Induced Seismicity Associated with Fluid Injections for Energy Resource Applications: Lessons Learned

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Acknowledgements

David Oppenheimer (USGS), Bill Leith (USGS)
Art McGarr (USGS), David Simpson (IRIS)
Steve Hickman (USGS), Bill Ellsworth, Nick Beeler (USGS), Jon Ake (NRC), Mark Walters (Calpine), Bill Smith (NCPA) Paul Segall (Stanford), Mark Zoback (Stanford), plus many more
DOE NETL Oil and Gas Program
DOE Geothermal Program

Induced Seismicity: Recent Issues

- High-profile press coverage and congressional inquiries have focused attention on induced seismicity related to energy projects in the U.S. and Europe: Led to actual cancelation!
  - The Geysers, CA; Basel, Switzerland; Soultz, France; Landau, Germany
  - Oil and gas: Texas
  - CO_2 sequestration sites (various)
- How does one assess hazard risk and economic risk
  - Investors want to know what needs to be done to satisfy regulators
  - Seismicity related to injection cannot be assessed the same as natural seismicity
  - Scale and distance of influence
- However, industry has dealt with induced seismicity issues for almost 100 years (mining, oil and gas, waste injections, reservoir impoundment, etc.)
- Seismicity can also be useful as a resource management tool

Earthquake Risk

- Risk in this context can be thought of as:

  R = AF(***a*** | eq)*(Pr(f | ***a***)*C($;LL | f)

Where R="risk", AF= annual frequency of ground motion ***a***, given occurrence of an earthquake(s), Pr(f | ***a***) =probability of failure of something of interest given ground motion ***a***, and C=consequences (dollars, or any metric of interest).

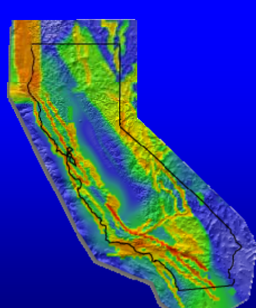
AF developed using Probabilistic Seismic Hazard Analysis (PSHA)

Seismic Hazard Analysis

Two main model components:

1) Earthquake ***Rupture*** Forecast

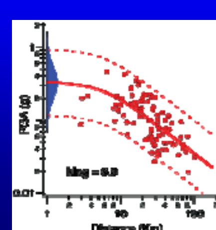
Gives the probability of all possible earthquake ruptures (fault offsets) throughout the region and over a specified time span



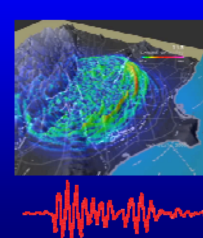
2) Earthquake ***Shaking*** model

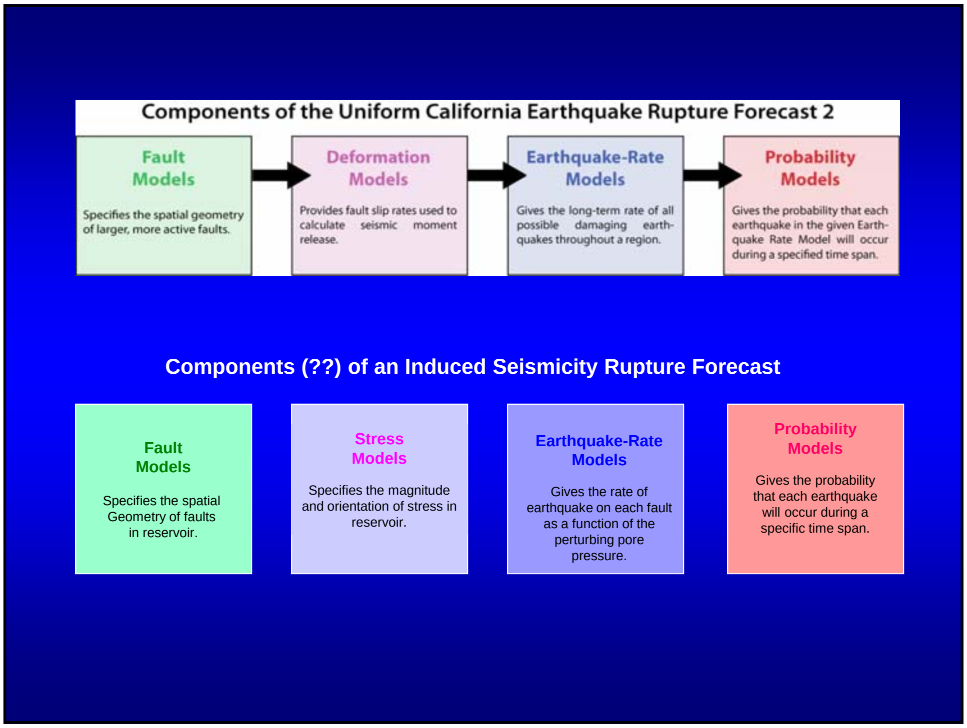
For a given earthquake rupture, this gives the probability that an intensity-measure type will exceed some level of concern

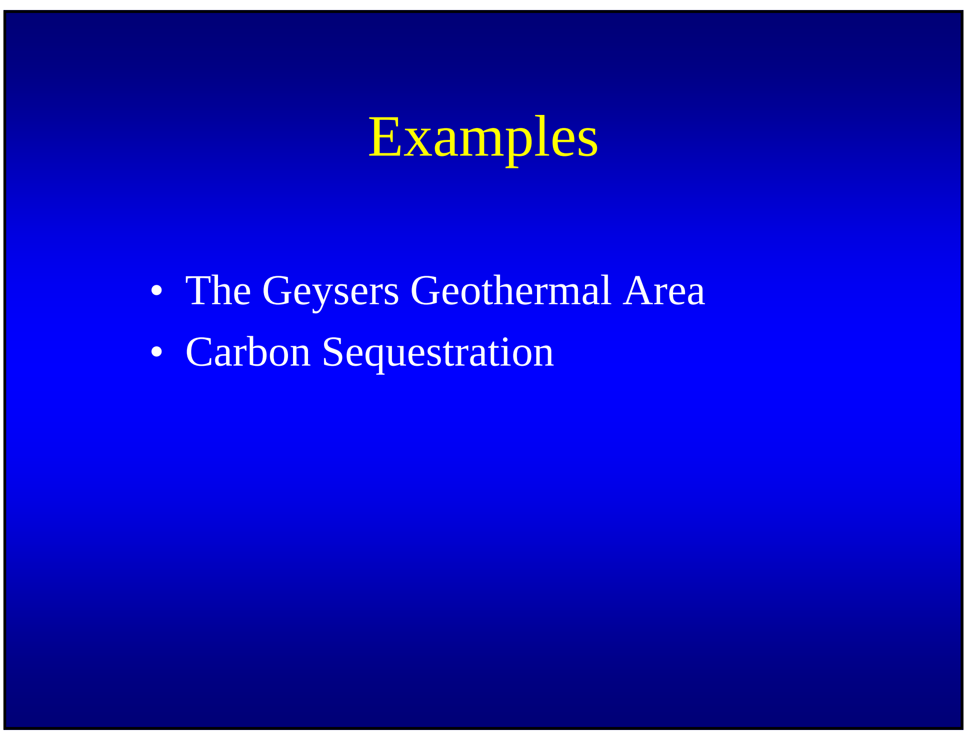
Empirical
"Attenuation Relationships"

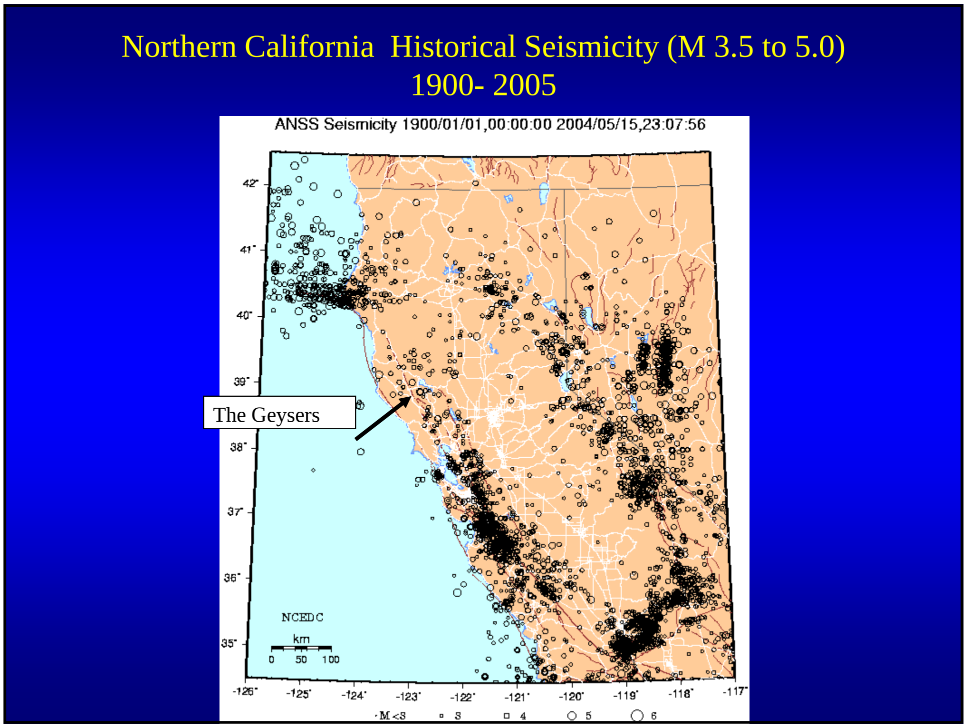


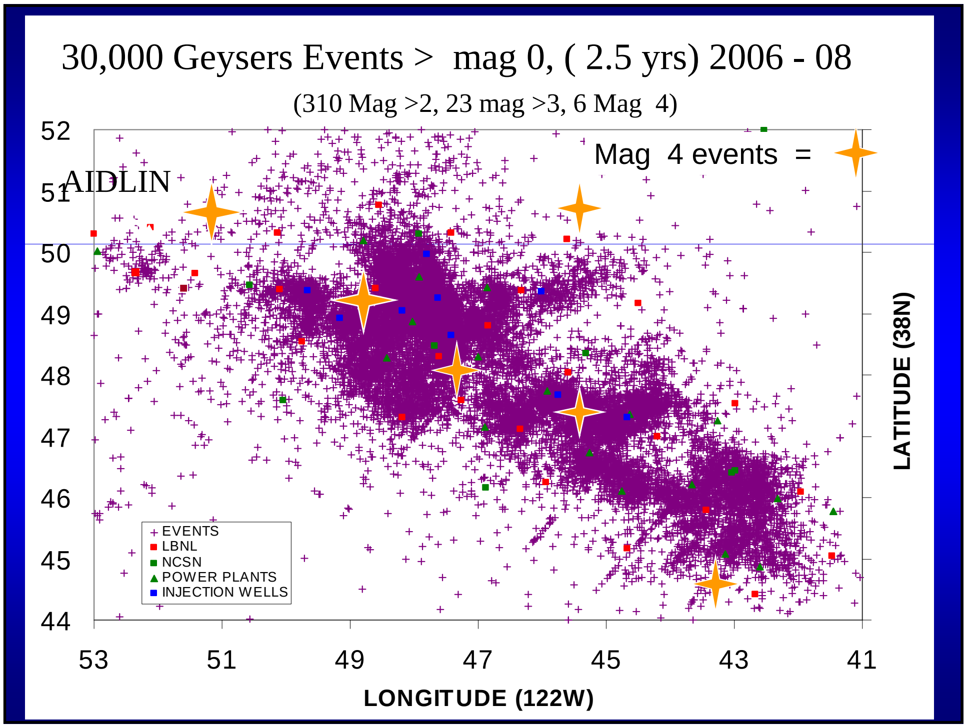
Physics-based
"Waveform Modeling"

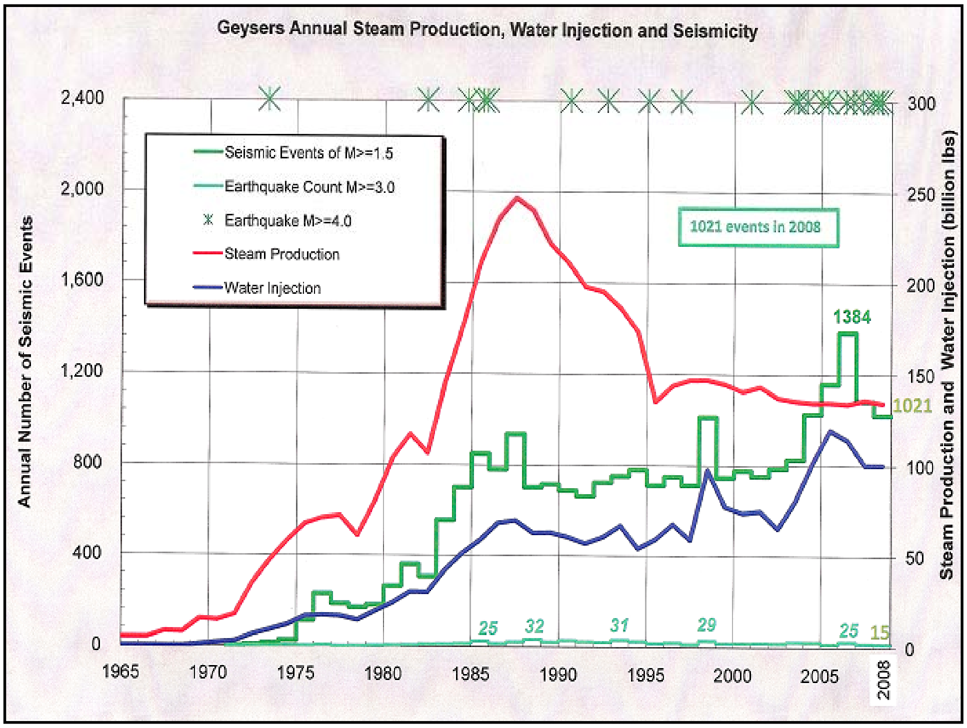



Components of the Uniform California Earthquake Rupture Forecast 2
Fault Models
Specifies the spatial geometry of larger, more active faults.
Deformation Models
Provides fault slip rates used to calculate seismic moment release.
Earthquake-Rate Models
Gives the long-term rate of all possible damaging earthquakes throughout a region.
Probability Models
Gives the probability that each earthquake in the given Earthquake Rate Model will occur during a specified time span.
Components (??) of an Induced Seismicity Rupture Forecast
Fault Models
Specifies the spatial Geometry of faults in reservoir.
Stress Models
Specifies the magnitude and orientation of stress in reservoir.
Earthquake-Rate Models
Gives the rate of earthquake on each fault as a function of the perturbing pore pressure.
Probability Models
Gives the probability that each earthquake will occur during a specific time span.


Examples
• The Geysers Geothermal Area
• Carbon Sequestration


Northern California Historical Seismicity (M 3.5 to 5.0)
1900- 2005
ANSS Seismicity 1900/01/01,00:00:00 2004/05/15,23:07:56
The Geysers
NCEDC
km
0 50 100
42°
41°
40°
39°
38°
37°
36°
35°
-126° -125° -124° -123° -122° -121° -120° -119° -118° -117°
M<3 3 4 5 6


30,000 Geysers Events > mag 0, (2.5 yrs) 2006 - 08
(310 Mag >2, 23 mag >3, 6 Mag 4)
Mag 4 events =
AIDLIN
52
51
50
49
48
47
46
45
44
53 51 49 47 45 43 41
LONGITUDE (122W)
LATITUDE (38N)
EVENTS
LBNL
NCSN
POWER PLANTS
INJECTION WELLS



Volume change for The Geysers

McGarr (1976)

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

Total Seismic Moment

Fluid injected

- Total volume change = 1.42 e^9 meters cubed (over 35 years)
- Sum Moments = $e^{18.45}$ N-m

1	Mag	6.2
10	Mag	5.2
100	Mag	4.2
1,000	Mag	3.2
10,000	Mag	2.2

etc.

- Not Far Off!!

Interesting observations

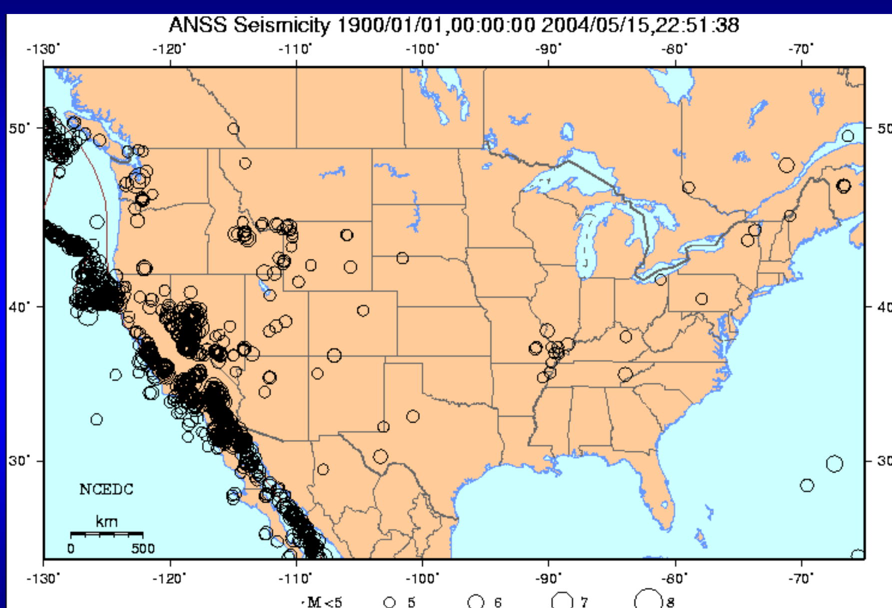
- Large events happen (sometimes) at the edges of the reservoir/after the injection stops
  - Implication of diffusion processes
- Variable rate dependency of injection versus seismicity
  - Sometimes anti-correlation between injection and seismicity
- Seismicity reaches an equilibrium (in certain magnitude ranges)
- Seismicity does not follow normal aftershock patterns (sometimes)
- Thermal stress/changes can play an important role
- Variable relation between foreshocks, aftershocks, b-values, etc.
- Induced seismicity appears to change mechanisms (triggering) over magnitude ranges

Carbon Sequestration

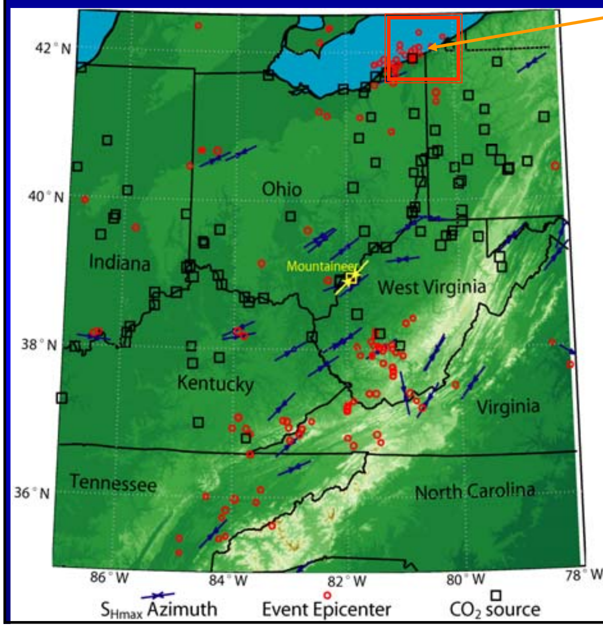
Deep Well Injection Risks

Three types:

1. Loss of integrity of “capping layer” degradation of water supply (EPA)
2. Damage due to induced/triggered seismicity
3. Loss of public trust/confidence



Regional Seismicity: 1960-present



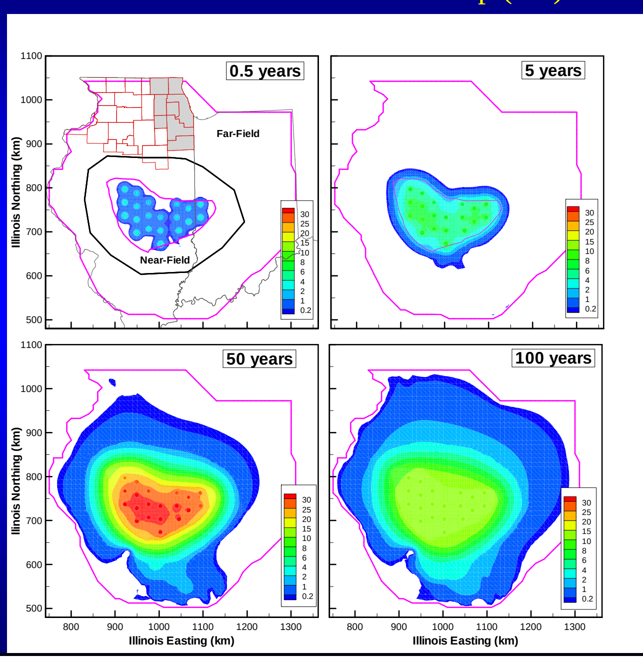
Perry Nuclear Power Plant

- January 31, 1986
- M_b 5.0 Event
- Pressures in nearby deep injection wells reached 11.2 MPa above ambient
- Pressure increase may have been responsible for triggering the event

Mountaineer Power Plant

- State of stress: Strike-slip frictional equilibrium
- Small pressure increases could result in reactivation

Basin-Scale Pressure Buildup (bar)



Cutoff Pressure: 0.1 bar

Example for CO_2 sequestration, 1 million tons/yr of injection

Also, assume that the relation between volume injected and Seismicity is similar as in geothermal case (let K =1)

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

Assuming normal magnitude: moment relations
Then one could expect total Magnitude = 4.6

Or	10	M = 3.6
	100	M = 2.6
	1000	M = 1.6 etc

What should/could be done? – Research

- What limits the magnitude of induced earthquakes (size of pressurized zone, length of fault) ?
- Do we need better knowledge of relation between stress change (particularly effective normal stress) and seismicity rate?
- Is there time dependence or stressing rate dependence in stress-seismicity rate changes? or is the theory of effective stress all we need to know?
- Do induced earthquakes follow the same attenuation relations as tectonic earthquakes in the same province?
- What do we need to know about slip-dilatancy (slip-permeability) relations better for fault zones?
- Do we care about fluid - mechanical processes (fault healing, permeability reduction) in the induced seismicity problem?
- What do we need to know about fault zone poroelasticity?
- What do we need to know about chemical processes?

What could/should we do? - Operational

- Deploy advanced monitoring systems
  - experimental data
  - continuous data-stream as basis for operational control decisions during development and long-term operation
- Active experiments to manipulate seismicity without compromising production
  - reservoir performance assessment
  - integrated reservoir analysis
- Risk-based decision making for operational control
  - adapt probabilistic seismic hazard/risk method coupled with physics-based approach incorporating uncertainty
- Mitigation and Control Procedures
  - Site characterization and selection; faults, communities
  - Engineering design – well locations, injection pressures, etc.
  - Data-driven operational control
- Establish a best practices/protocol based on accepted scientific knowledge in order to allow implementation of energy projects – i.e., set out the rules!!

What have we learned?

- Issues are similar to other induced seismicity cases which have been successfully addressed
- Issues are both technical and non-technical
  - Must pay attention to both
  - Seismicity can be a benefit in understanding the resource
  - Technical issues remain on fully utilizing seismicity as a reservoir management tool
- Induced seismicity is not (or does not need to be) an impediment to reservoir development

Examples (largest events)

	Mag	*Date*
• Reservoir Impoundment		
– Hoover, USA	5.0	1939
• earliest recognized case of RIS		
– Koyna, India	6.5	1967
• structural damage, 200 killed		
– Aswan, Egypt	5.3	1981
• largest reservoir, deep seismicity		
• Mines and Quarries		
– Wappingers Falls, NY	3.3	1974
– Reading, PA	4.3	1994
– Belchatow, Poland (coal)	4.6	1980
• Oil and Gas fields		
– Long Beach, CA	5.2	1930s
– Dallas-Ft. Worth	3.4	2008
– Lacq, France	~ 4	various
• Gas extraction		
– Gazli, Uzbekistan	~ 7	1976
• Previously aseismic region, three M7 events		
• Injection related		
– Denver	5.3	1960s
– Geothermal	4.6	1984

Public/Industry Concerns About Induced Seismicity

- How does one assess the risk?
  - What is the largest earthquake expected?
  - Will small earthquakes lead to bigger ones?
  - Can induced seismicity cause bigger earthquakes on distant faults?
  - Even small felt (micro)earthquakes are annoying.
  - Can induced seismicity be controlled?
  - What controls are (will be) in place to mitigate future induced seismicity?
  - What is the plan if a large earthquake occurs?
- How do you use seismicity as a management tool?

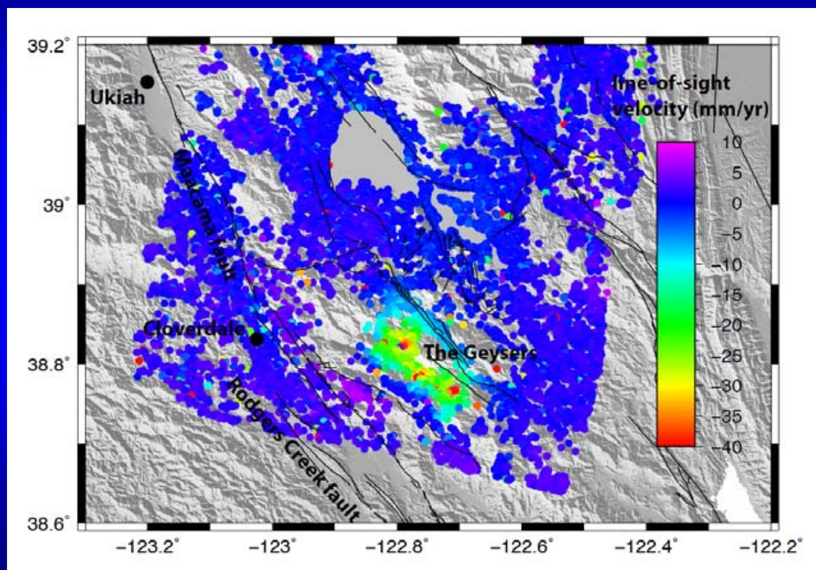
Some basic assumptions

- Earthquakes occurs on faults
- There is a relation between fault size and energy release (Kanamori and Anderson, 1975; Kanamori, 1975; Wells and Coppersmith, 1994; Shaw, 2009)
  - Mw = 1.23 X 10 e^{22} S (3/2) dyne-cm, S in sq km (K & A)
  - Mw = log A + 3.98 (A = area in sq km)
- Larger events tend to occur deeper than smaller events (Kanamori and Brodsky, 2001)
  - i.e. stress increases with depth
- B-value acts as a stress meter that depends inversely on differential stress (Schorlenmer, Weimer and Wyss, 2005)
- Connection between net volume injected and seismicity (McGarr, 1976)
  - Sum Mo = K x (shear modulus) x Volume Change
- Little events do not cause big events

Causal Mechanisms

- Earthquakes (fault rupture) 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 rupture.
- This can result from either:
  - 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
    - Stress diffusion
    - Other

PSInSAR from ERS satellite track 113
Average velocities 1992-2000



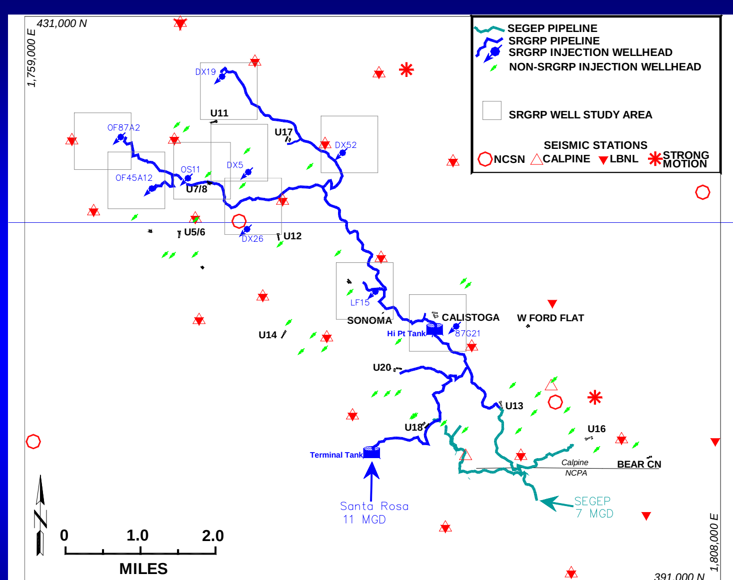
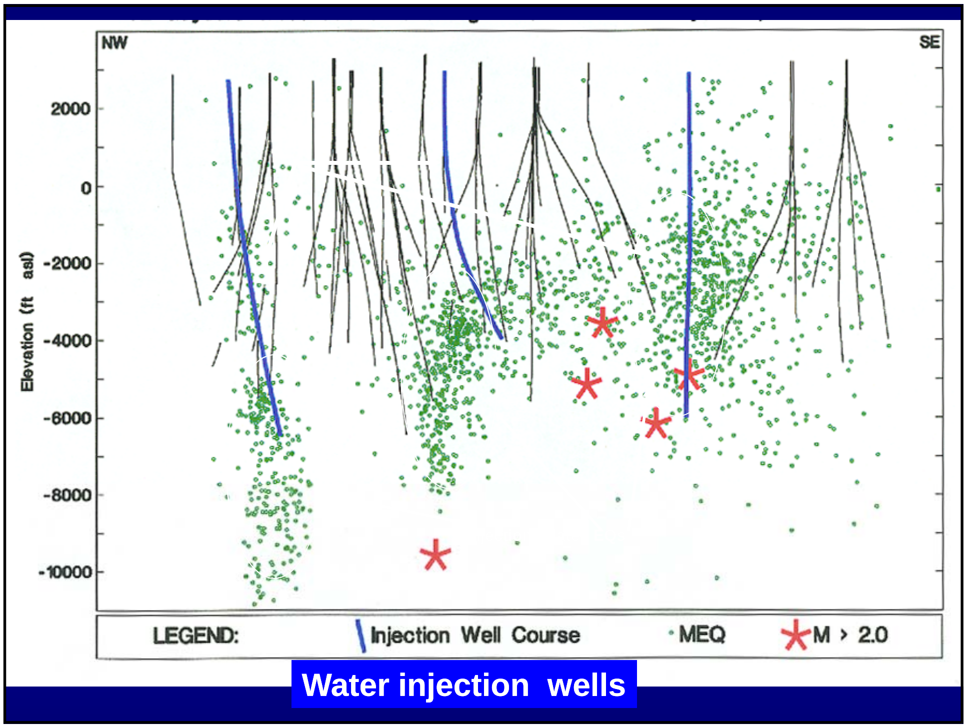
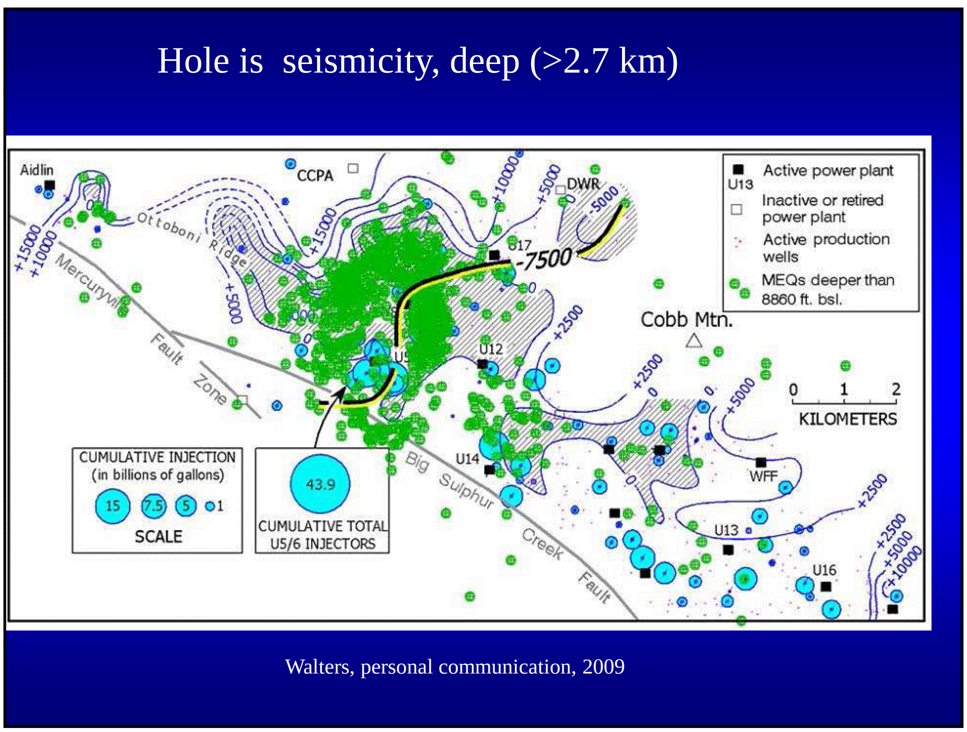
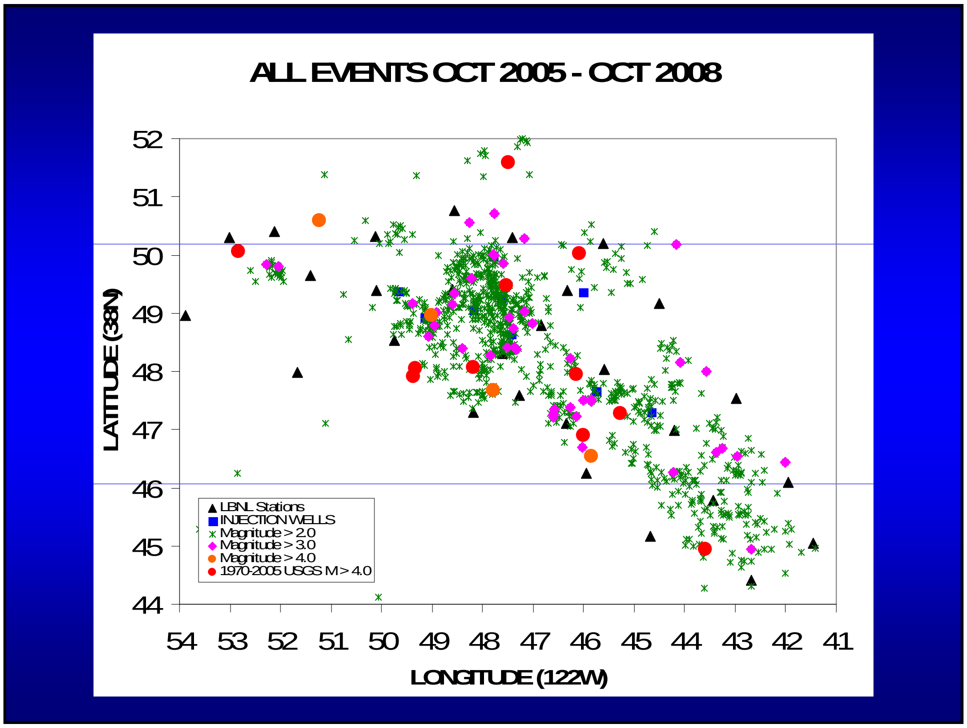


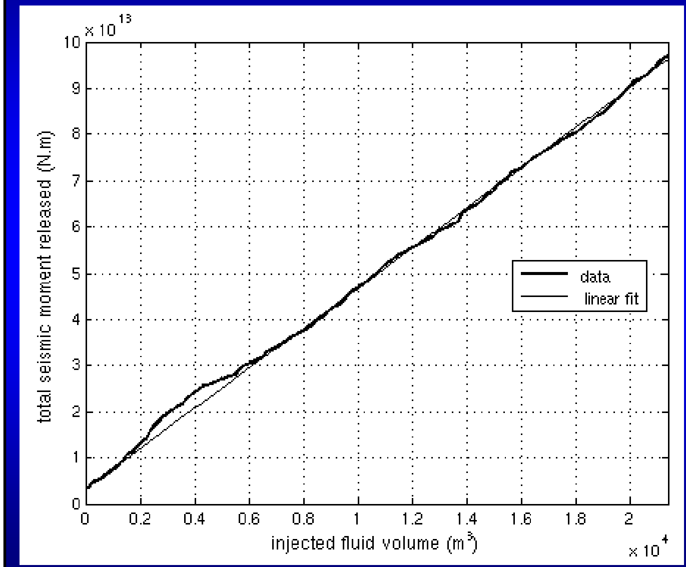
Figure 1. Location of USGS stations, current Calpine array, and the new LBNL stations. Also shown are the locations of the pipelines used for the water from Santa Rosa. (from Calpine)


NW
SE
2000
0
-2000
-4000
-6000
-8000
-10000
Elevation (ft asl)
LEGEND:
Injection Well Course
MEQ
M > 2.0
Water injection wells


Hole is seismicity, deep (>2.7 km)
Aidlin
CCPA
DWR
Ottoboni Ridge
Mercuryville Fault Zone
Big Sulphur Creek Fault
-7500
U17
U12
U14
U13
U16
WFF
Cobb Mtn.
Active power plant
Inactive or retired power plant
Active production wells
MEQs deeper than 8860 ft. bsl.
0 1 2
KILOMETERS
CUMULATIVE INJECTION (in billions of gallons)
15
7.5
5
1
SCALE
43.9
CUMULATIVE TOTAL U5/6 INJECTORS
Walters, personal communication, 2009



Seismic Moment & Injection Rate



McGarr (1976)

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

Total Seismic Moment

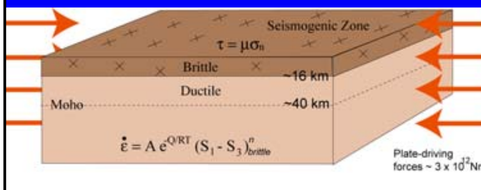
Fluid injected

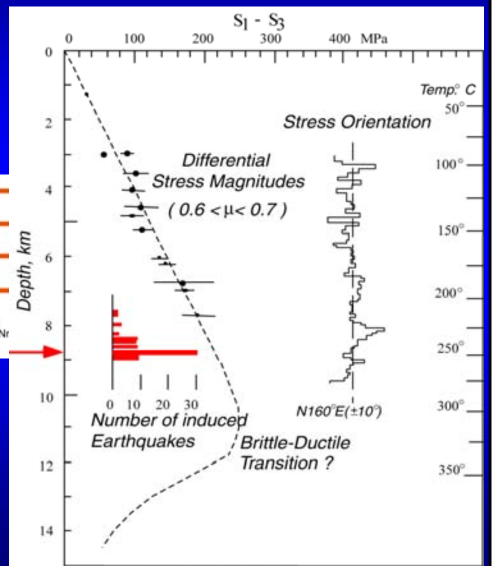
K ~ 0.5

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

Potential for Intraplate Seismicity Limits Injection Pressures

Brittle failure in critically-stressed crust results from creep in lower crust and upper mantle





Kanamori and Anderson, BSSA, 65, 1975

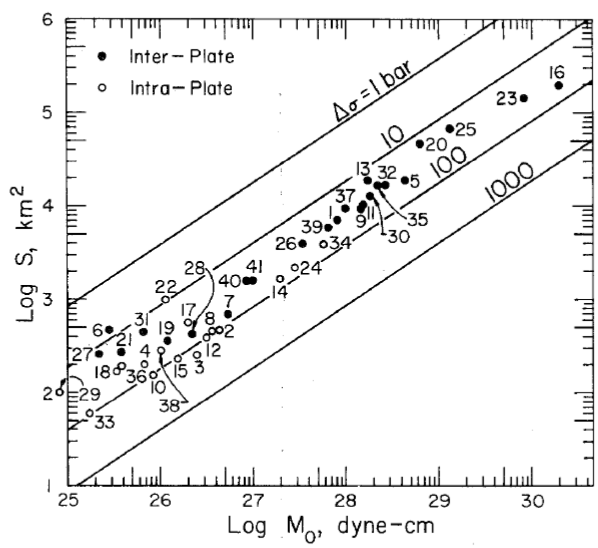
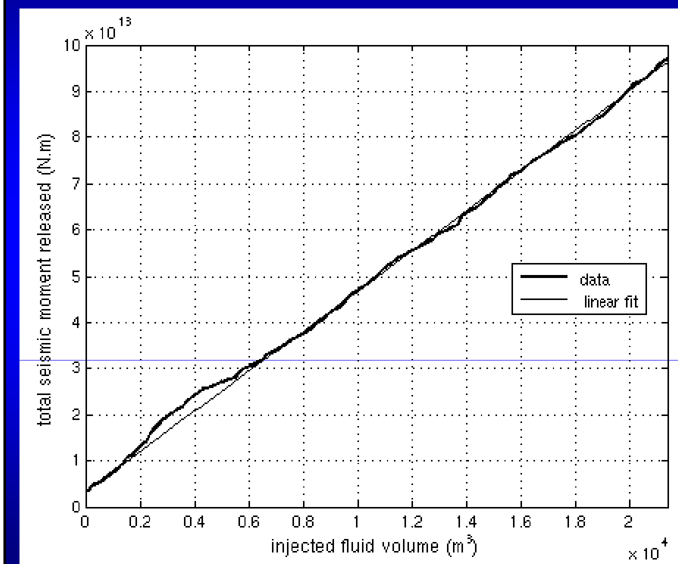


FIG. 2. Relation between S (fault surface area) and M_o (seismic moment). The straight lines give the relations for circular cracks with constant $\Delta\sigma$ (stress drop). The numbers attached to each event correspond to those in Table 1.

Seismic Moment & Injection Rate

Amount of seismic failure in response to shear stresses induced by volume change



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)

What's the Big Deal?

- Level of concerns has been raised to Congressional levels
- Induced seismicity has canceled projects
- Induced seismicity concerns could shut down several critical energy projects
- Operators must know the risks from a financial and hazard point of view