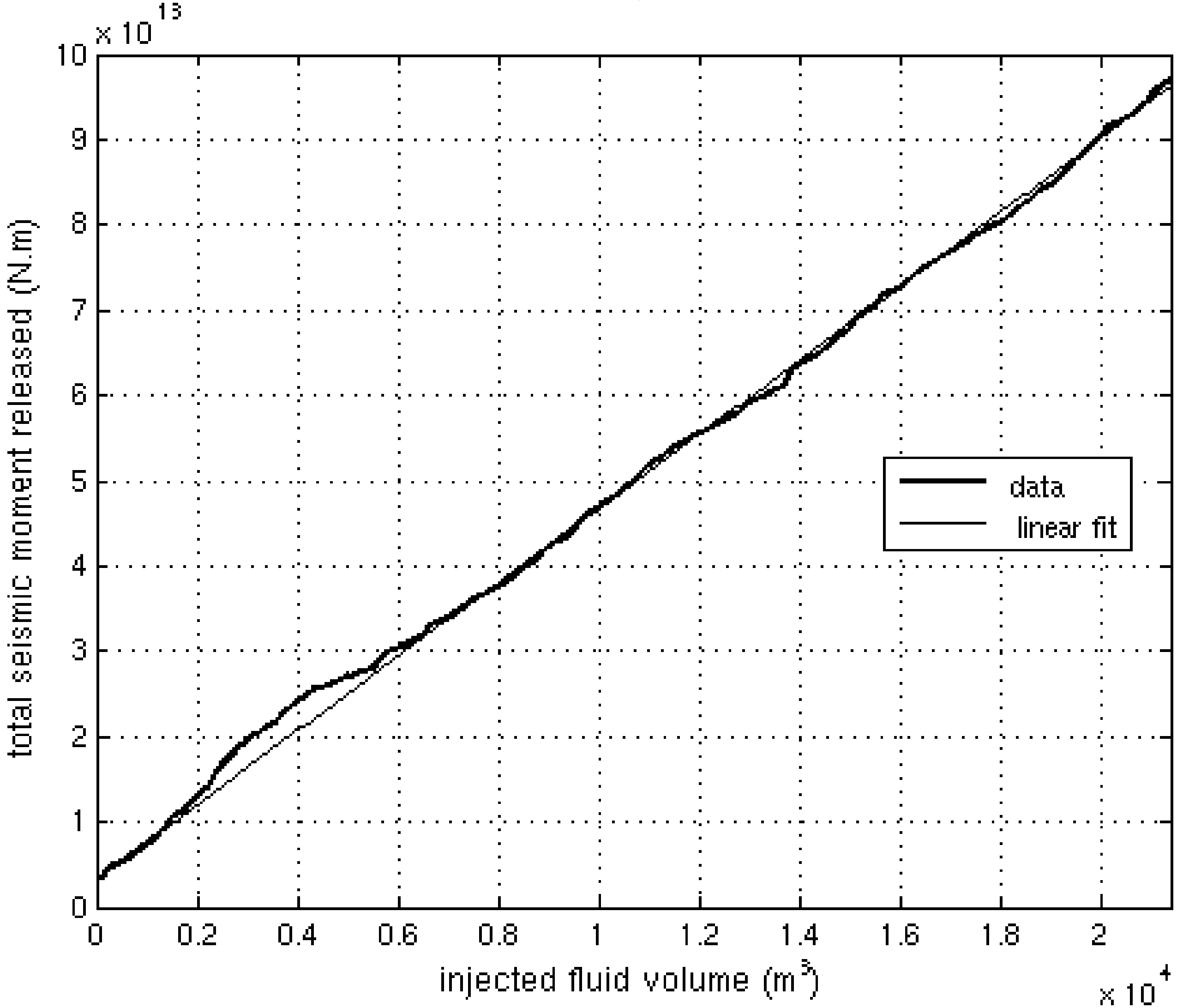


Establish Procedures for Responding to Events

- Work with regional authorities to establish protocols
- Set thresholds for a range of actions depending on magnitude of event (where magnitude is tied to shaking potential)
  - Eg., no action if events smaller than M2; suspend injection if >M4
  - Take into consideration natural seismicity and location of event
- Consider vibration monitoring of some structures in cultural areas

Some Remaining Questions

Total Seismic Moment May Be Correlated With Injected Volume



McGarr (1976)

$$\sum M_0 = K.\mu.|\Delta V|$$

Total Seismic Moment

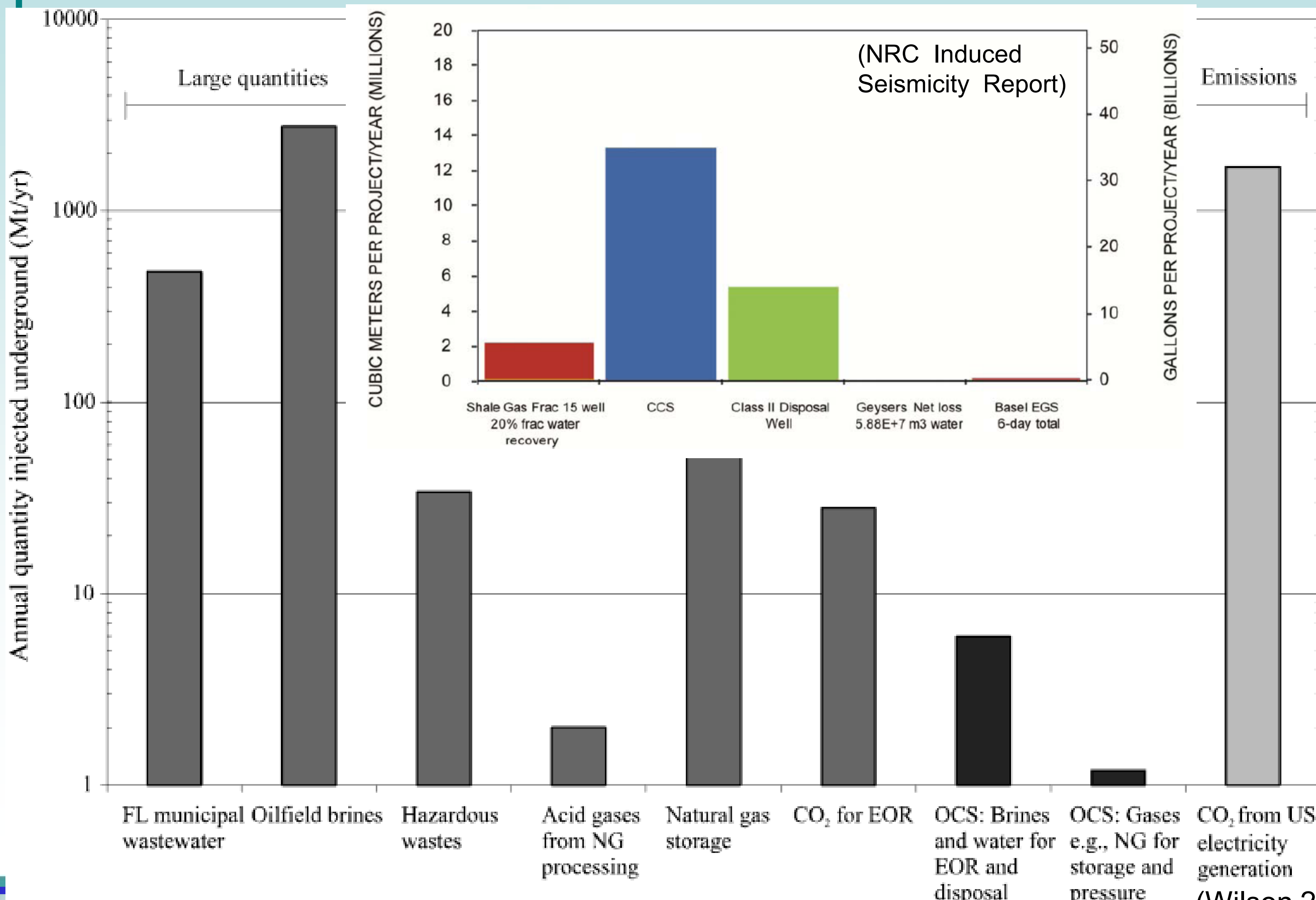
Fluid injected

K ~ 0.5

Volume added to region in expansion in direction NW/SE(σ2) and NE-SW (σ3)

Correlation of total seismic moment and injected volume at Geysers (E Majer, LBNL)

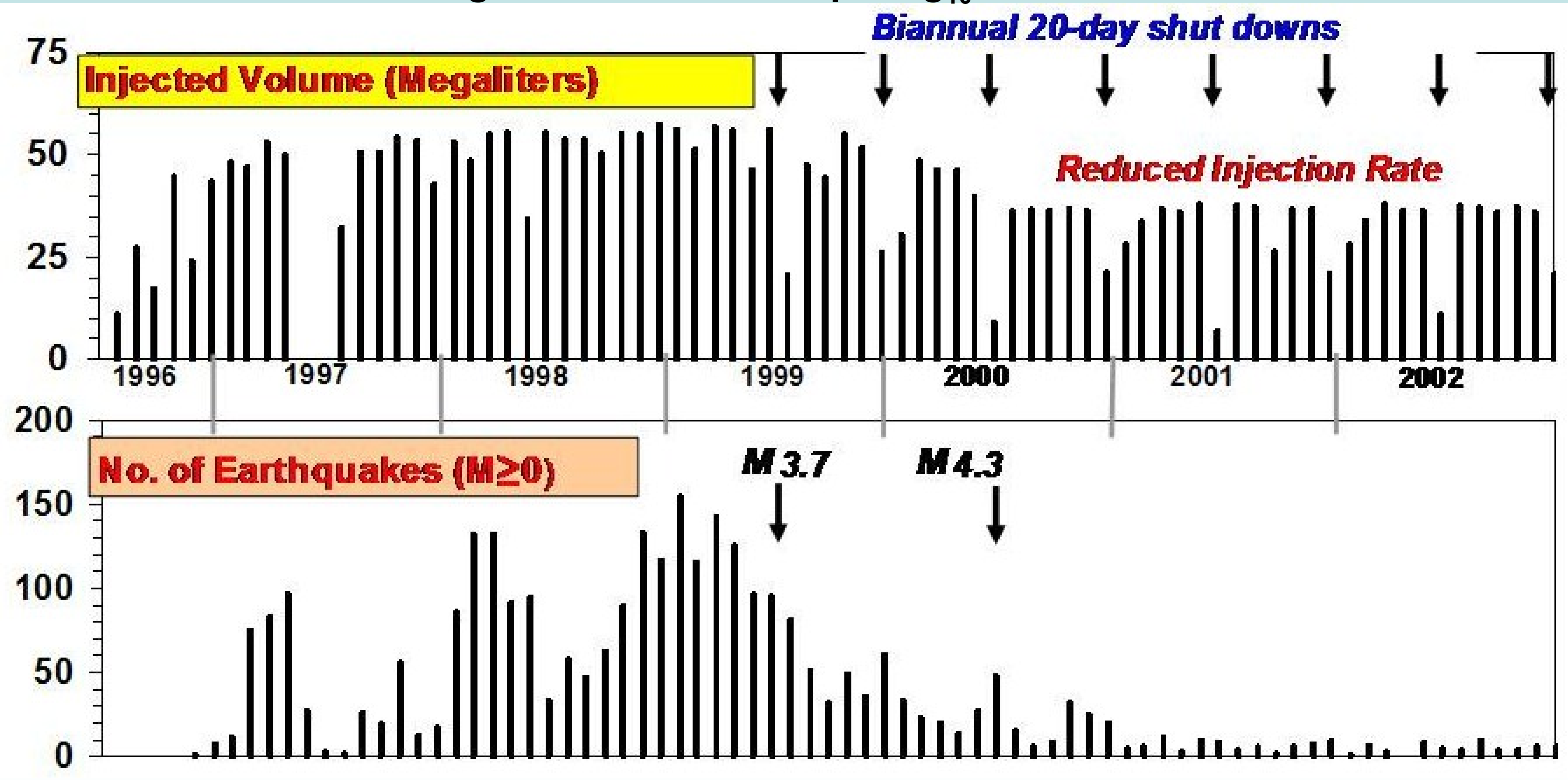
Are Injected CCS Injected Volumes Unprecedented?



(Wilson 2003)

"b" Values For Induced and Natural Seismicity May Be Different

Gutenberg-Richter relationship: $\text{Log}_{10}\, N = a - bM$



Induced seismicity from salt water injection in Paradox Vslley, Colorado. "b" values have changed over time. (Ake, US Bureau of Reclamation, NRC)

Summary

- Induced seismicity represents a potential risk for CCS, though it also has potential as a reservoir monitoring tool
  - Very little induced seismicity in CCS projects to date
- Observations indicate induced seismicity very often associated with pre-existing faults, but attributes of induced events may differ from natural seismicity
- Induced seismicity should be addressed as part of the risk assessment carried out for CCS projects; results of risk assessment inform project operations
- The potential for induced seismicity can be managed using best practice approaches in site characterization, monitoring, injection operations and public outreach