Induced and Triggered Seismicity Associated with Wastewater Injection and Hydraulic Fracturing

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ANH
AGENCIA NACIONAL DE HIDROCARBUROS
COLOMBIA

STANFORD UNIVERSITY

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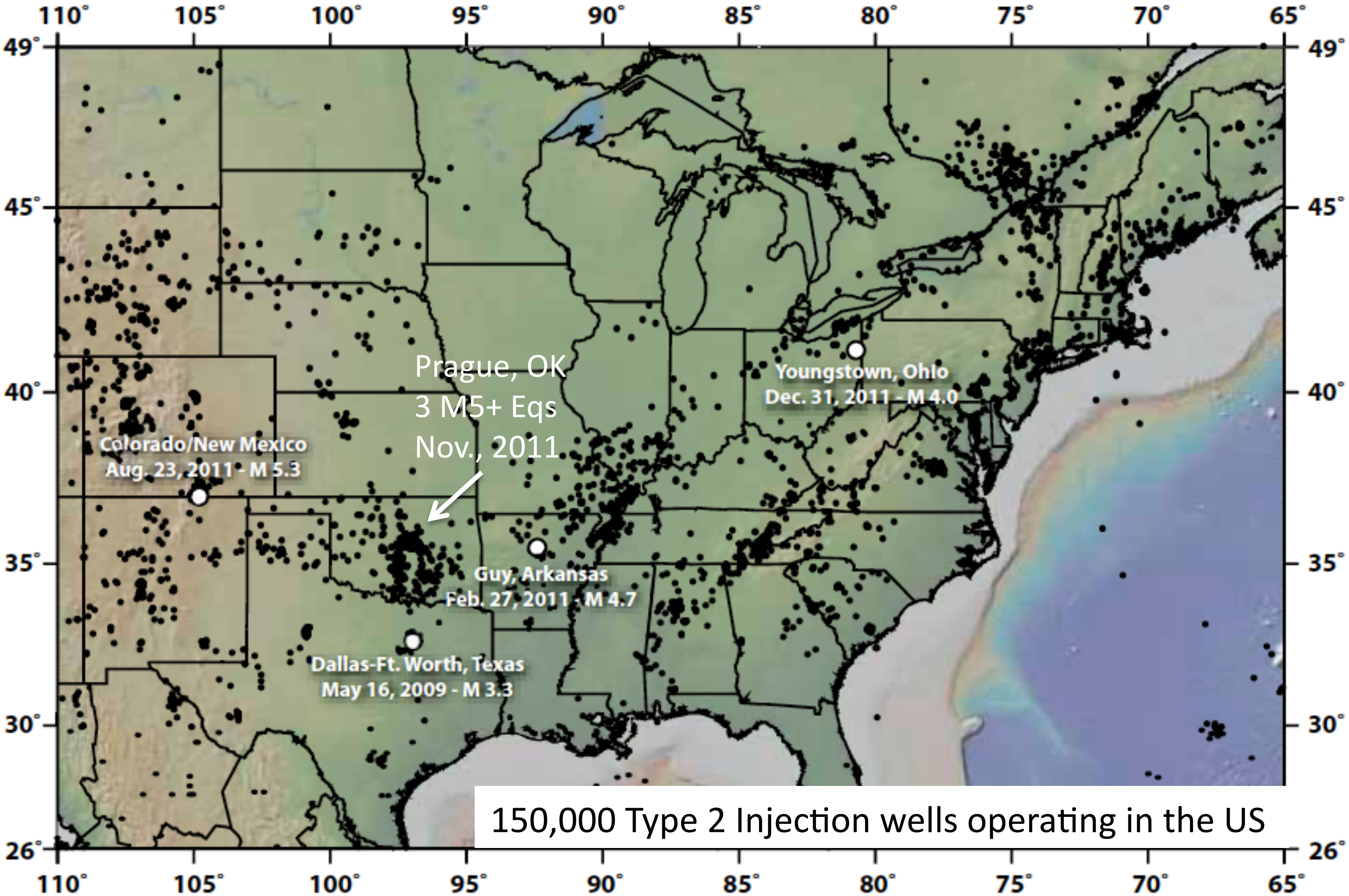
Outline

- Presentation 1 - The Principles of Natural and Induced Seismicity
  - Understanding Crustal Earthquakes
  - Earthquake Magnitude and the Richter scale
  - The Critically-Stressed Crust
  - Triggered Seismicity and Induced Seismicity
  - Characterizing the Potential for Triggering Fault Slip

- Presentation 2 - Seismicity Induced by Waste Water Injection and Hydraulic Fracturing
  - Waste water injection and triggered seismicity
  - Case studies
  - Hydraulic fracturing and induced seismicity
  - Case Studies
  - How to plan and manage potential risks
  - Specific baseline data required
  - Recommendations on baseline data collection

Wastewater Triggered Seismicity - 2011



Modified from Zoback, Earth, April 2012

Induced Seismicity Potential in Energy Technologies

NATIONAL RESEARCH COUNCIL
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THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

Shale gas extraction in the UK: a review of hydraulic fracturing

June 2012

THE ROYAL SOCIETY

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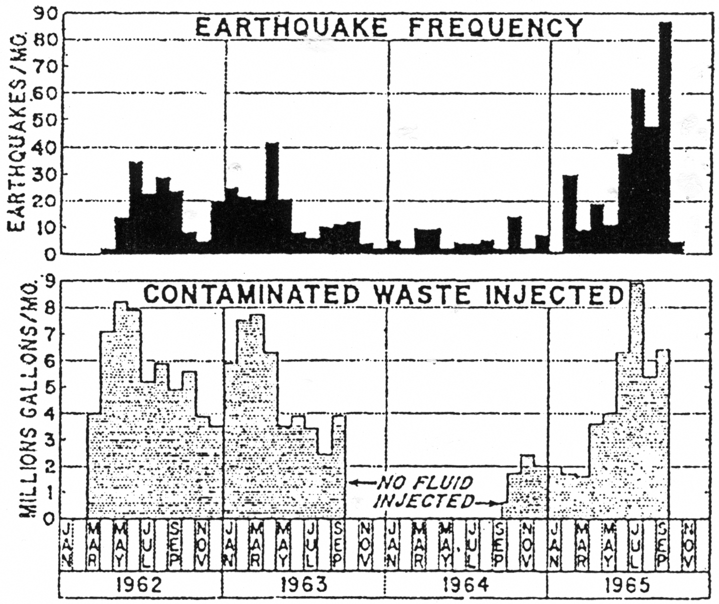
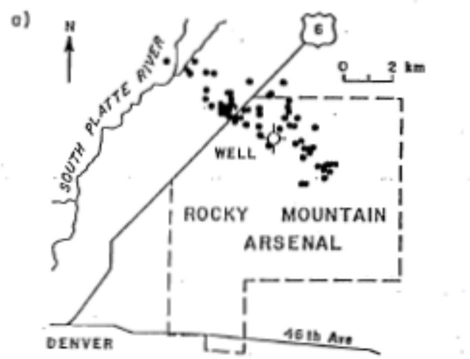
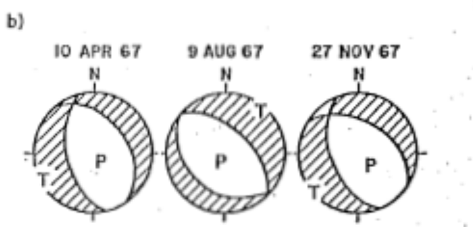
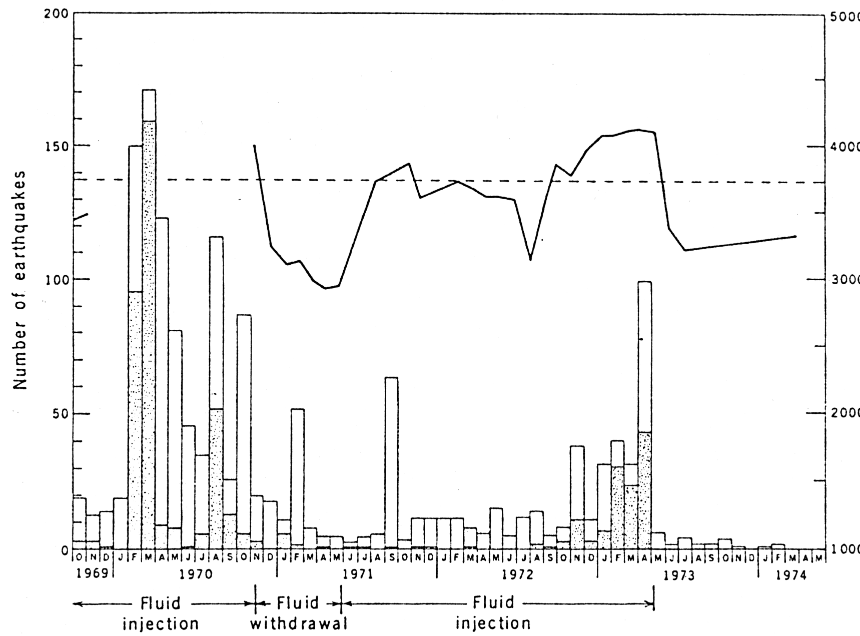
Waste Injection
Denver Arsenal

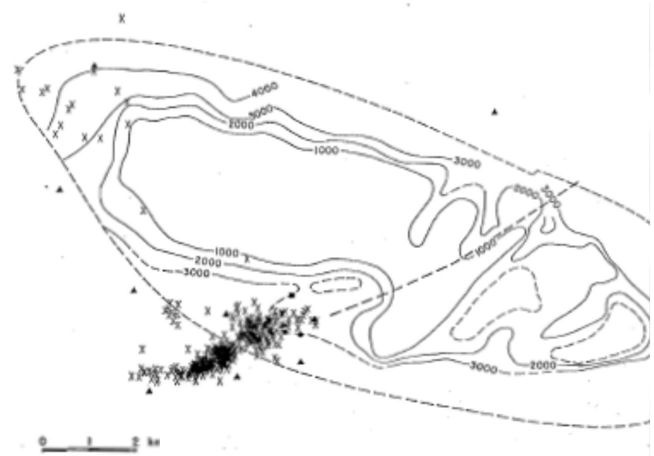
Fluid Injection
Rangely Oil Field











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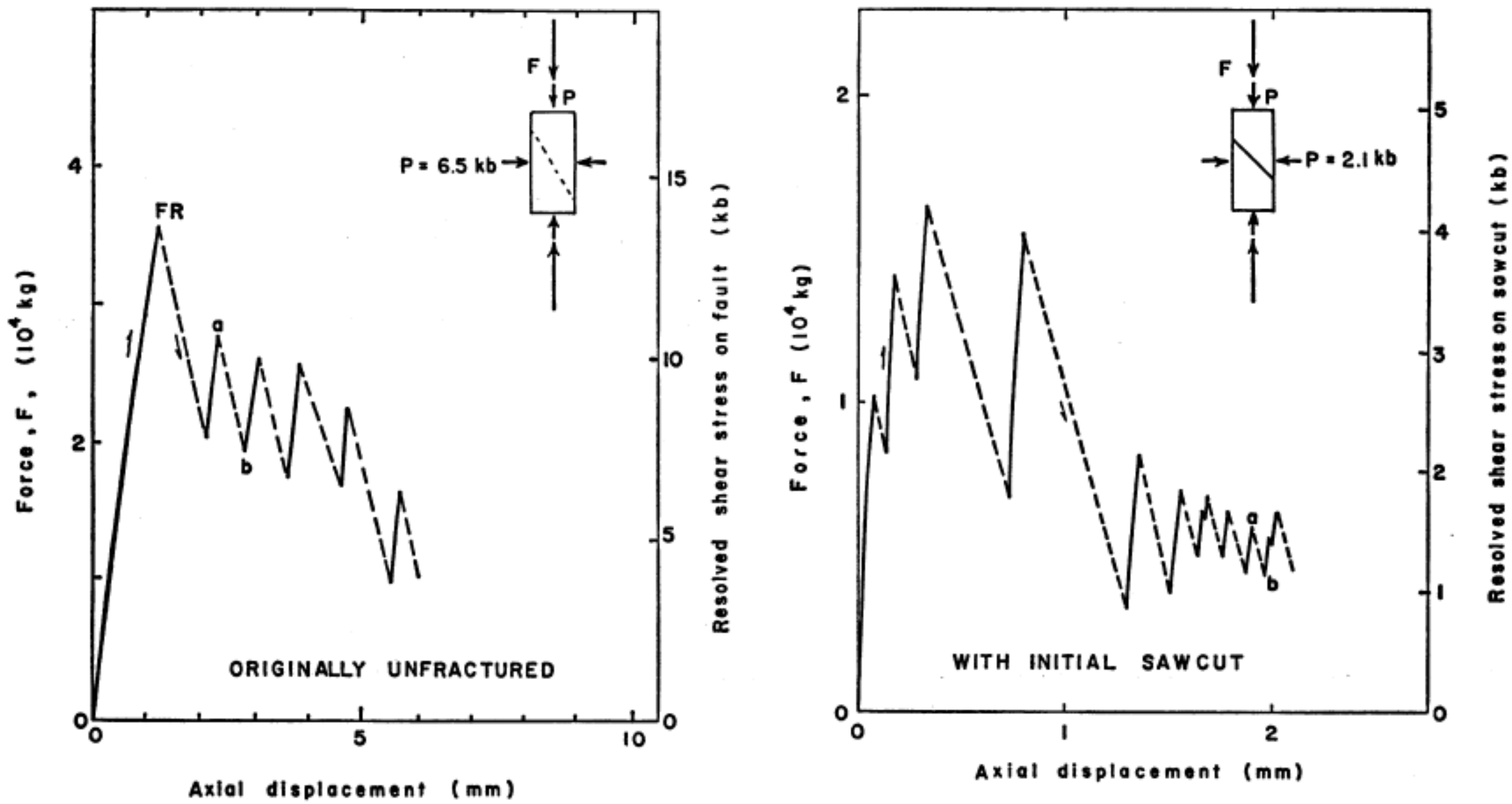
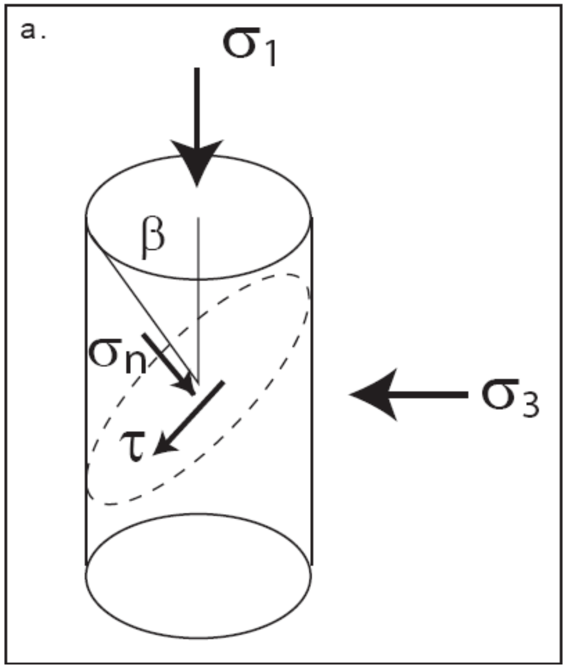
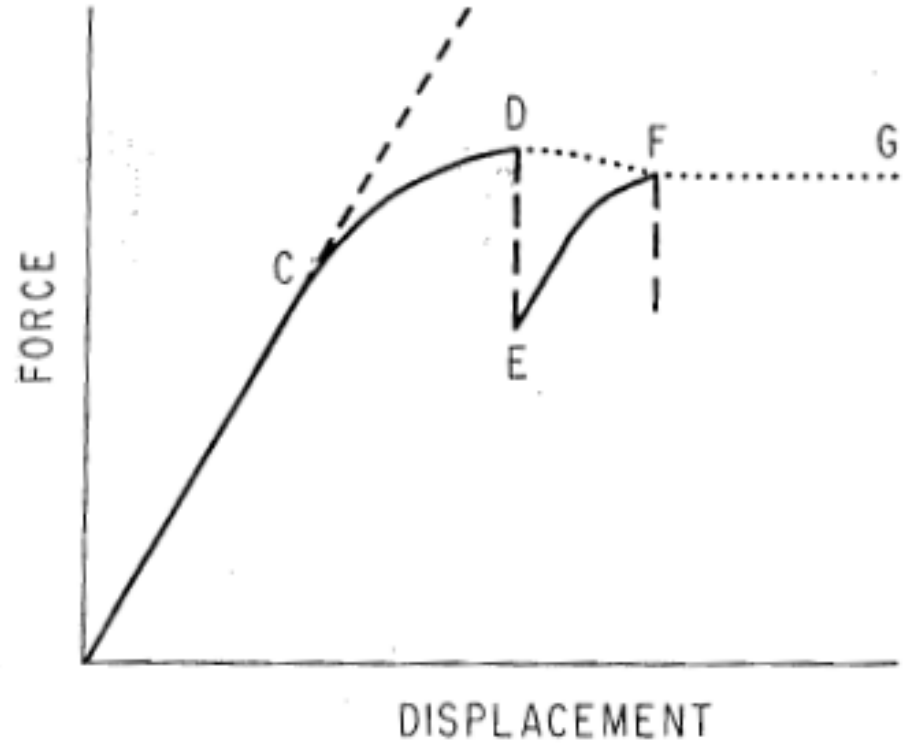
Stick-Slip and Crustal Earthquakes



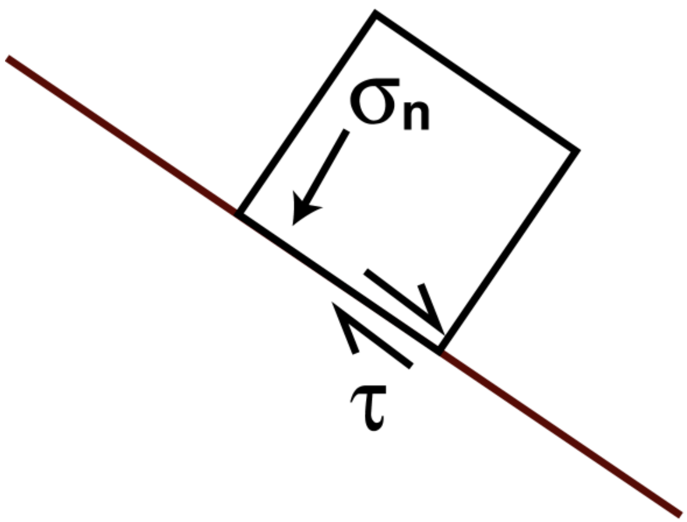
Laboratory friction experiments on both intact and saw-cut decimeter-scale samples exhibit stick-slip behavior similar to that observed on crustal-scale faults. Is it possible to use laboratory friction experiments to learn about plate bounding faults? Is the physics the same?

Stick-slip and Fault Friction





Coulomb Criterion – Frictional Sliding

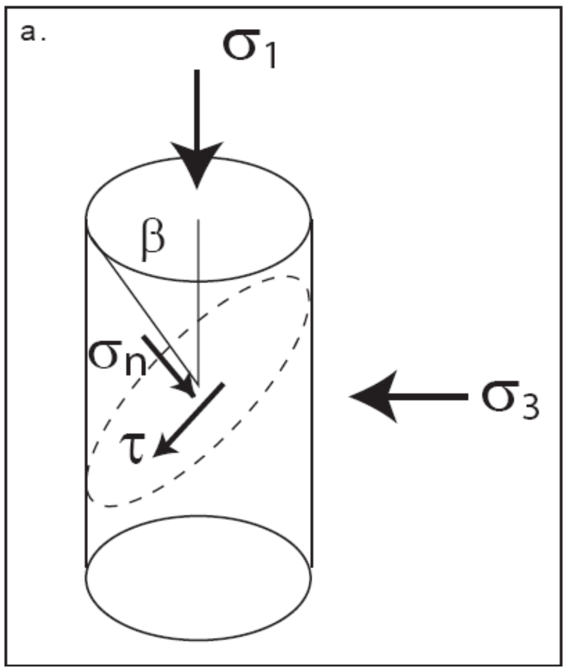


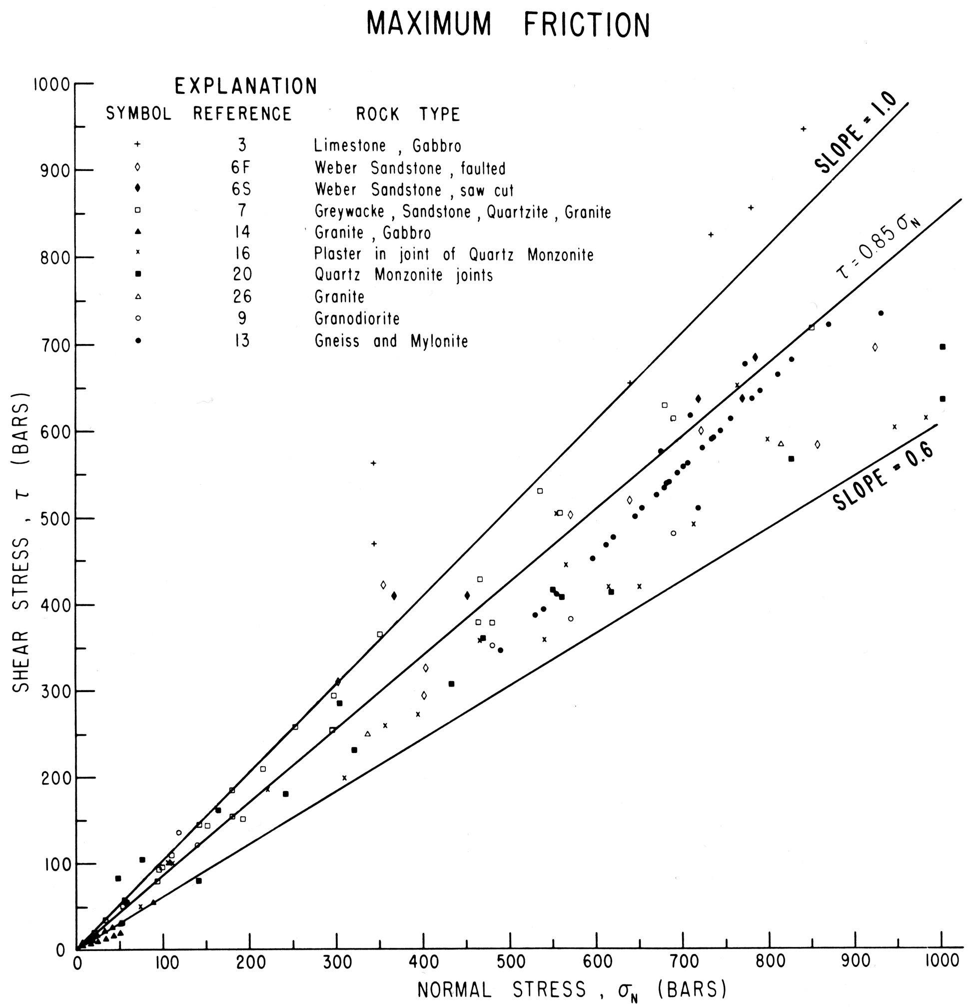
Sliding occurs when Amonton's Law is satisfied:

$$\frac{\tau}{\sigma_n} = \mu$$

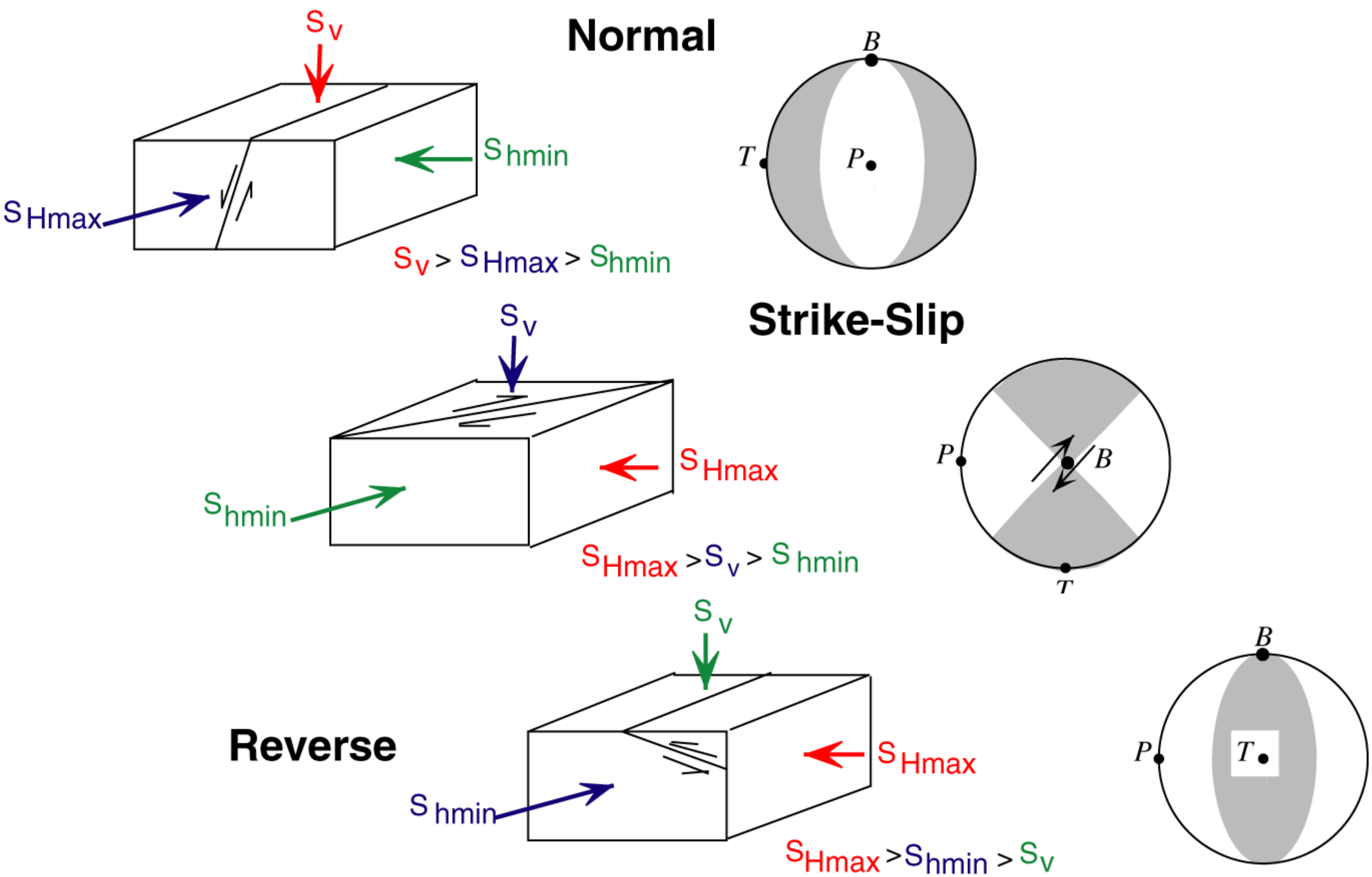
Coefficient of Friction (sliding friction)

Maximum Friction for a Variety of Rock Types

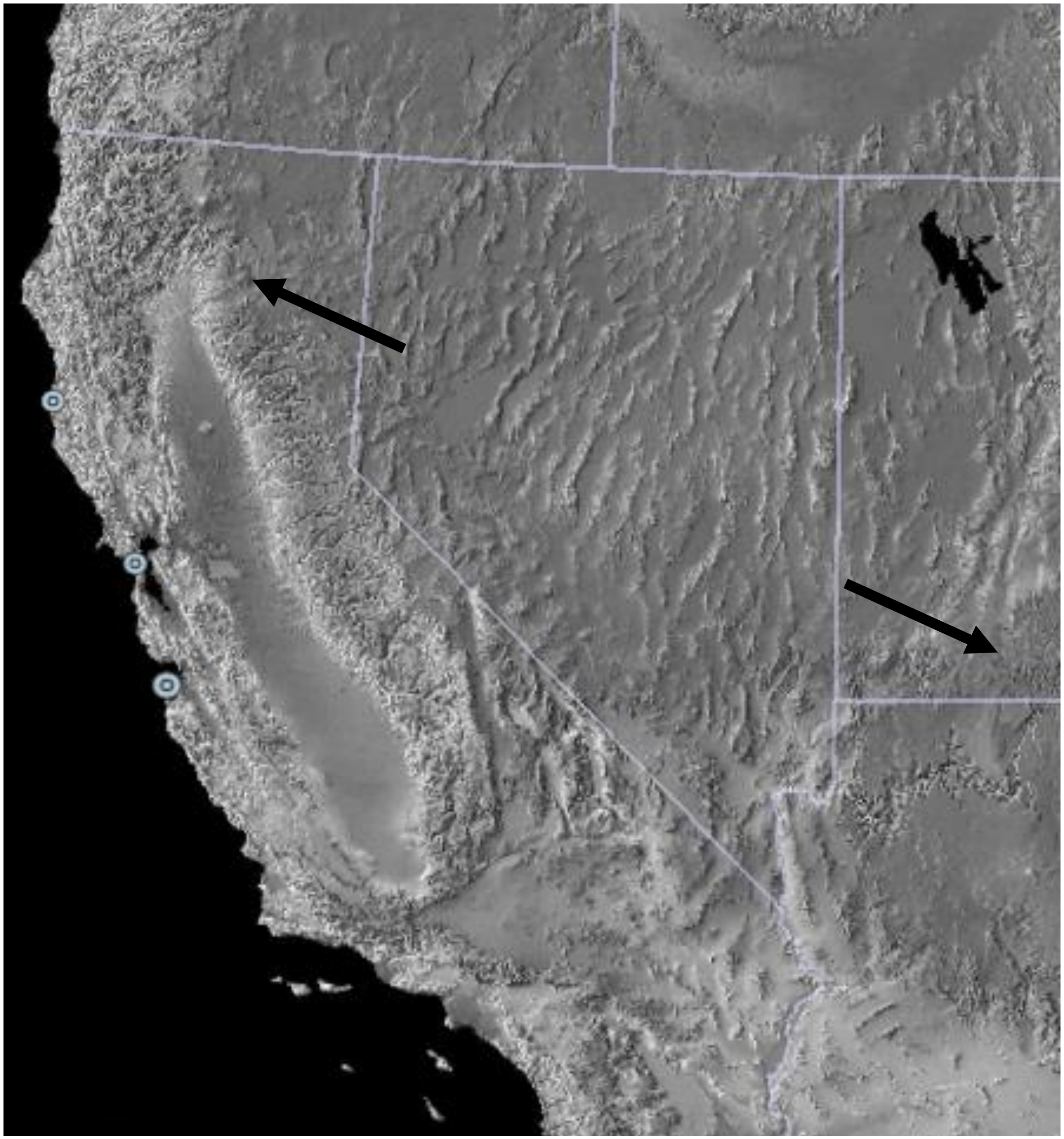




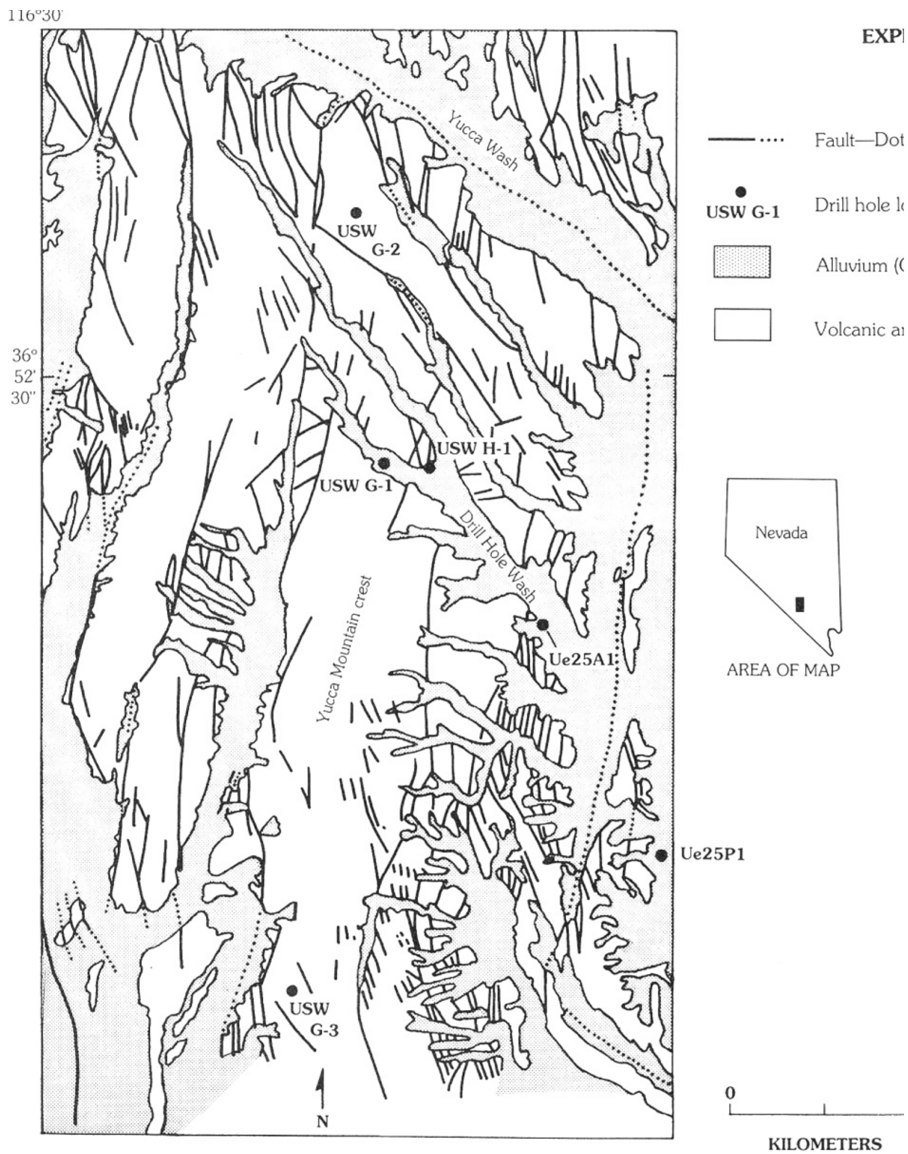
Different Tectonic Environments

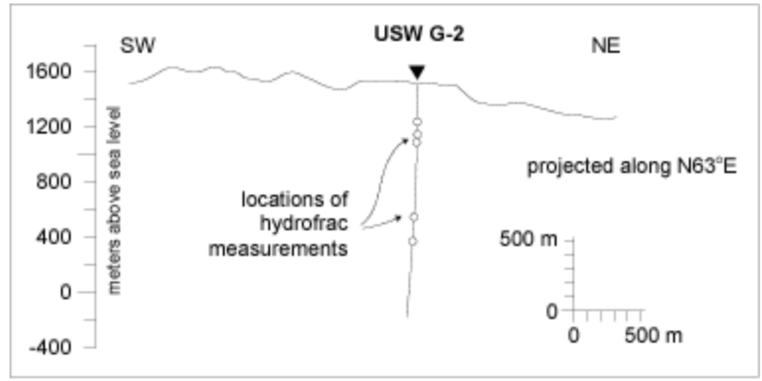


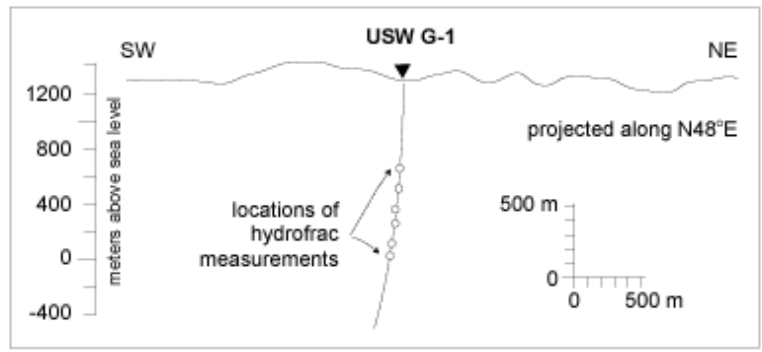
Basin and Range Extension

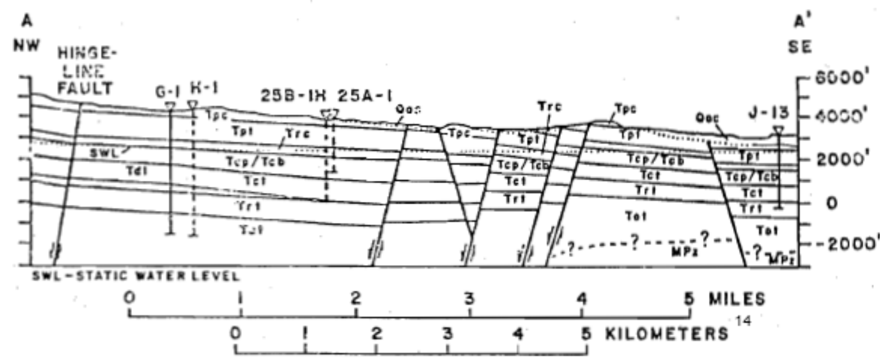


Yucca Mountain - Nevada Test Site



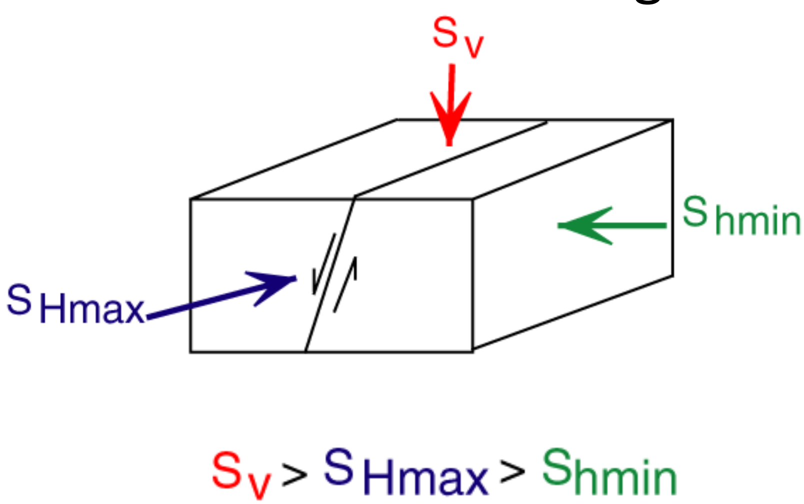




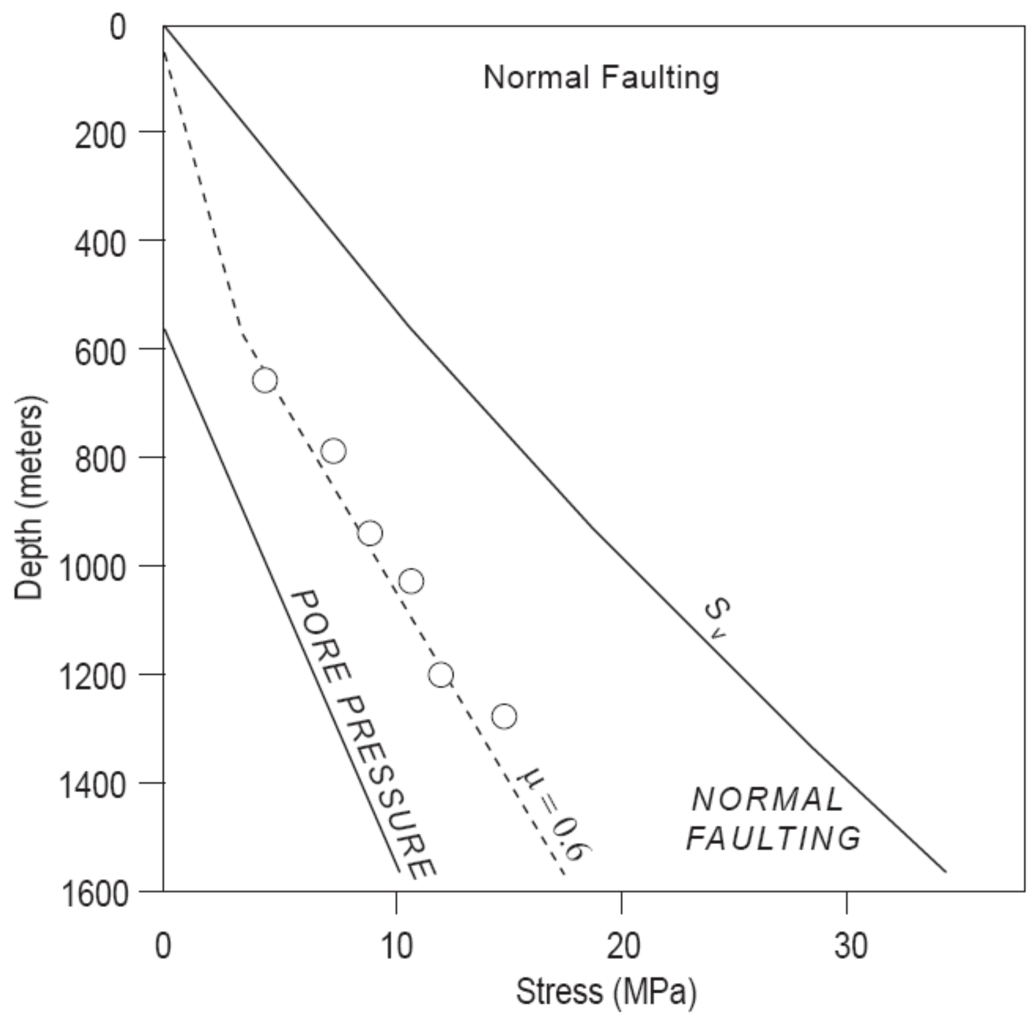


Testing Laboratory Friction Experiments

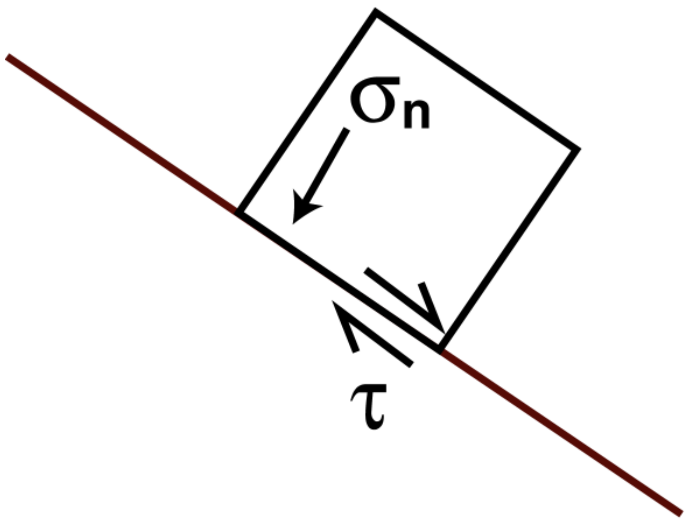
Normal Faulting



Normal faulting is controlled by the difference between the vertical stress, S_v, and the least principal horizontal stress, S_{hmin}



How Fluid Pressure Affects Frictional Sliding



Sliding occurs when Amonton's Law is satisfied:

$$\frac{\tau}{\sigma_n} = \mu$$

Coefficient of Friction (sliding friction)

Effective Normal Stress:

$$\sigma_n = S_n - P_p$$

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Simple Formulas Relate Earthquake Slip to Magnitude

Seismic Moment M_o = Slip × Fault Area × Shear Modulus

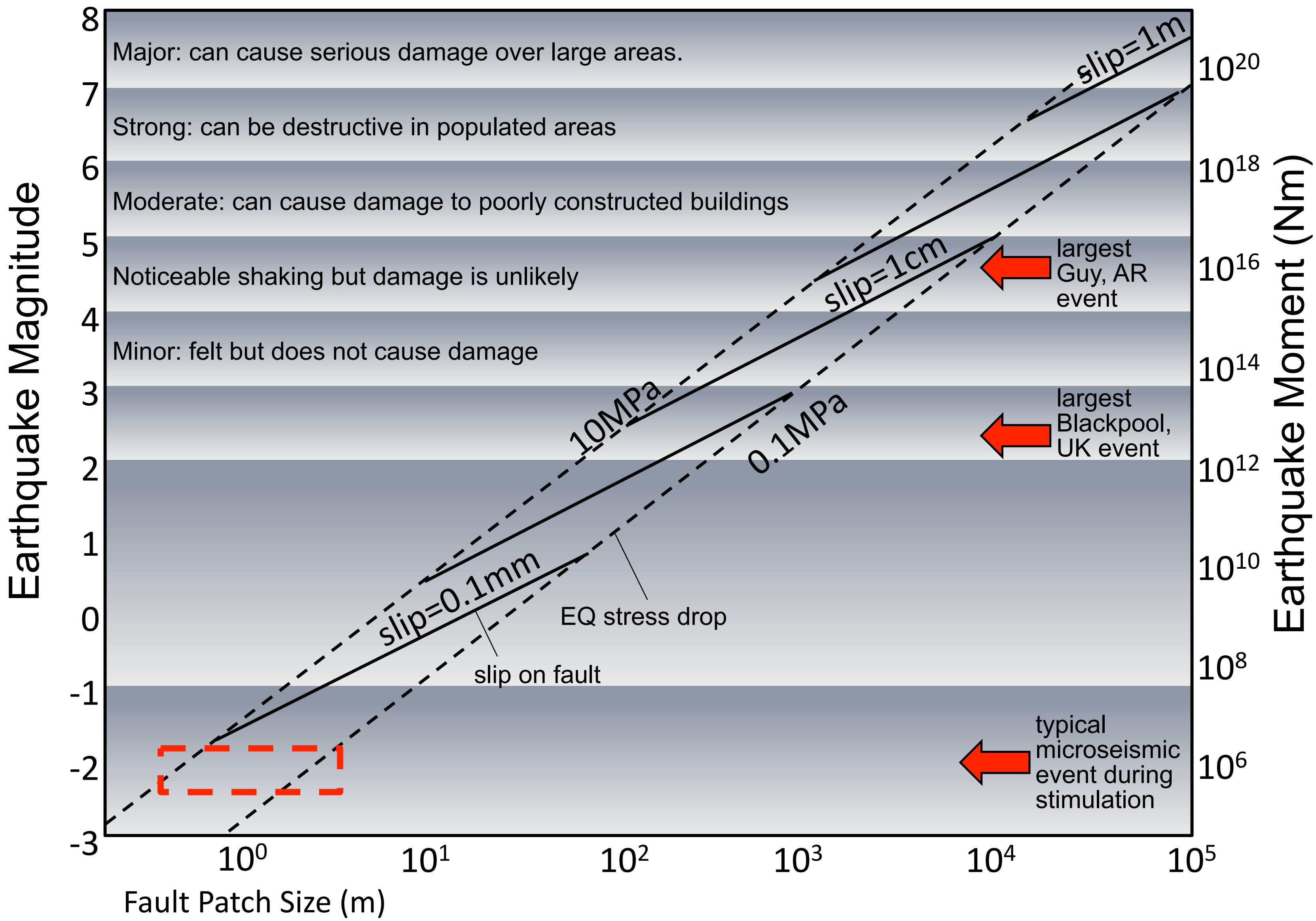
Moment Magnitude M_w (an alternative Richter magnitude, especially useful for very large earthquakes)

$$M_w = \frac{2}{3}\log_{10} M_o - 10.7 \quad \text{if } M_w \text{ units dyn cm}$$

$$M_w = \frac{2}{3}\log_{10} M_o - 6 \quad \text{if } M_w \text{ units N m}$$

Fundamentally, Earthquake Magnitude is a Measure of How Big the "Patch" of a Fault Slips and How Far it Slips

Earthquake/Fault Scaling Relationships



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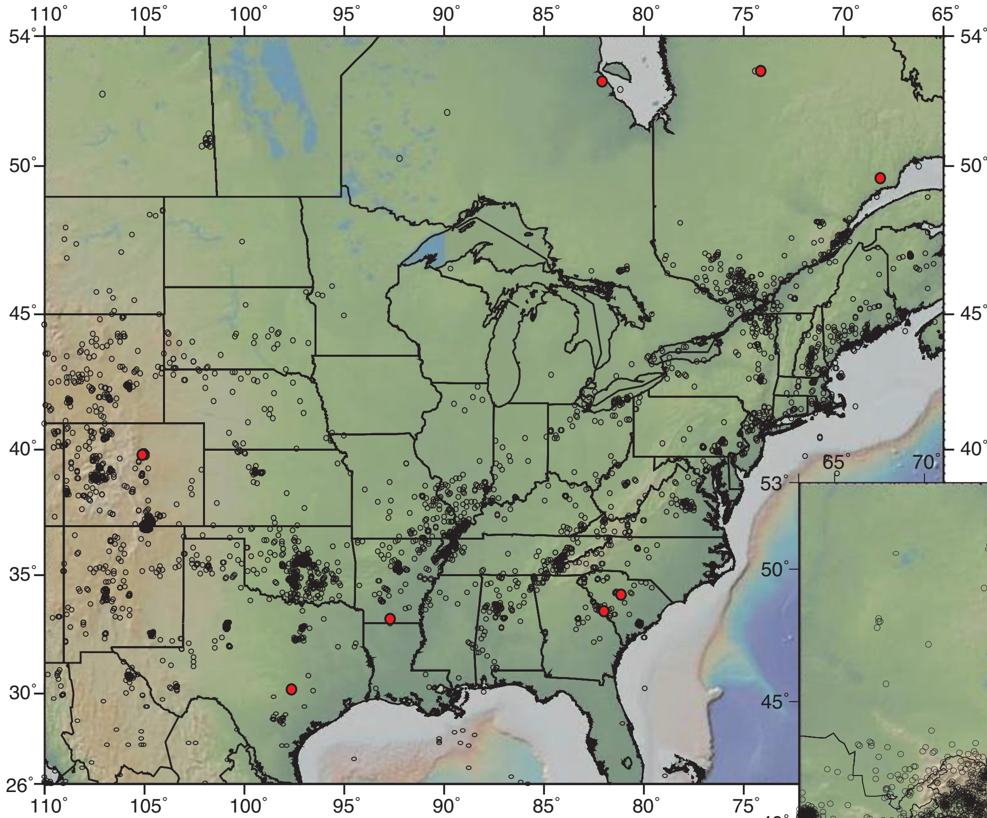
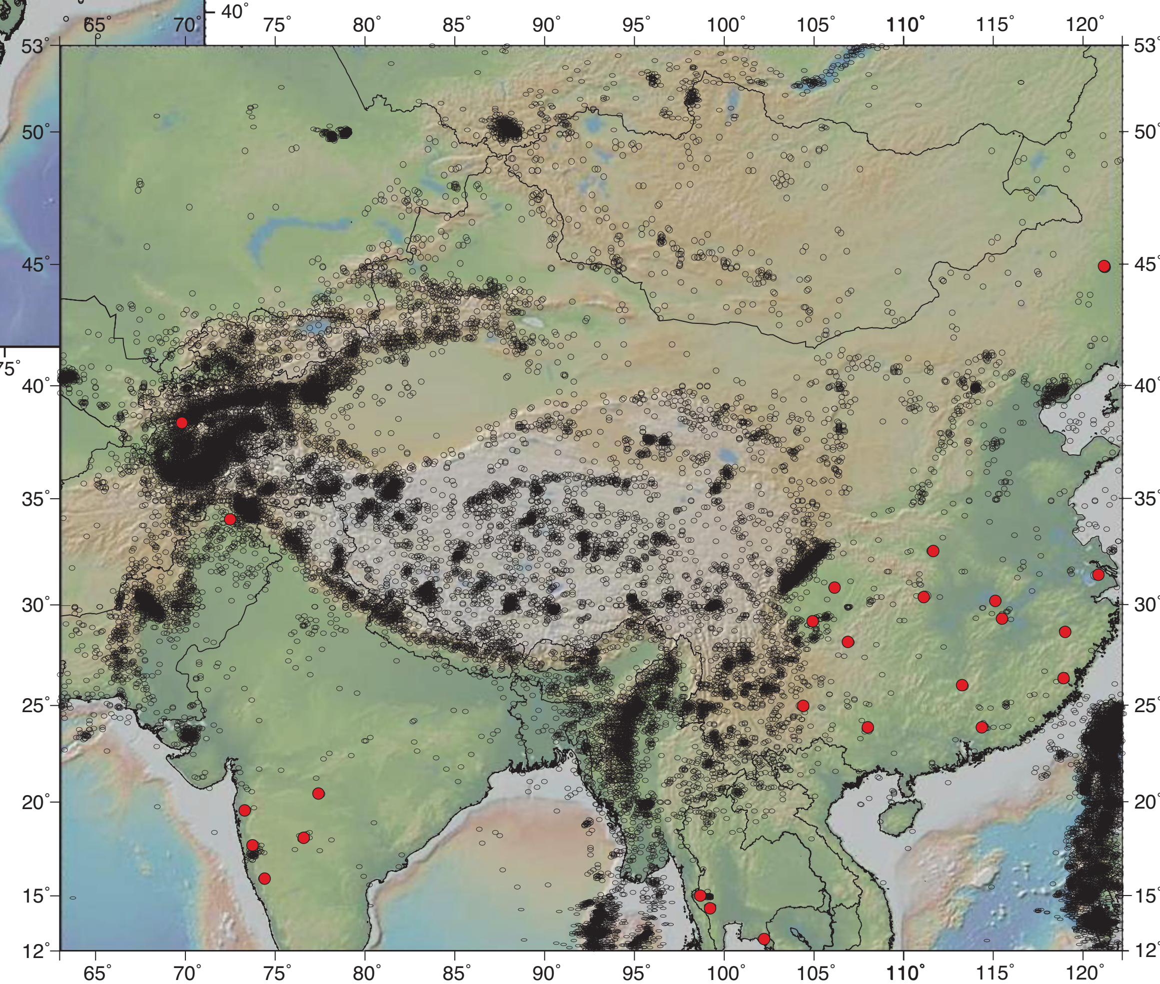
A Critically-Stressed Crust

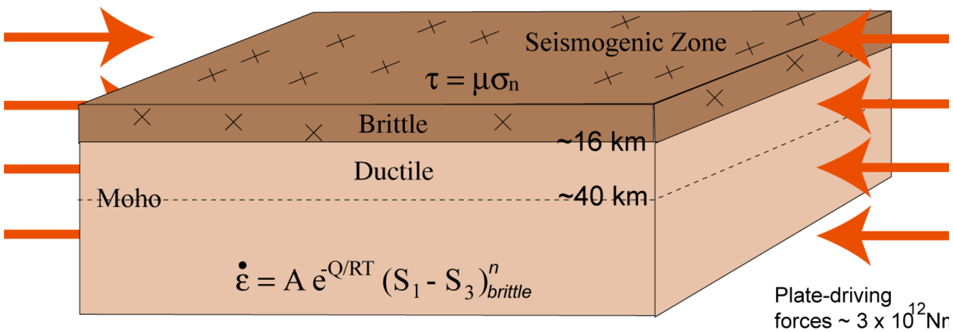


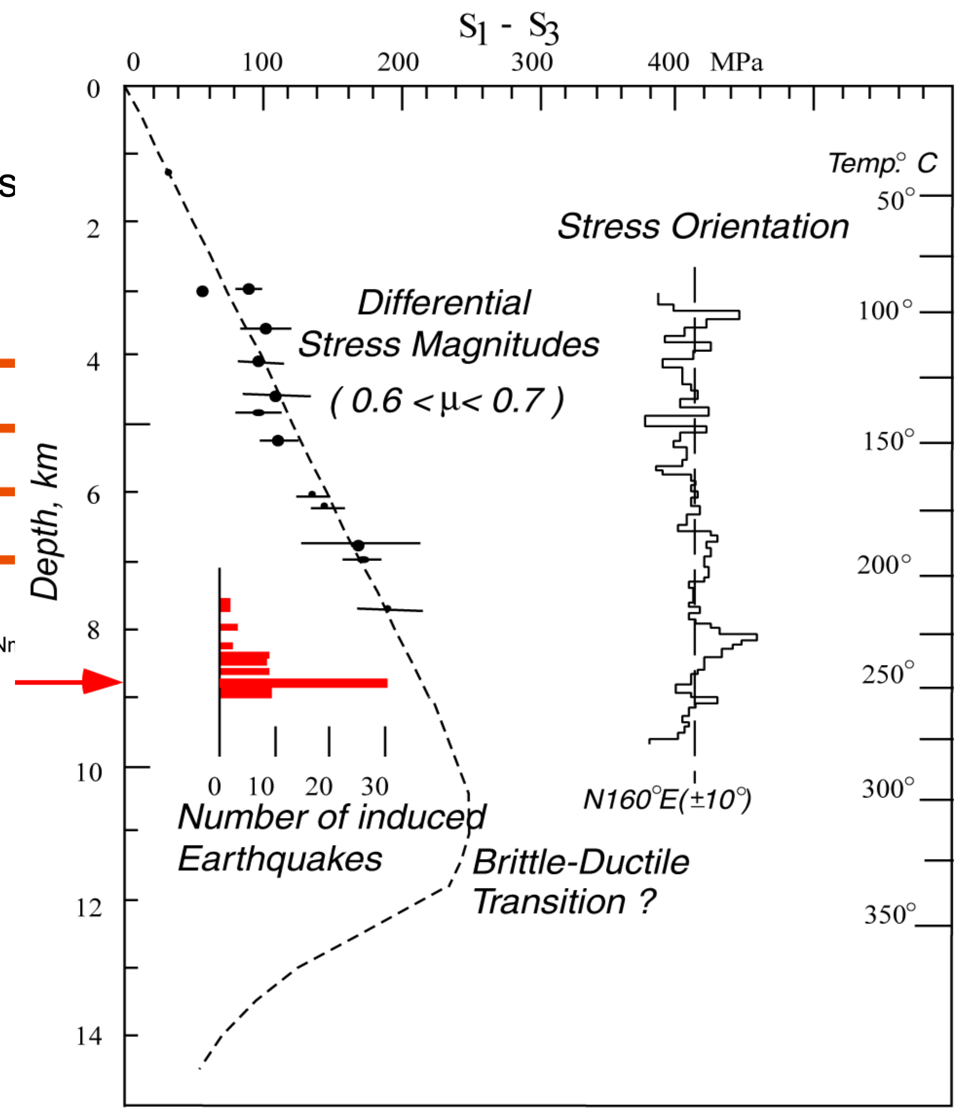


- Earthquakes Occur Nearly Everywhere in Intraplate Areas
- Small Perturbations Capable of Triggering Seismicity, Even in "Stable Areas"
- Rate of Earthquakes Reflect Intraplate Strain Rate, Not Stress State

Brittle Crust in Failure Equilibrium

Brittle Failure in Critically-Stressed Crust Results From Creep in Lower Crust and Upper Mantle





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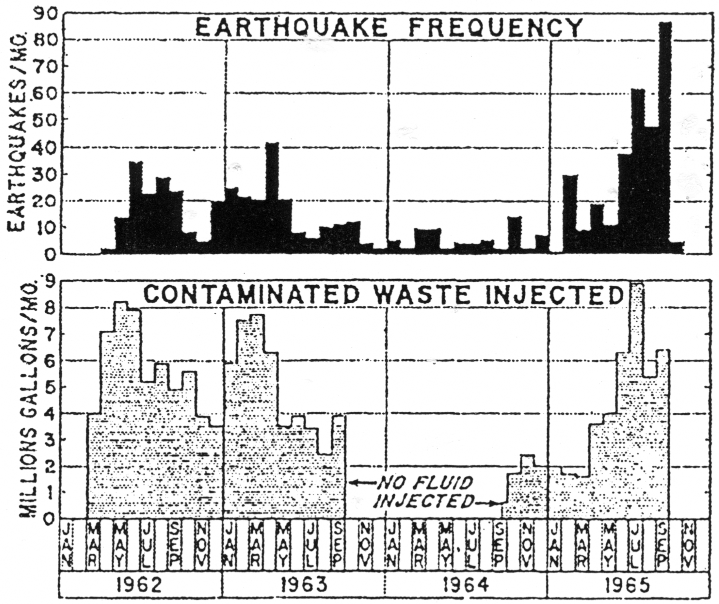
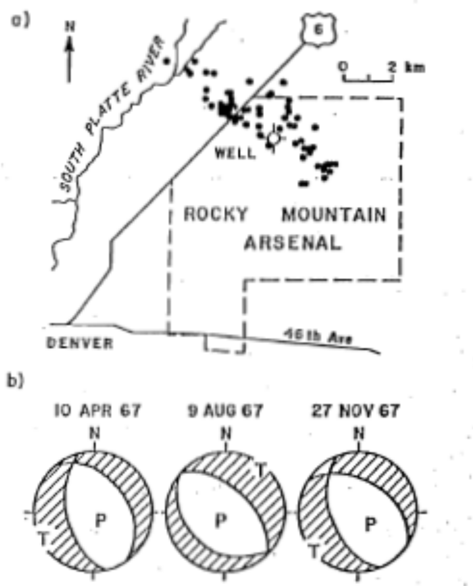
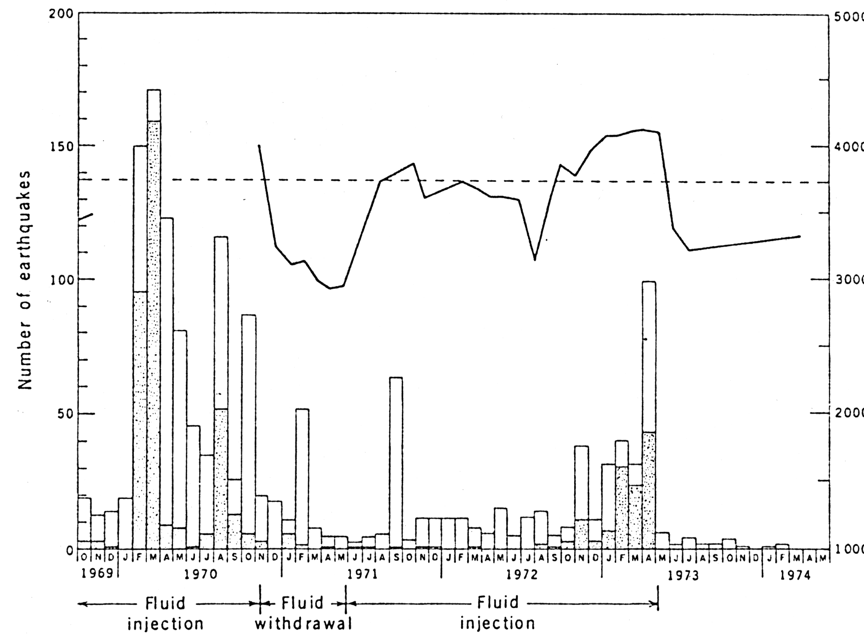
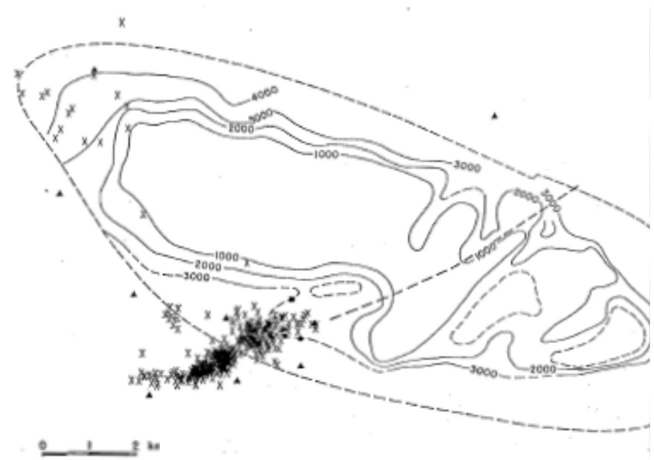
Waste Injection
Denver Arsenal





Fluid Injection
Rangely Oil Field





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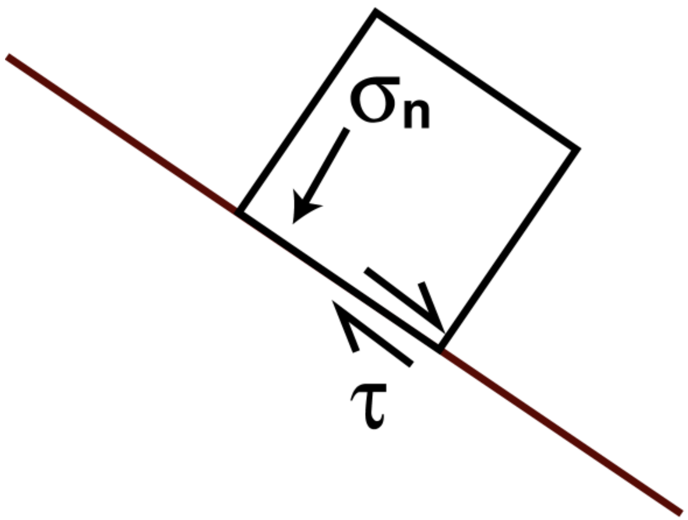

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Coefficient of Friction (sliding friction)

Effective Normal Stress:

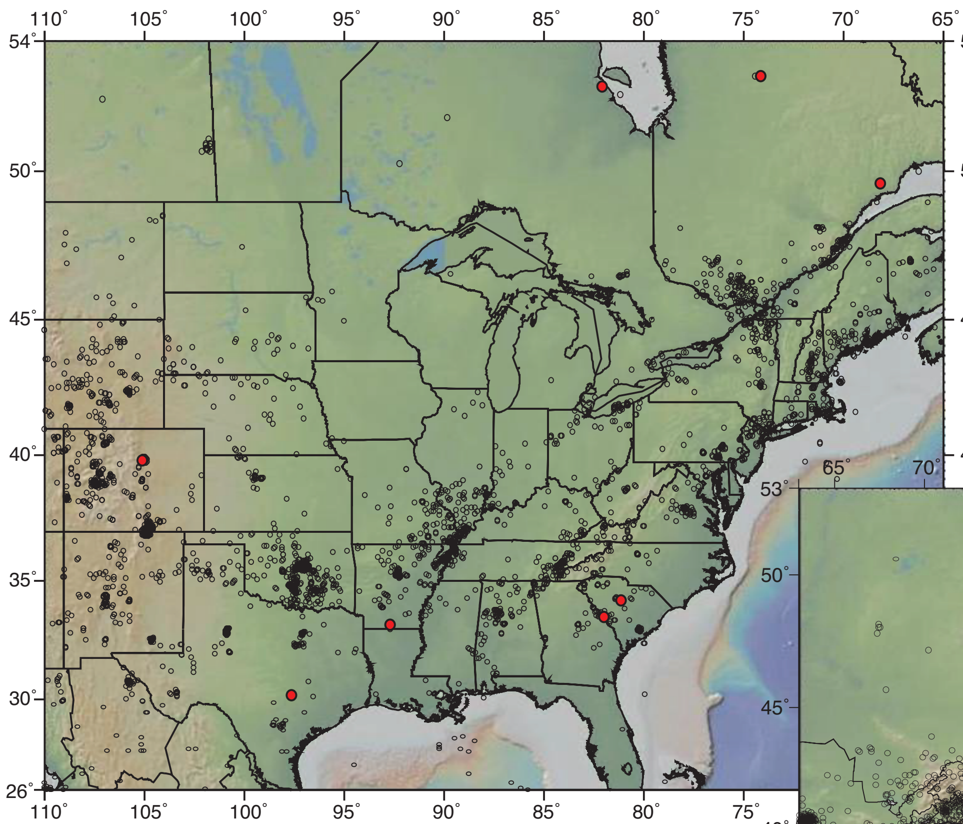
$$\sigma_n = S_n - P_p$$

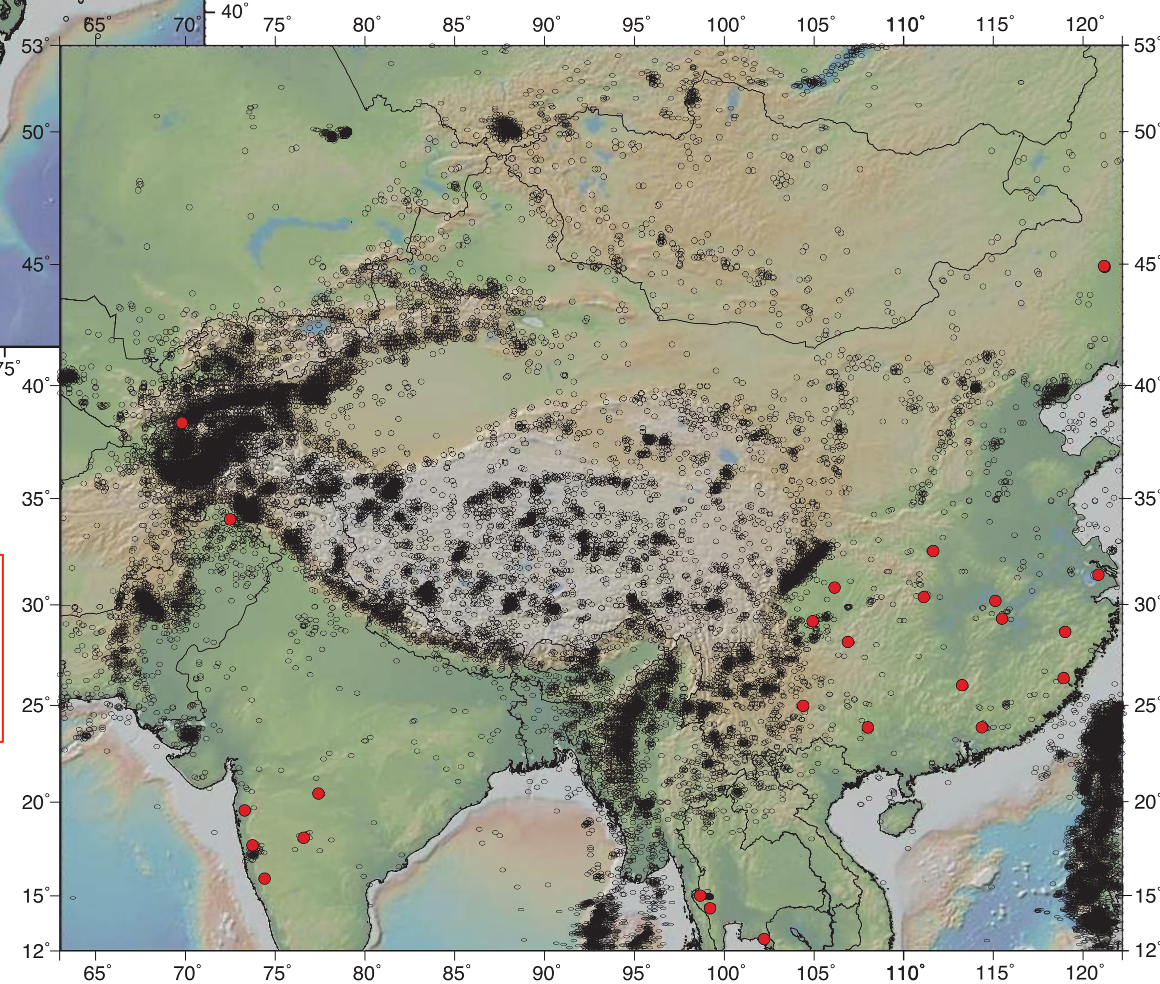
Important Definitions

- Triggered Earthquakes – A small perturbation triggers slip on a geologically active faults. The earthquake would have occurred someday as a natural geologic process. The earthquake could be quite big (if it occurs on a big fault) but the perturbation could be quite small.

- Induced Earthquakes – Occur on geologically inactive faults. The earthquakes occur only because of a very large perturbation. The size of the earthquake depends on the size of the perturbation.

Reservoir *Induced* Earthquakes Are Actually Triggered Earthquakes





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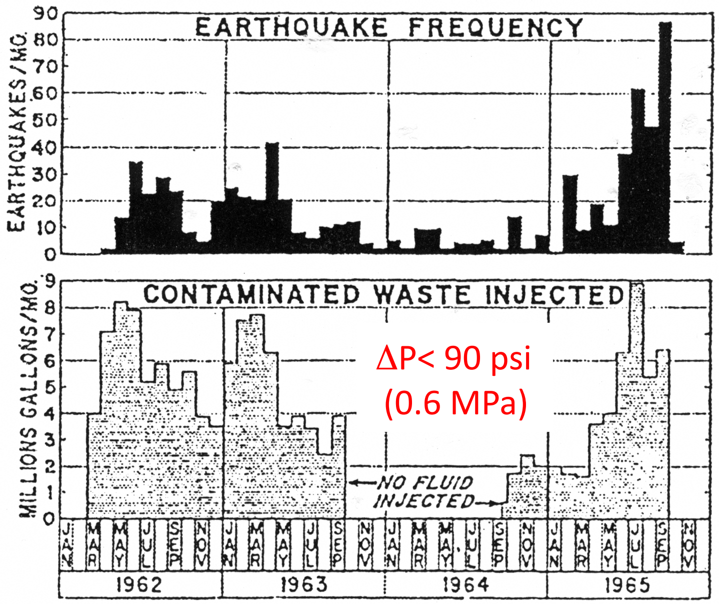

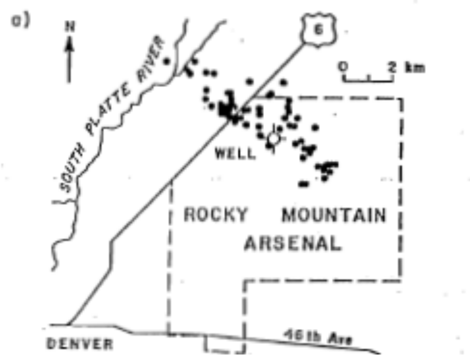

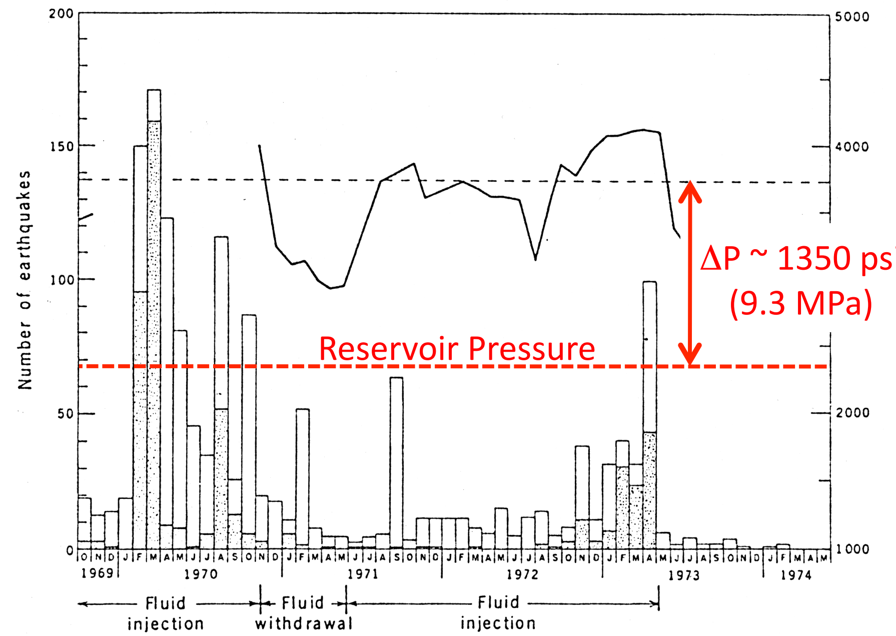

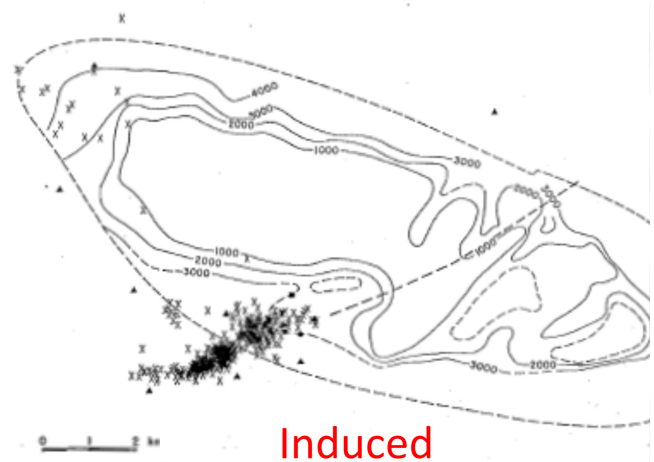

Triggered

Induced

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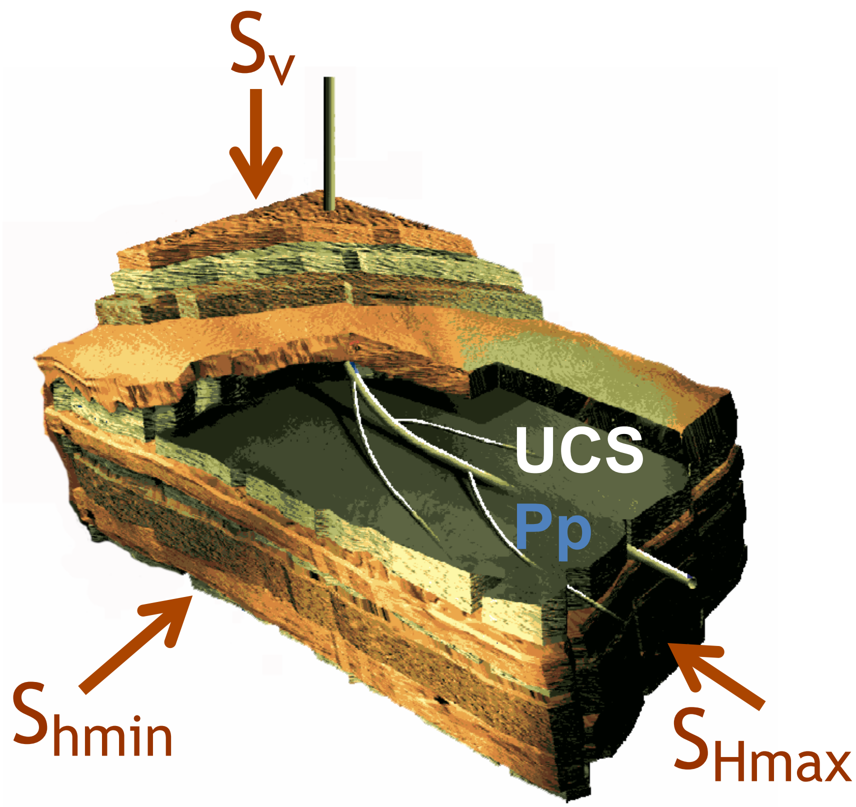
Step 1 - Develop a Geomechanical Model



Principal Stresses at Depth

S_v – Overburden

S_{Hmax} – Maximum horizontal principal stress

S_{hmin} – Minimum horizontal principal stress

Additional Components of a Geomechanical Model

P_p – Pore Pressure

UCS – Rock Strength (from logs)

Fractures and Faults (from Image Logs, Seismic, etc.)

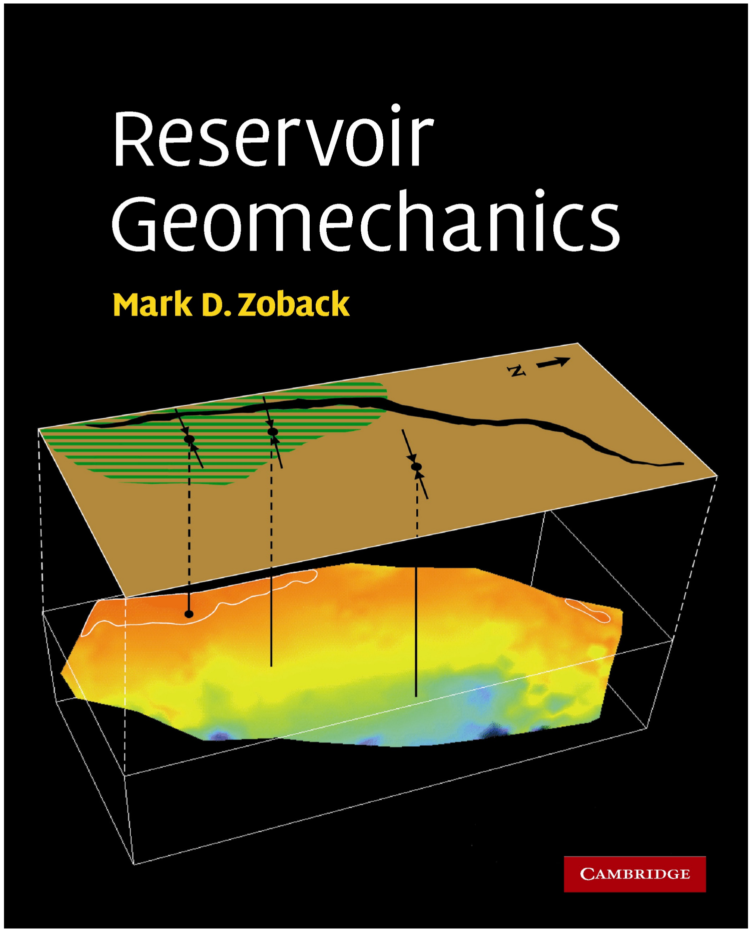
Determination of stress orientation and magnitude in deep wells

M.D. Zoback[a,*], C.A. Barton[b], M. Brudy[b], D.A. Castillo[b], T. Finkbeiner[b], B.R. Grollimund[b], D.B. Moos[b], P. Peska[b], C.D. Ward[b], D.J. Wiprut[b]

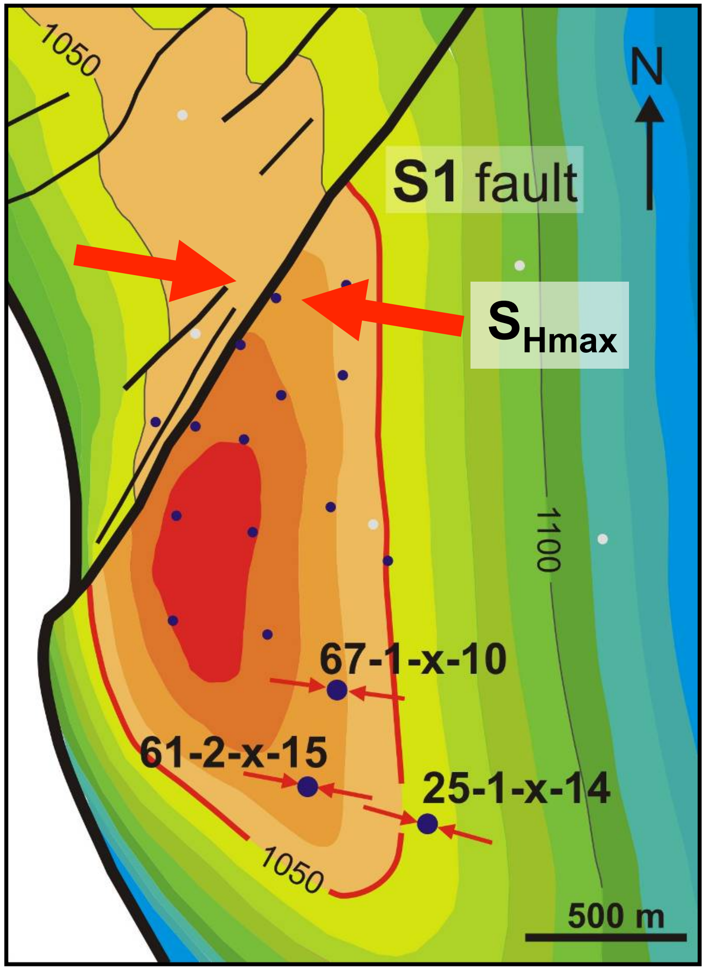
[a] Department of Geophysics, Stanford University, Stanford, CA 94605-2215, USA
[b] GeoMechanics International, Palo Alto, CA, USA

International Journal of Rock Mechanics & Mining Sciences 40 (2003) 1049–1076

International Journal of Rock Mechanics and Mining Sciences



Step 2 – Evaluate Potentially Faults



Mean S_{Hmax} orientation
N116°E

- 420 Consistent Observations of Stress Orientation
- Range of depths: 400 – 1800 m
- Tensleep Fm. ~1650 m

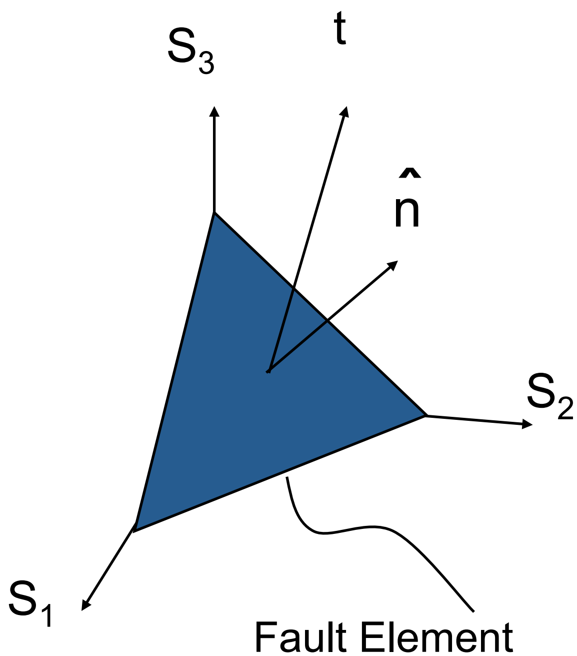
Strike-Slip/Normal Stress Magnitudes
$S_{Hmax} \approx S_v > S_{hmin}$

Step 3 – Resolve Stress onto Faults

$$\tau = \mu(S_n - P_p)$$

$$P_p = S_n - \tau / \mu$$

$P_p - P_{ref}$ = Critical Pressure Perturbation



$$\mathbf{S} = \begin{bmatrix} S_{Hmax} & 0 & 0 \\ 0 & S_v & 0 \\ 0 & 0 & S_{hmin} \end{bmatrix}$$

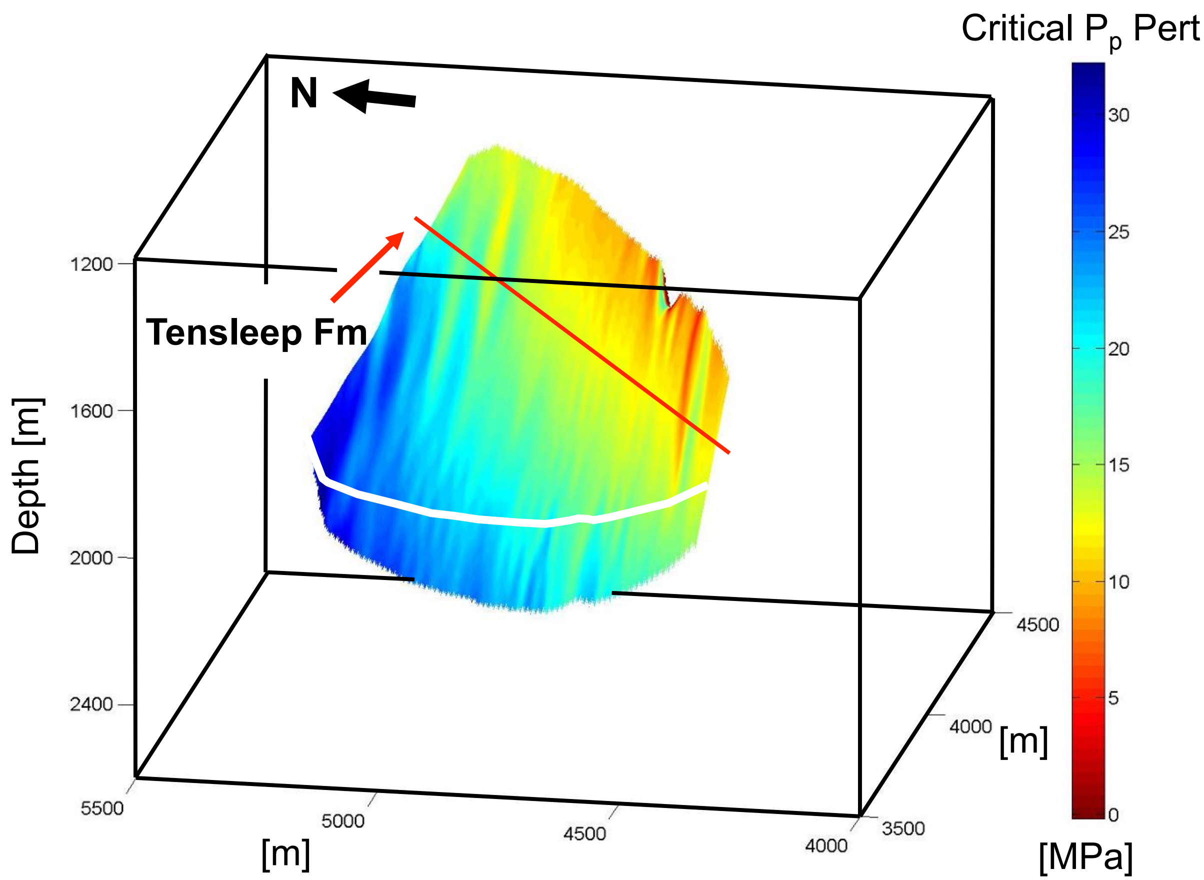
$$t = \mathbf{S}\,\hat{n}$$

$$S_n = \hat{n} \cdot t$$

$$\tau^2 = t^2 - S_n^2$$

Step 4 - Predict Slip Potential

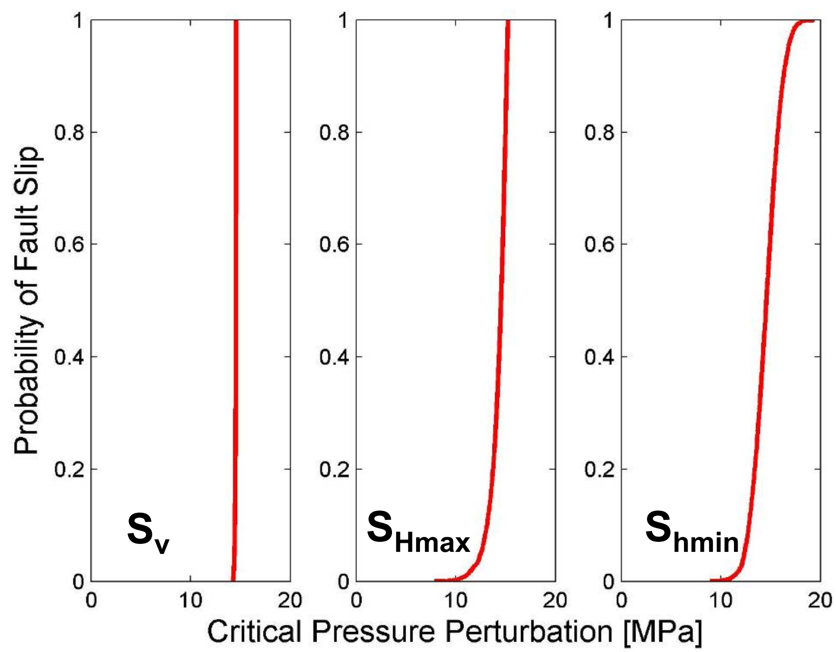
Required Critical Pressure Perturbation ~ 16 MPa



Step 5 – Evaluate Sensitivity to Uncertainties

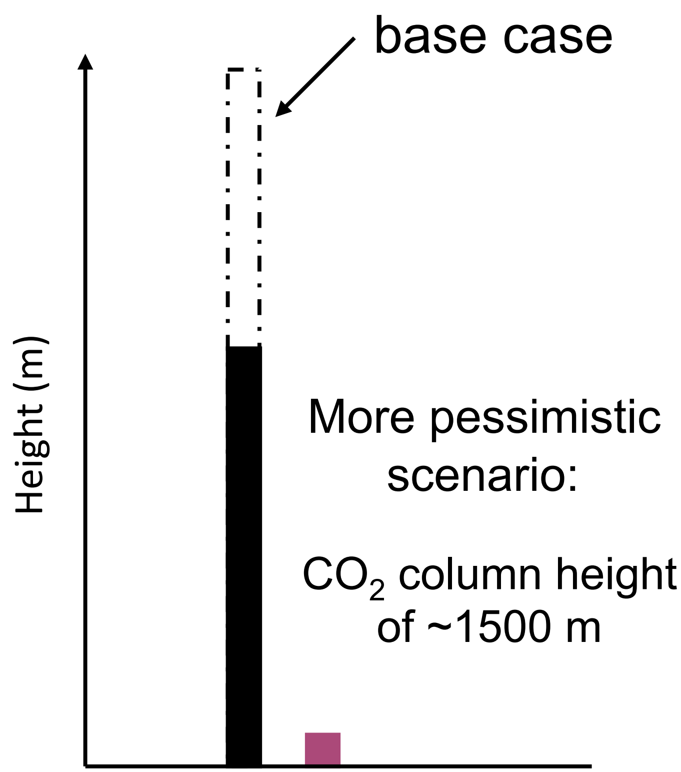
Quantitative Risk Assessment

Normal Faulting Environment



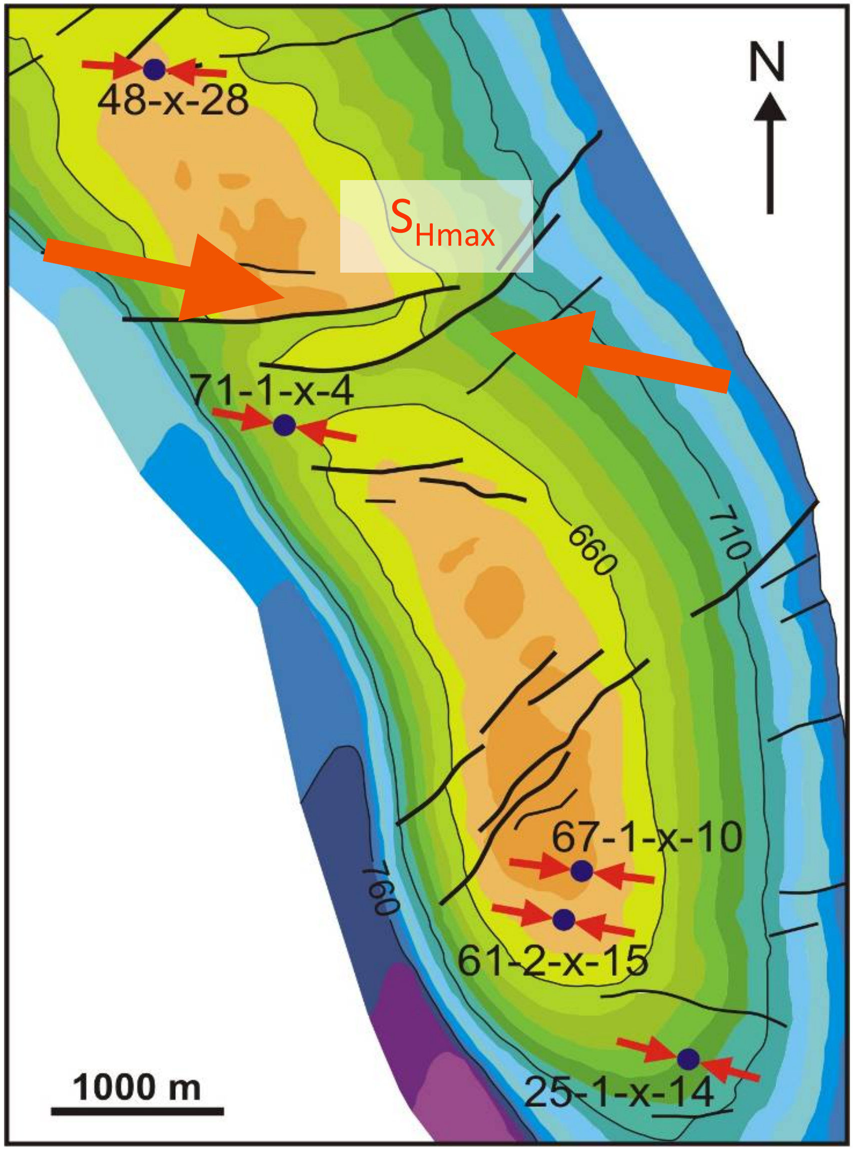
99.9% cases Critical Pressure Pert. > 9 MPa

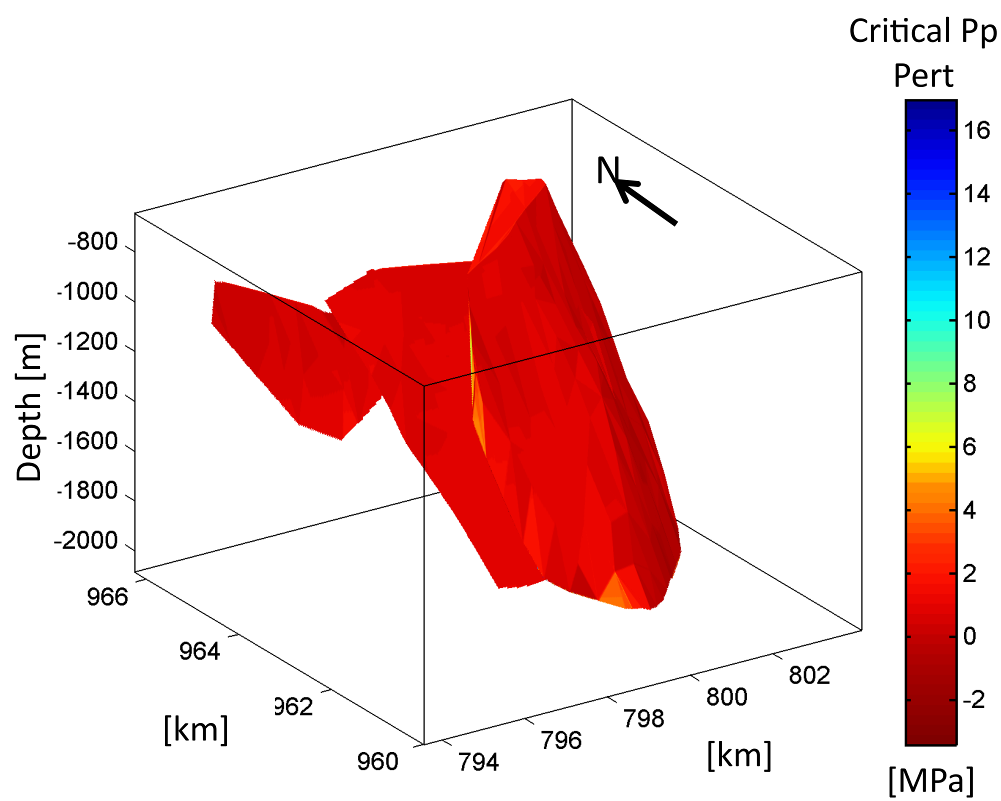
10,000 Monte Carlo Simulations



Tensleep average structural closure ~ 100m

S2 Fault Zone System





From QRA 99.9% cases

Critical Pressure Pert. < 2 MPa

Break

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Water Re-use – Western Pennsylvania

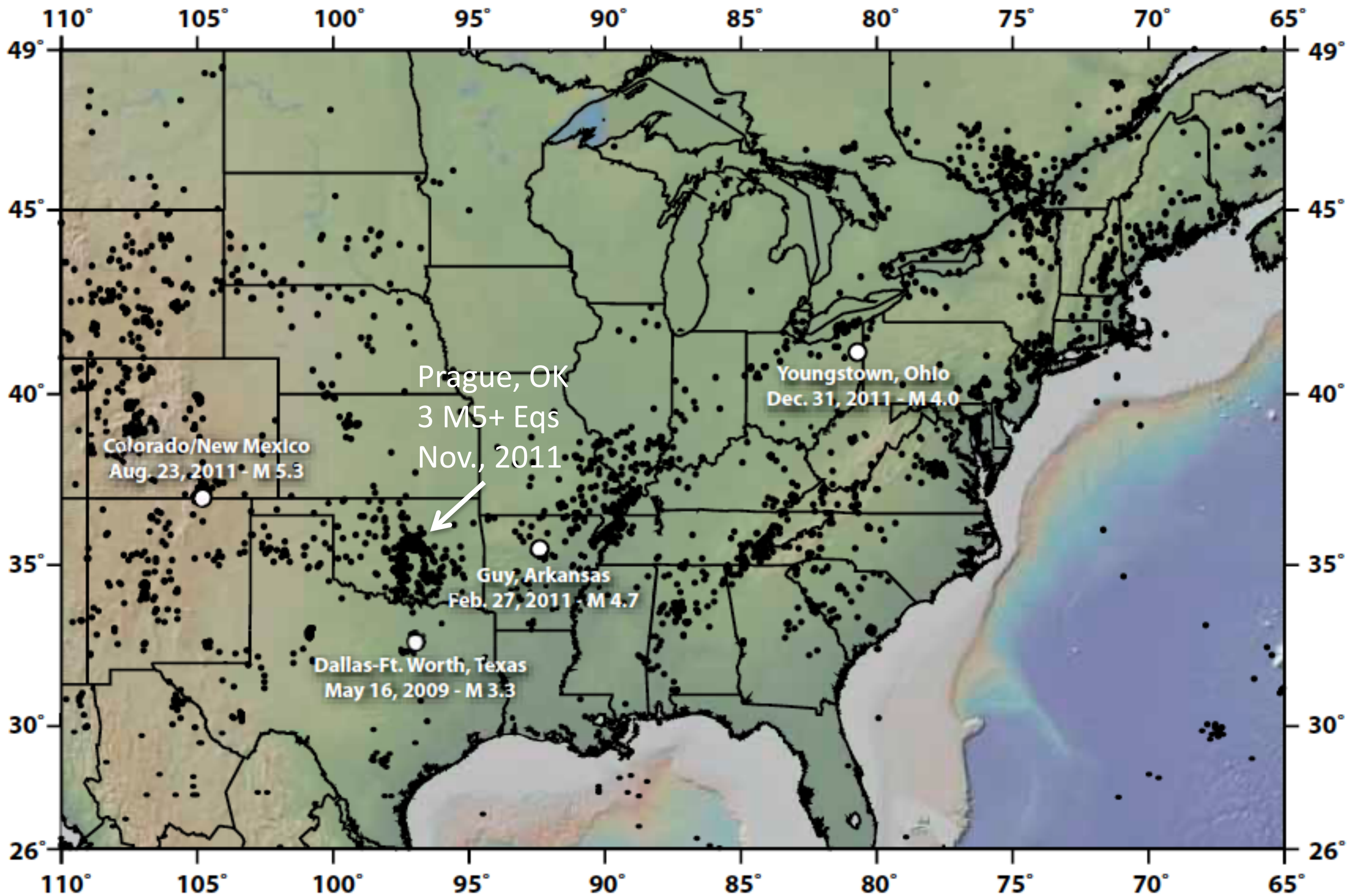
Hydraulic Fracturing Flow-Back Water

Utilization/Disposal of Saline Water

Figure 13. The Apache 34 pad in the Horn River Development of Northern British Colombia is a total of 6.3 acres where twelve multiple fractured horizontal wells recover gas from approximately 5000 acres.

Courtesy George King, Apache Corp.

Wastewater Triggered Seismicity - 2011



About 150,000 Class II EPA Injection Wells Operating in the US

Why the Increase in Seismicity?

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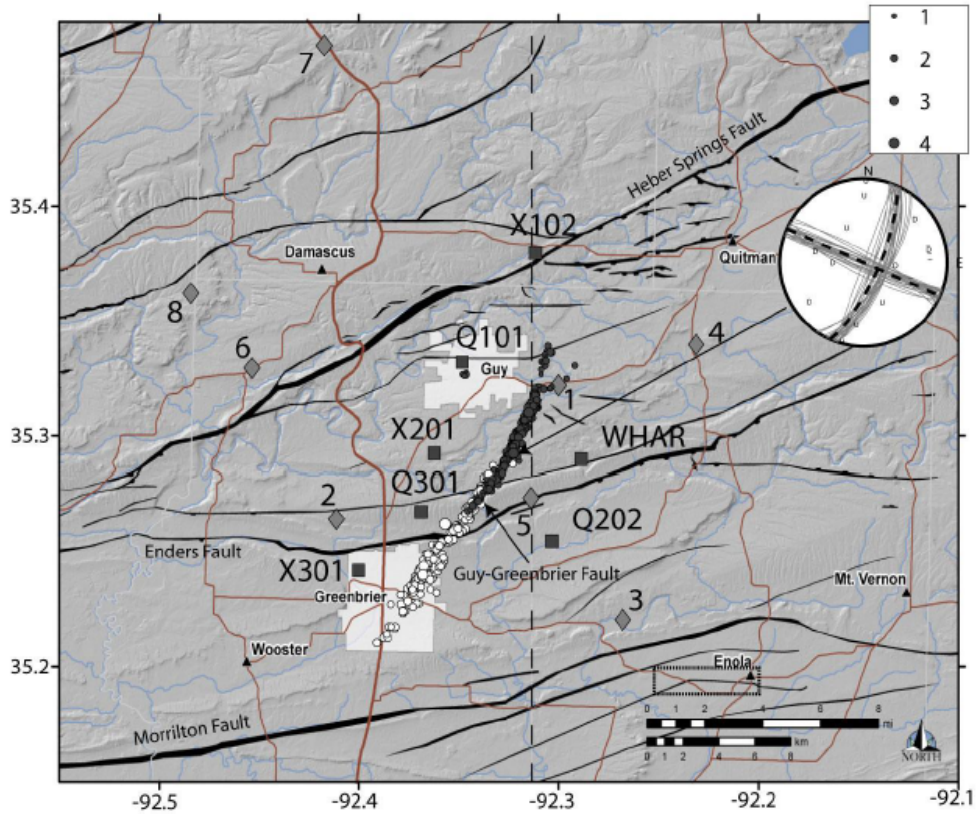
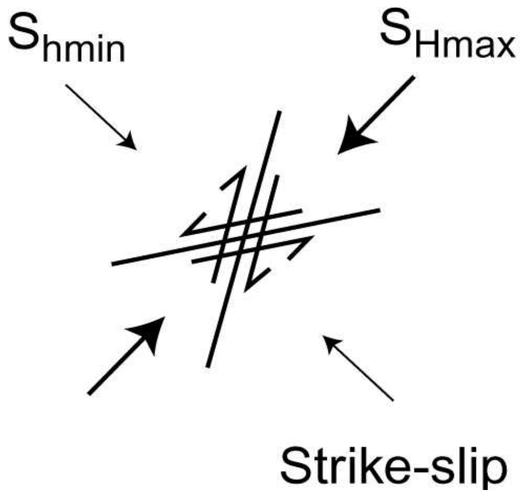
Seismicity Triggered by Flow-Back Injection

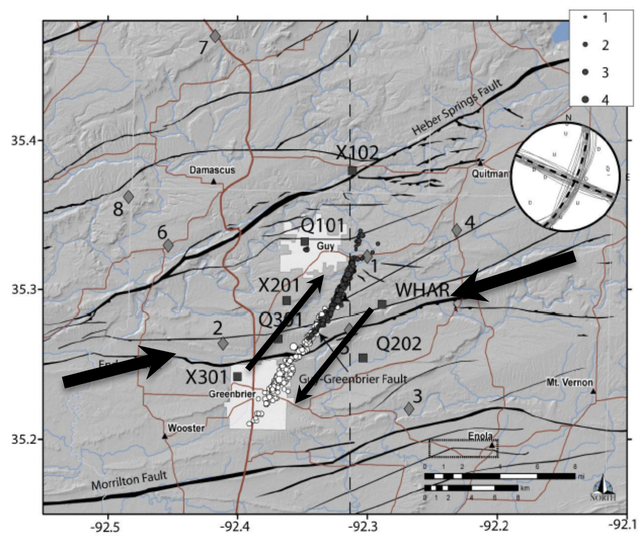


Horton (2012)

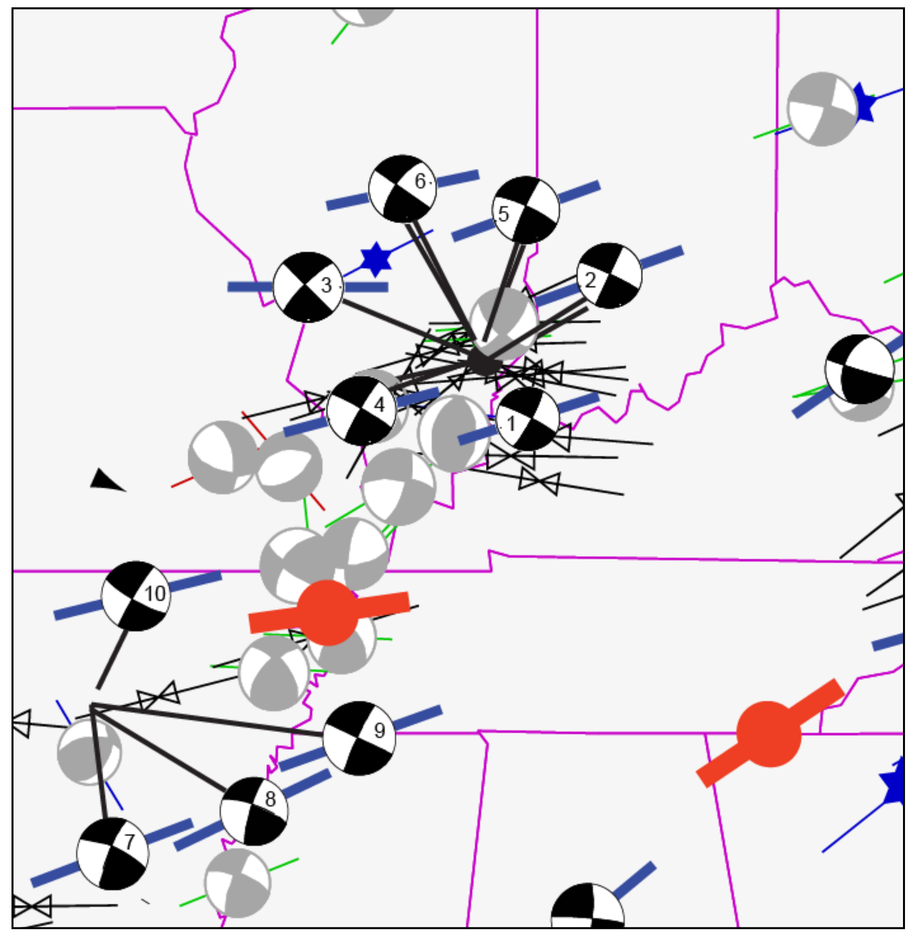
Guy Arkansas
Earthquake Swarm

Earthquakes Spreading Out Along an Active Fault



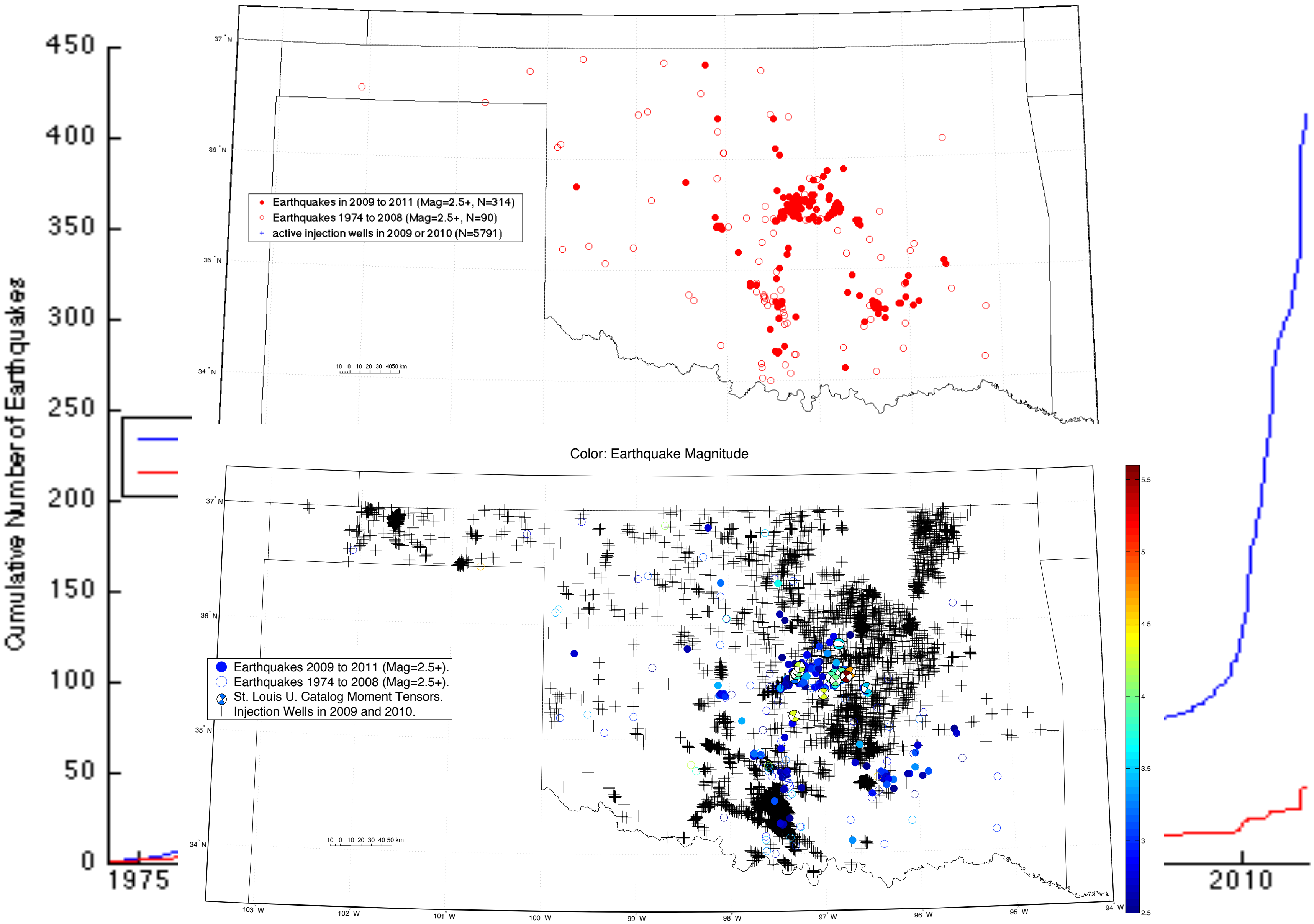


Horton (2012)

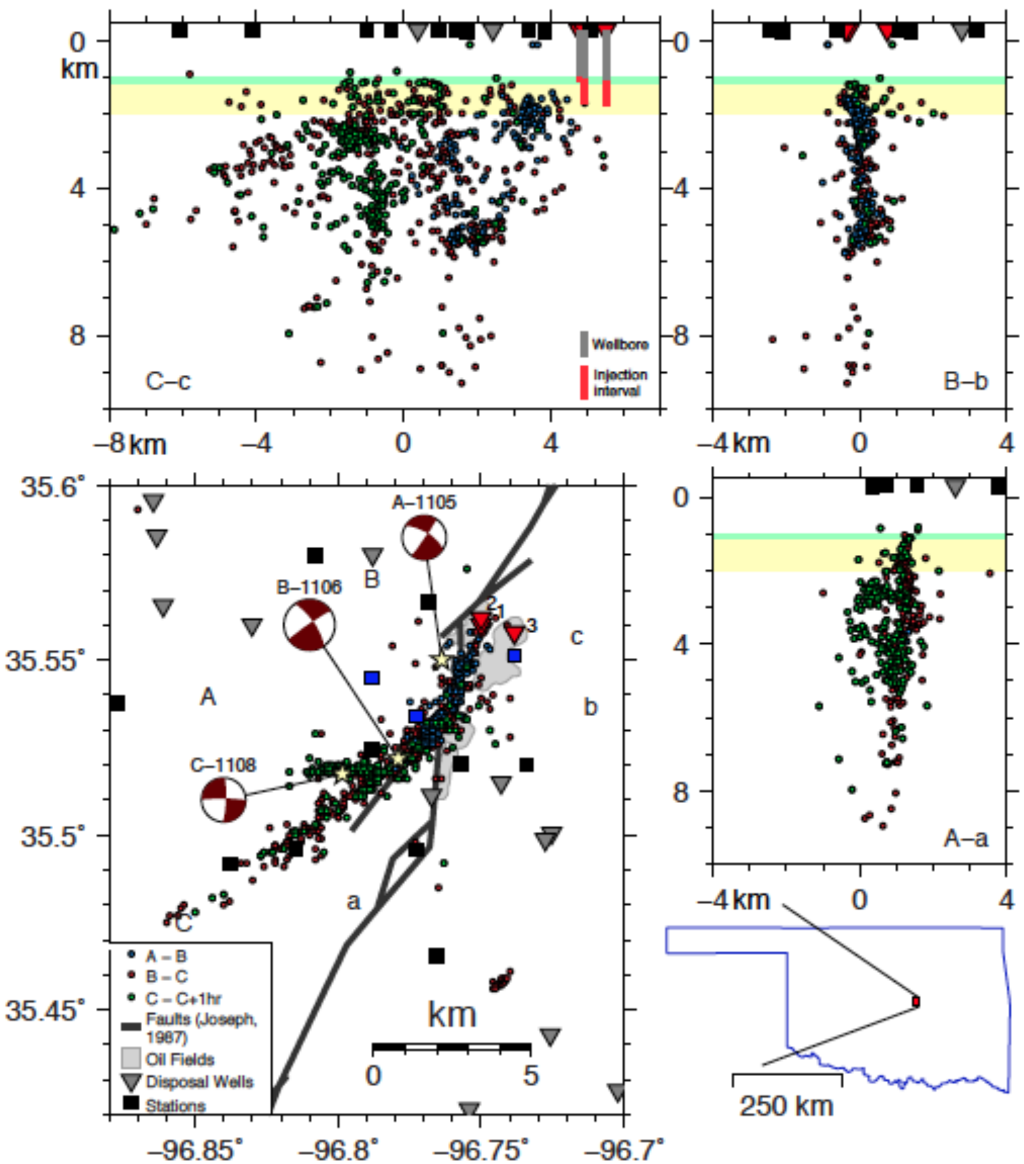


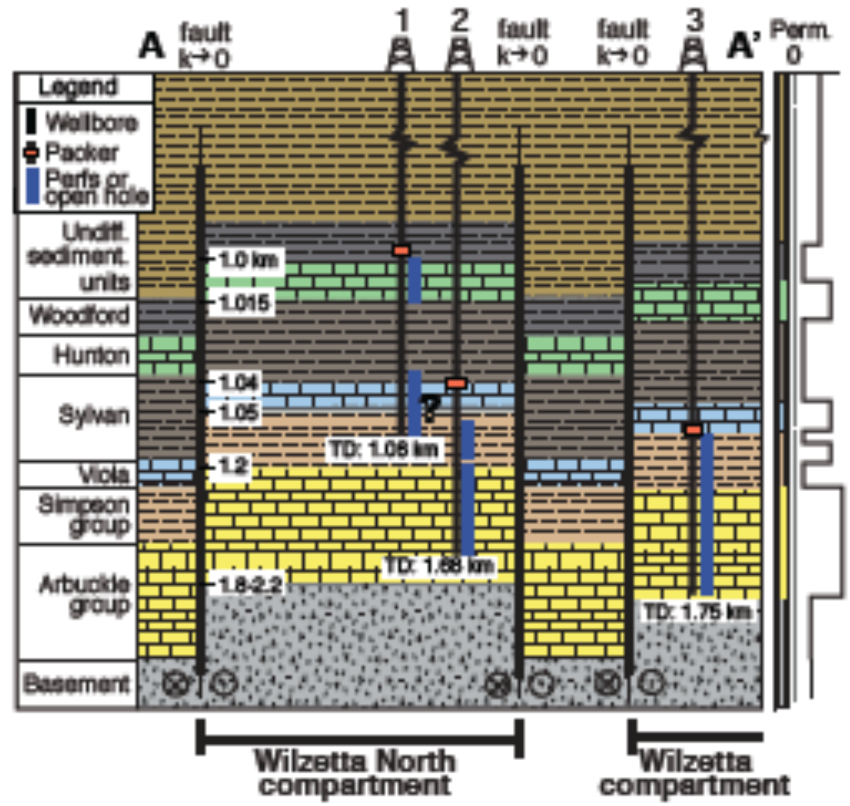
Hurd and Zoback (2012b)

What is Happening in Oklahoma?



Prague Earthquakes – Triggered By Produced Water?

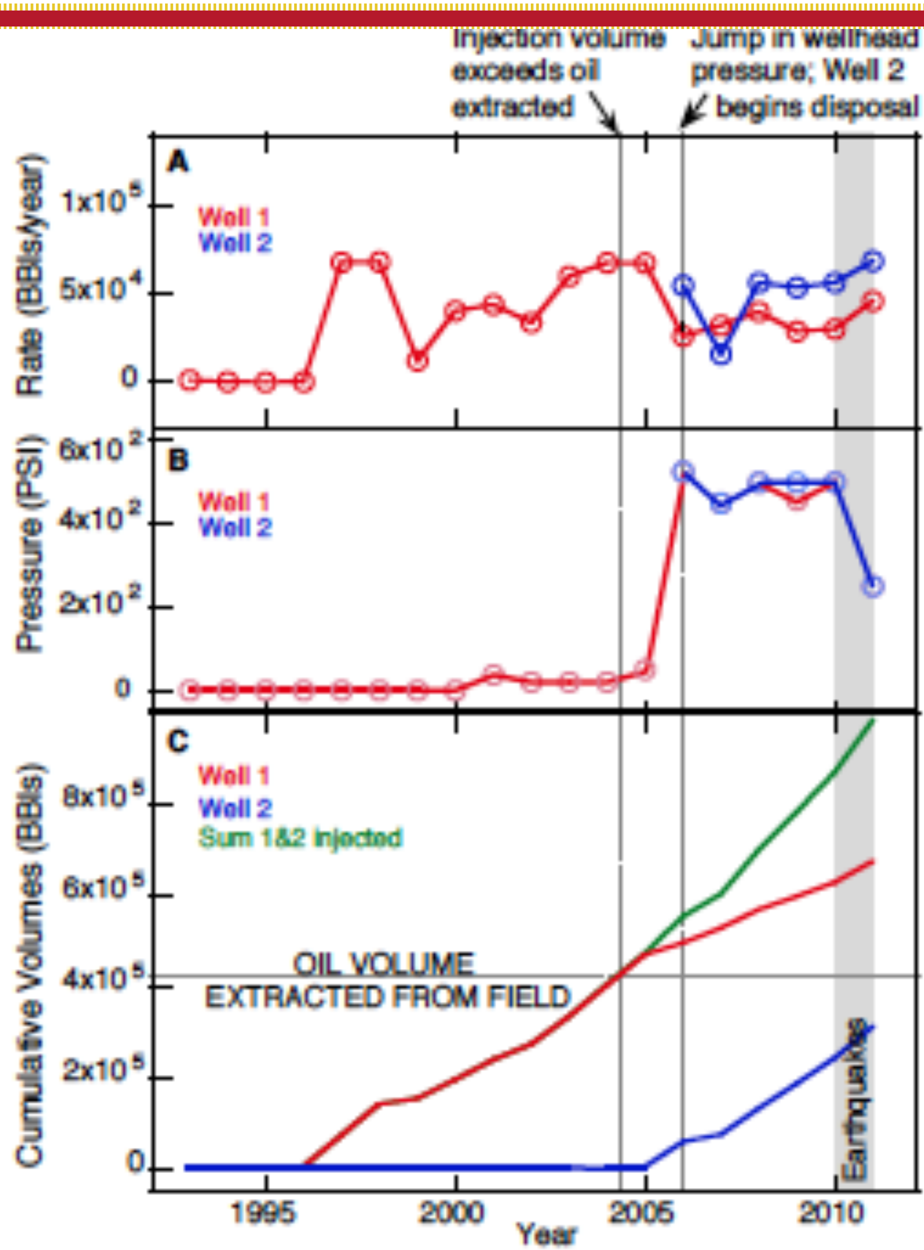


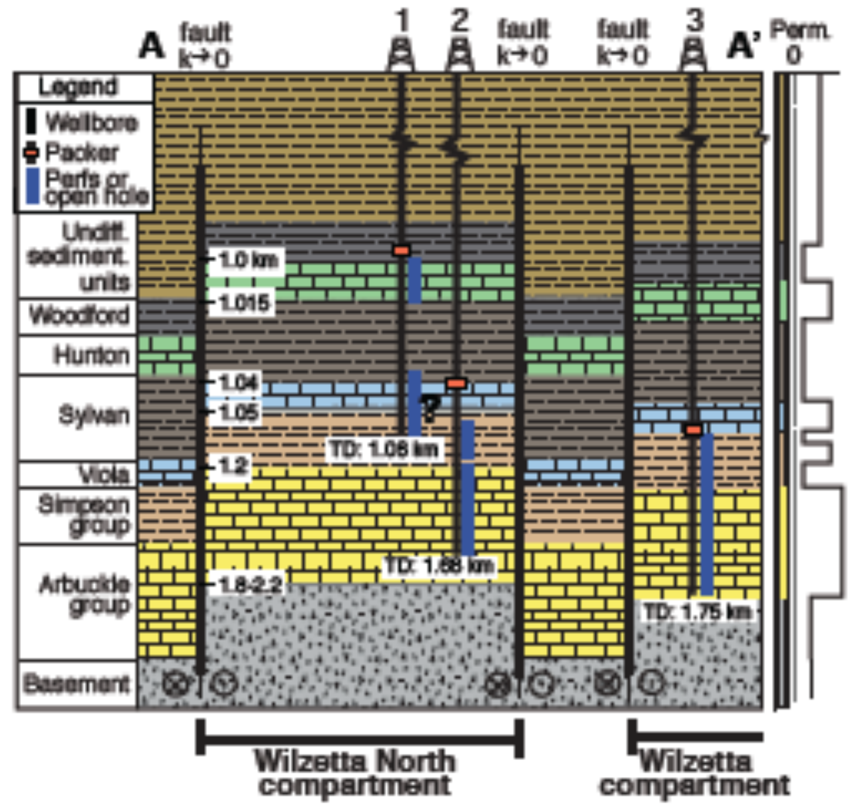


Involvement of Basement Faults

Katie Keranen and others (in press)

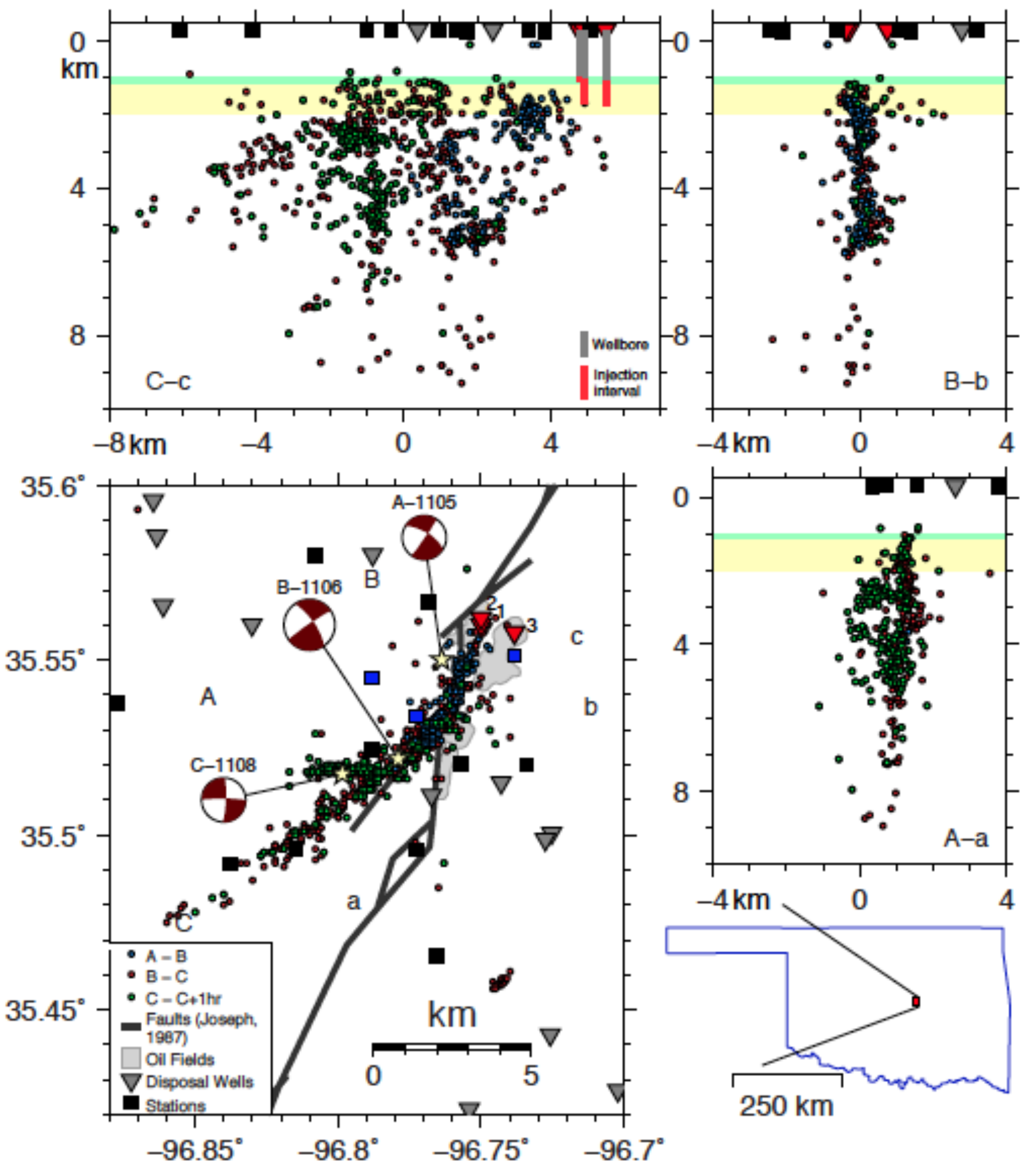
Prague Earthquakes

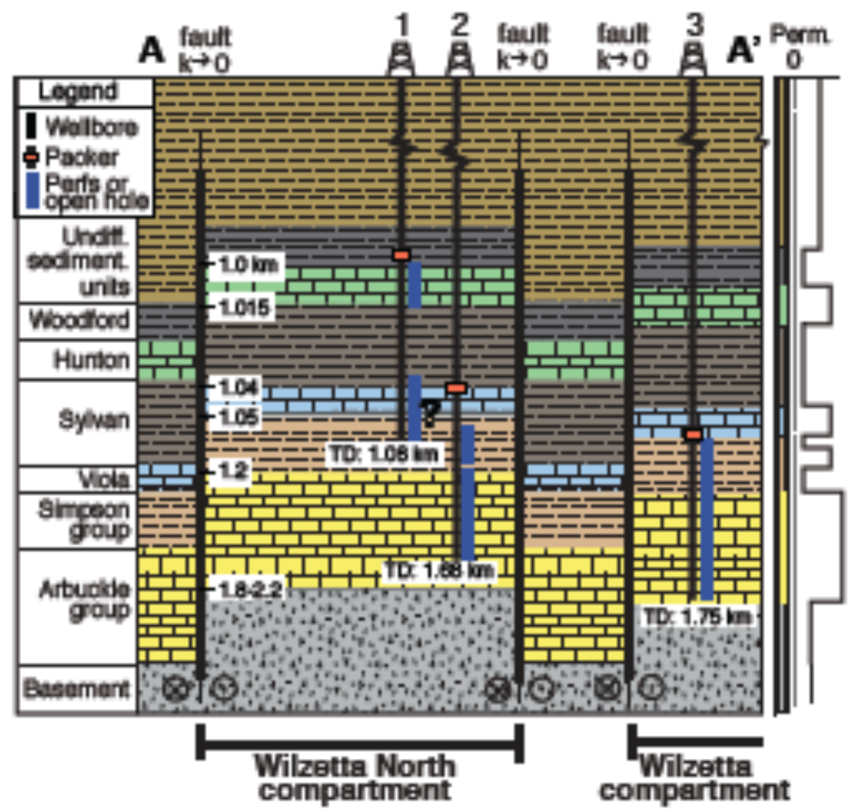




Volumetric Balance Difficult to Constrain

Prague Earthquakes – Triggered By Produced Water?



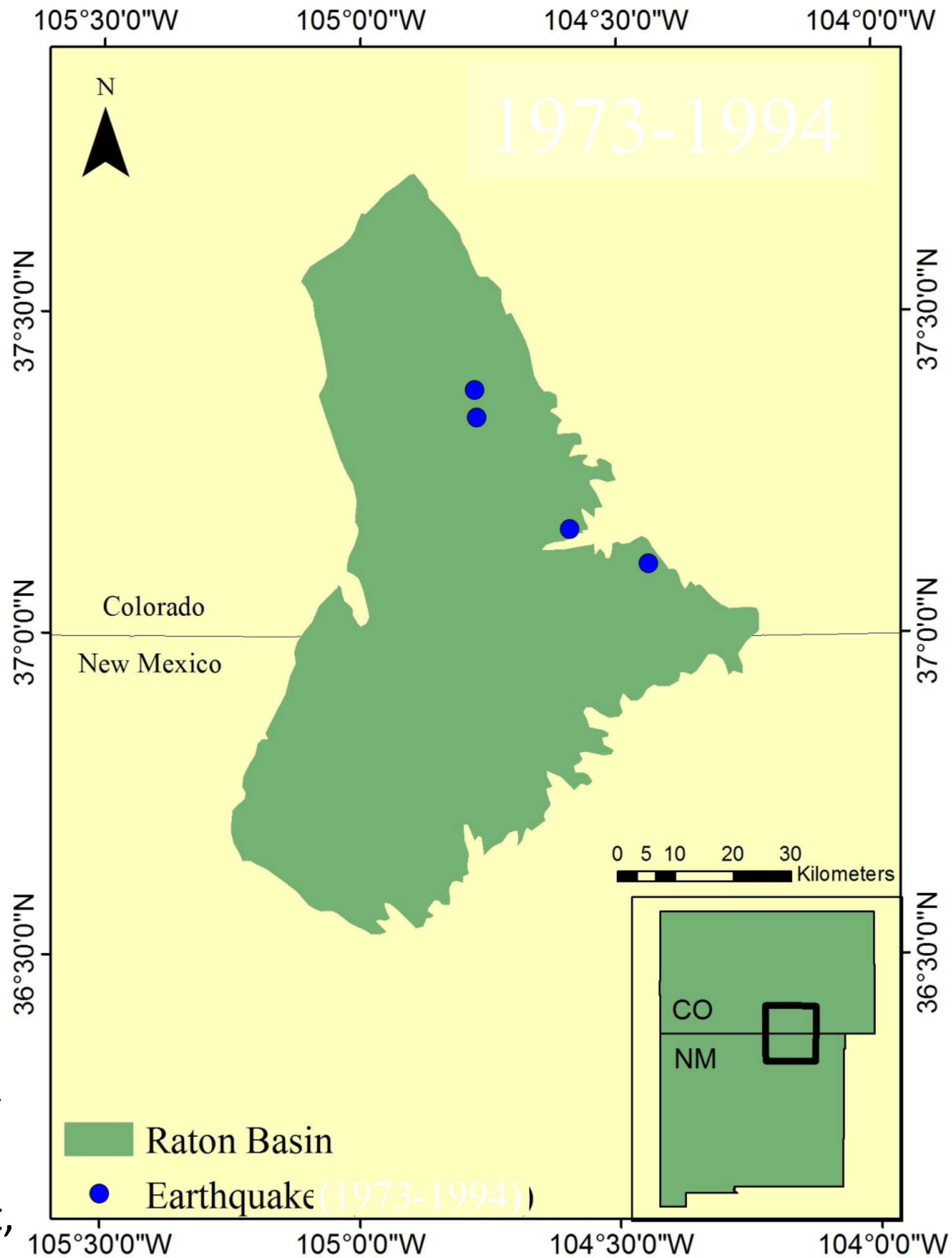


Earthquake A – Triggered by Injection?
Earthquakes B and C – Triggered by Earthquakes A/B

Raton Basin
CBM Produced Water

Background Seismicity?

- 2 EQs 1973
  - Largest M4.3
- 2 EQs 1992
  - Largest M3.3



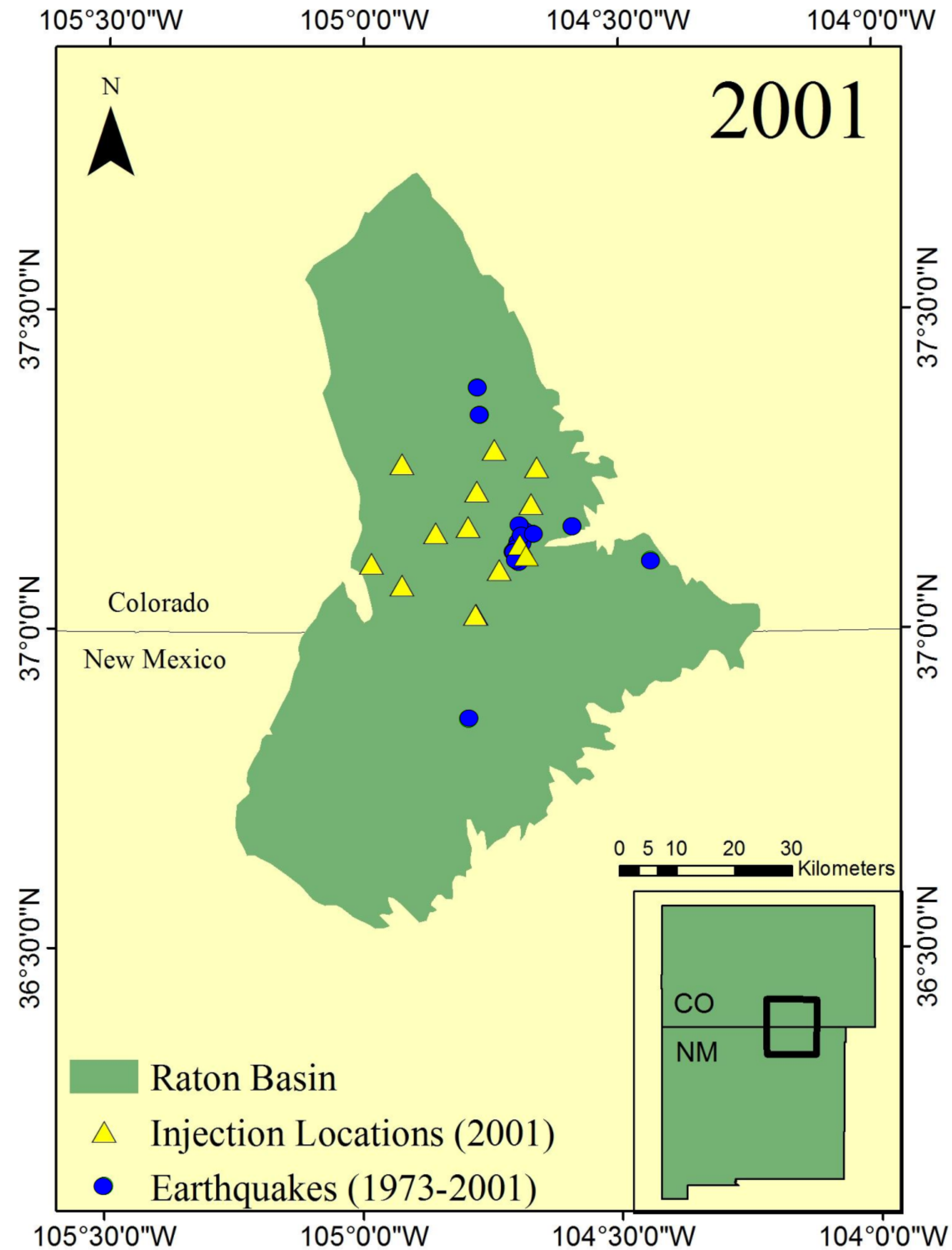
Weingarten, M. and S. Ge (2012), A case study of waste fluid injection and induced seismicity in the Raton Basin, Trinidad, CO, USA, Abstract, AGU Fall Meeting, San Francisco, CA, S34A-05.

Spatial Correlation

- Injection Wells begin waste fluid injection Nov. 1994

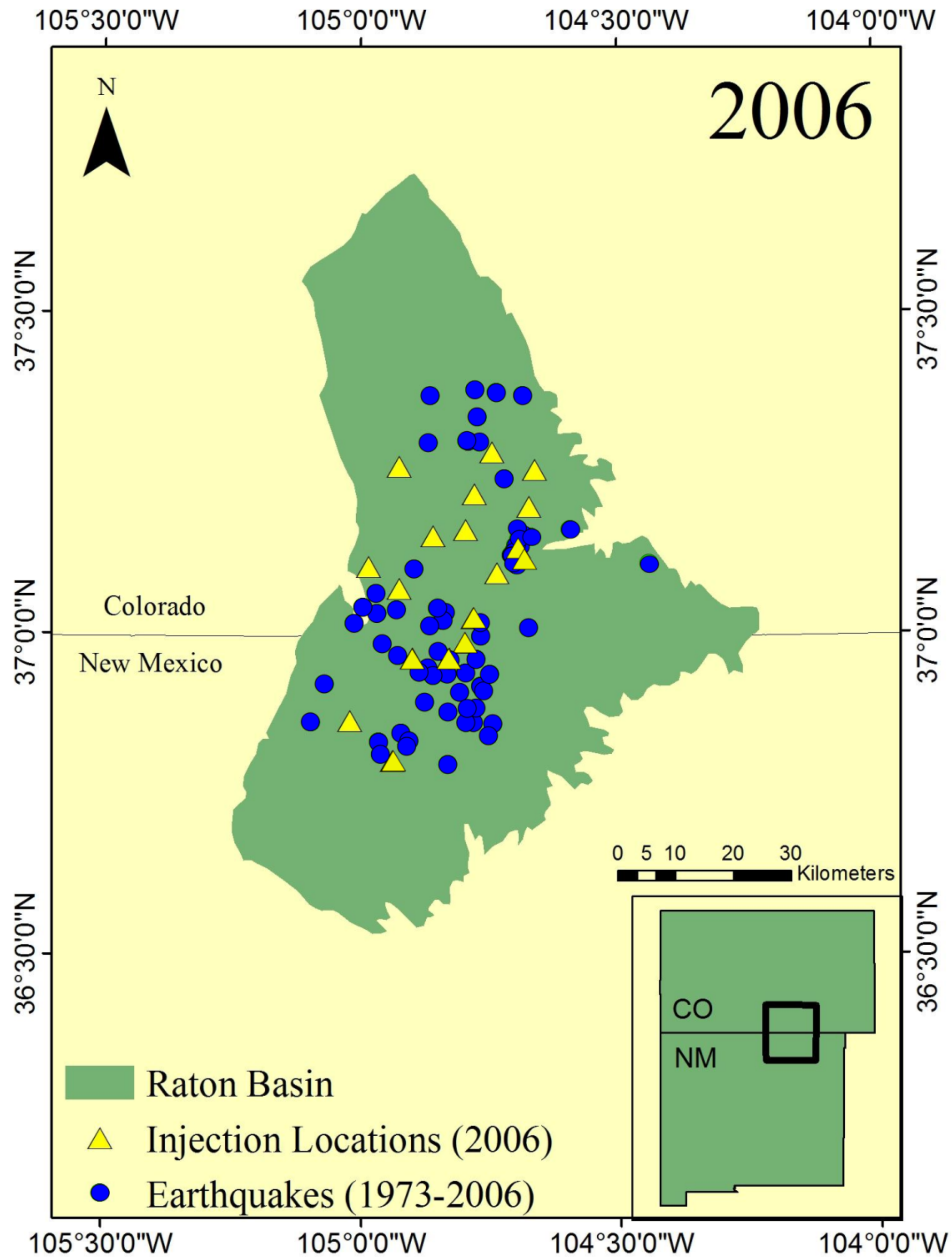
- 2001 EQ Swarm
  – Highlights NE-SW trending structure

  – Largest EQ M4.5



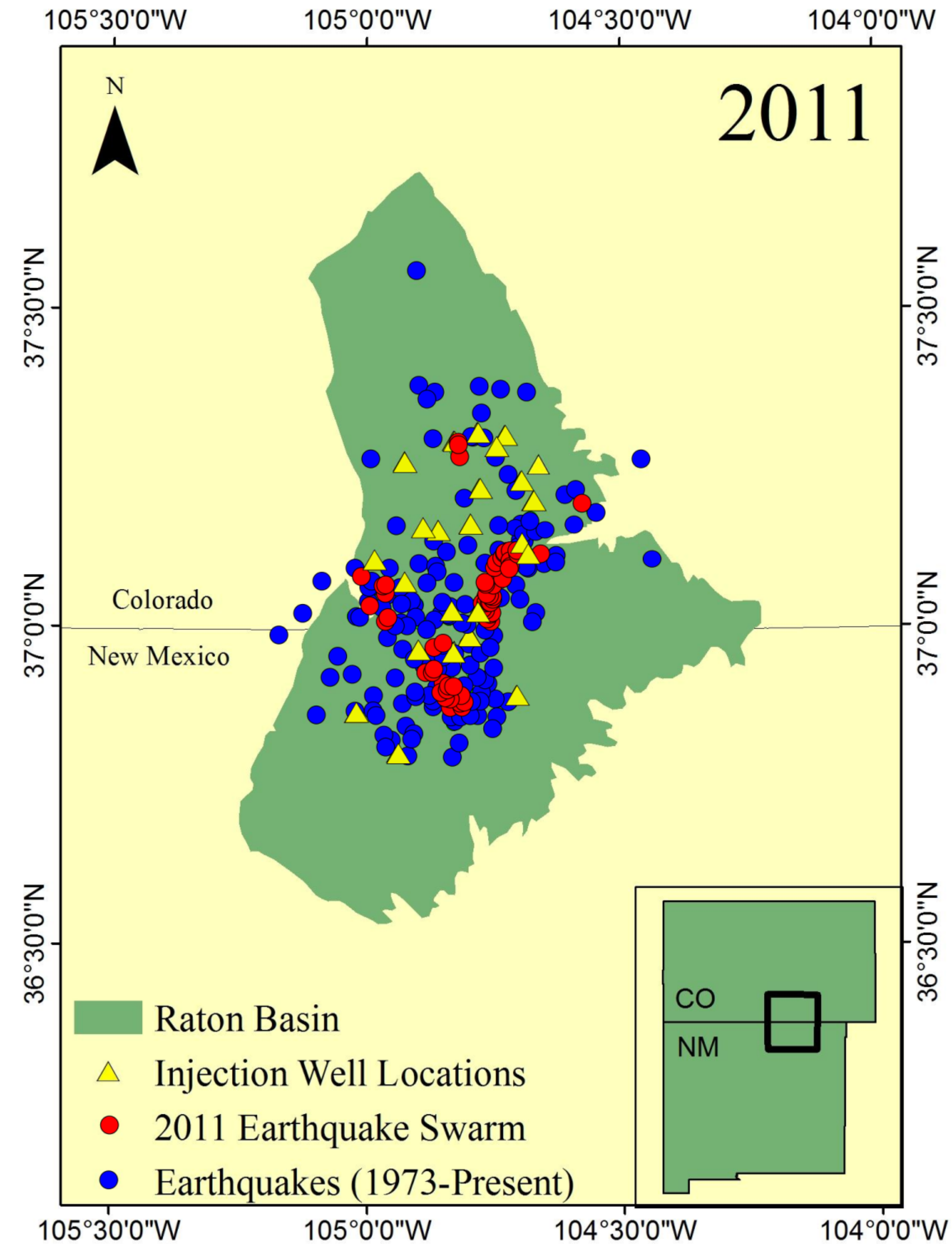
Monitor Seismicity

- Several NM waste fluid wells report injection activities
- Seismicity increases in NM portion of Raton Basin



Spatial Correlation

- 2011 EQ Swarm
  - NE-SW trending structure propagated further to the SW
  - Largest EQ M5.3 on NE trending basement fault



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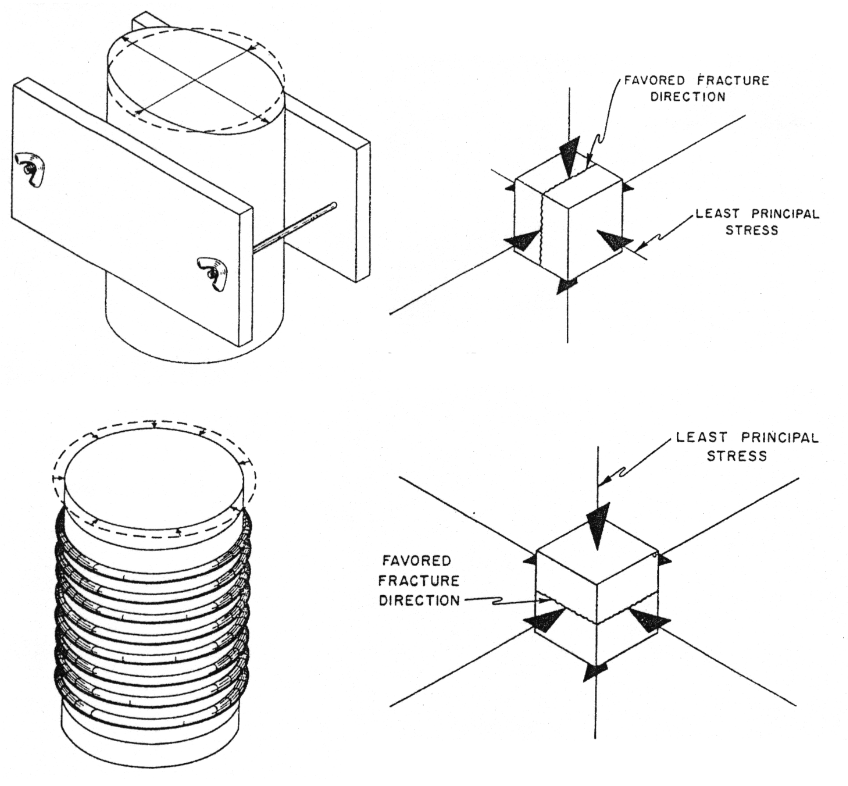
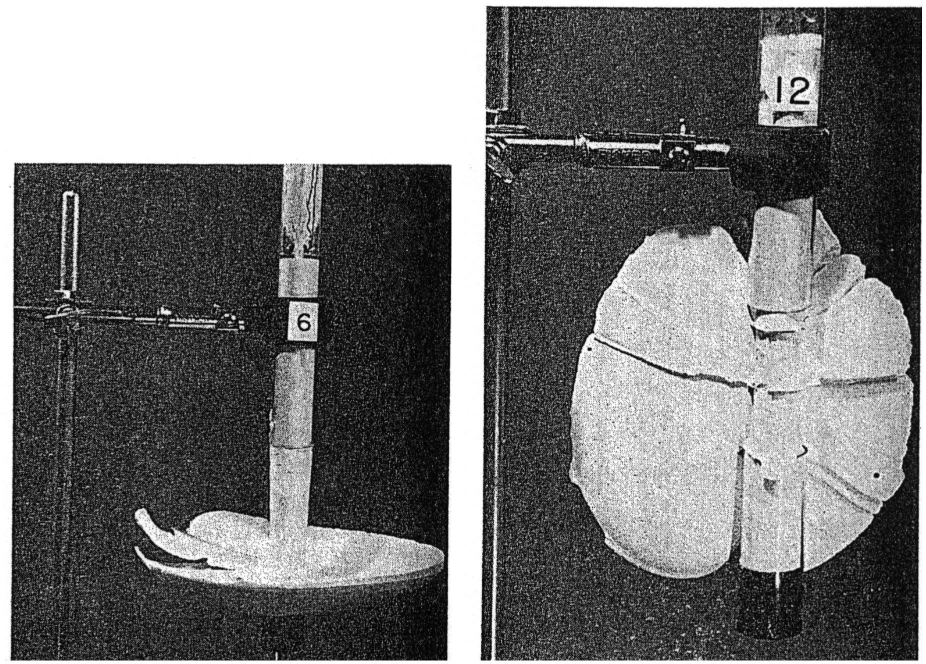
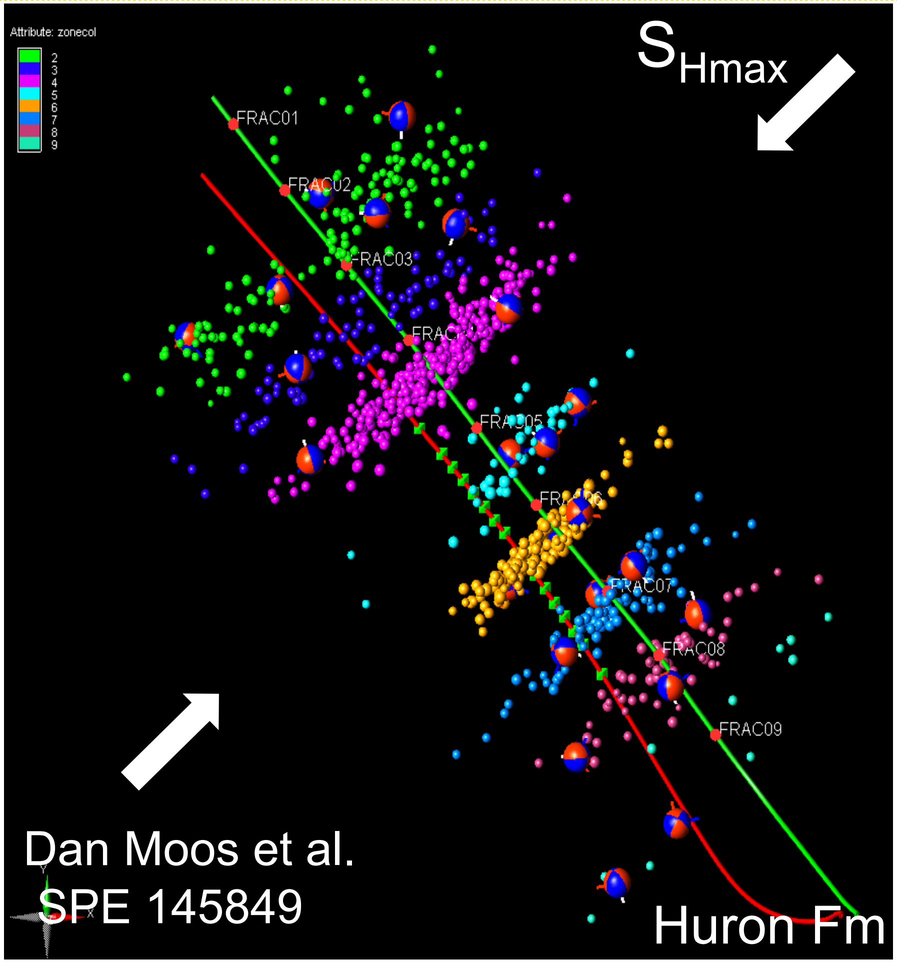
Propagation of Hydraulic Fractures





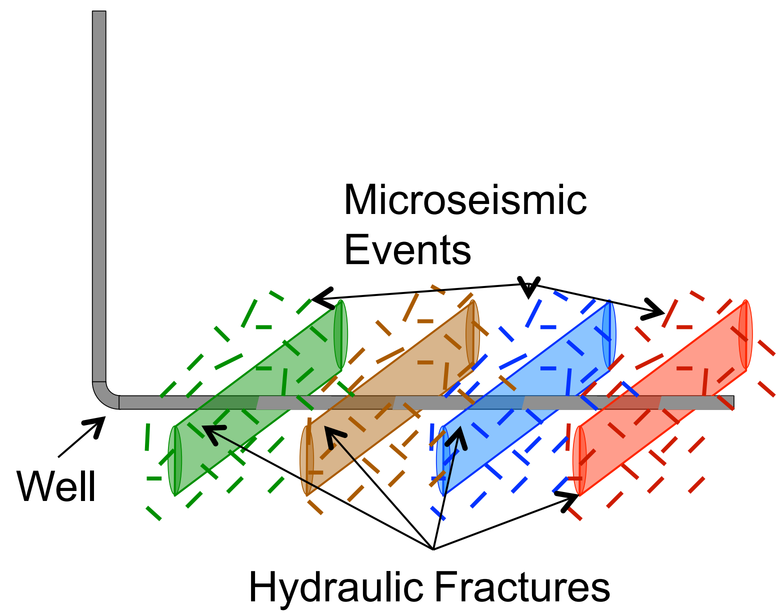
Hubbert and Willis (1957)

Multi-Stage Hydraulic Fracturing



Shear Slip on Pre-existing Fractures and Faults Enhances Permeability Of Shale and Stimulates Production

Horizontal Drilling and Multi-Stage *Slick-Water* Hydraulic Fracturing Induces Microearthquakes (-1 > M > -3) To Create a Permeable Fracture Network



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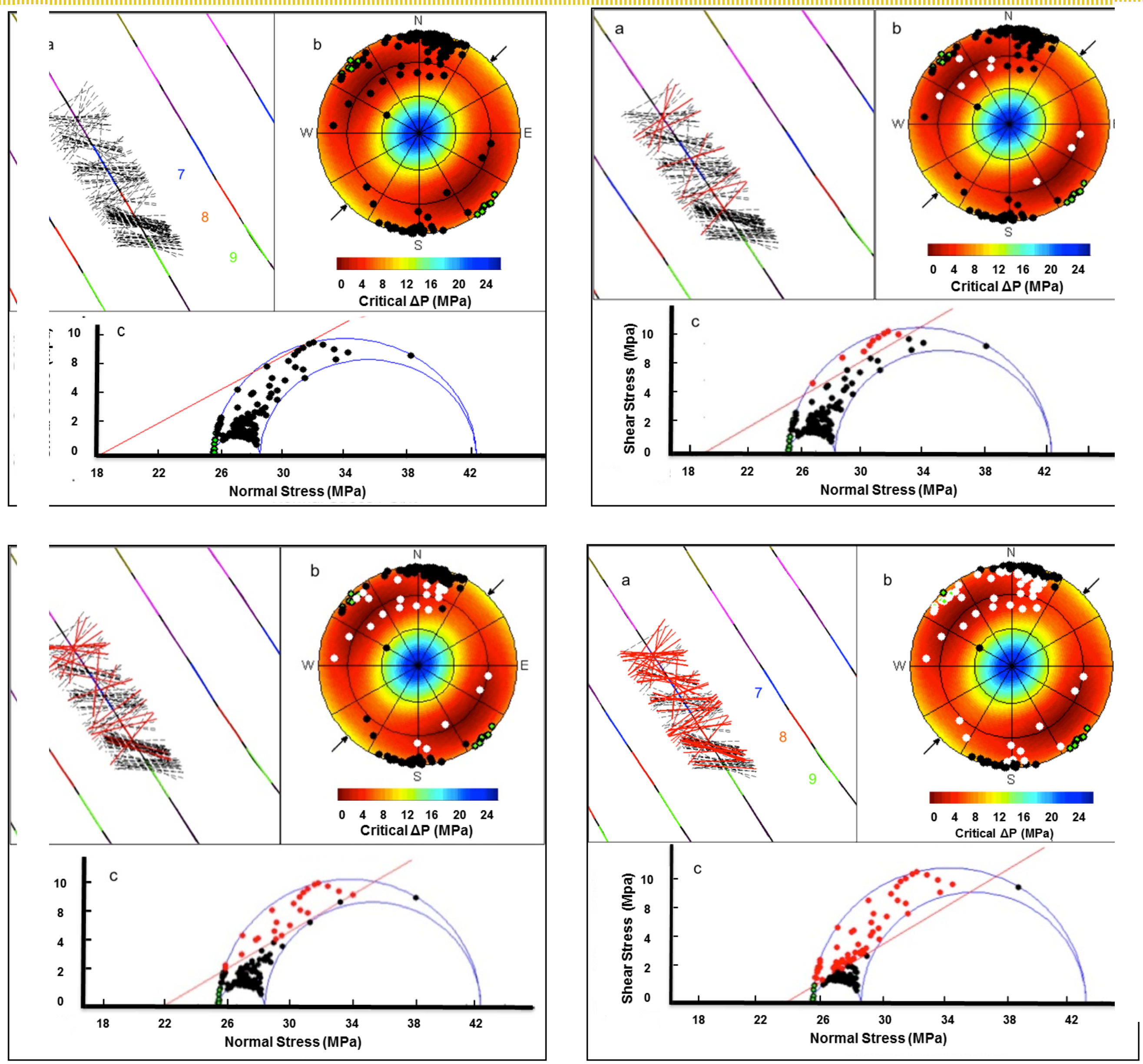
Inducing Slip on Mis-Oriented Faults

Prior to Stimulation



During Stimulation

Bowland Basin UK

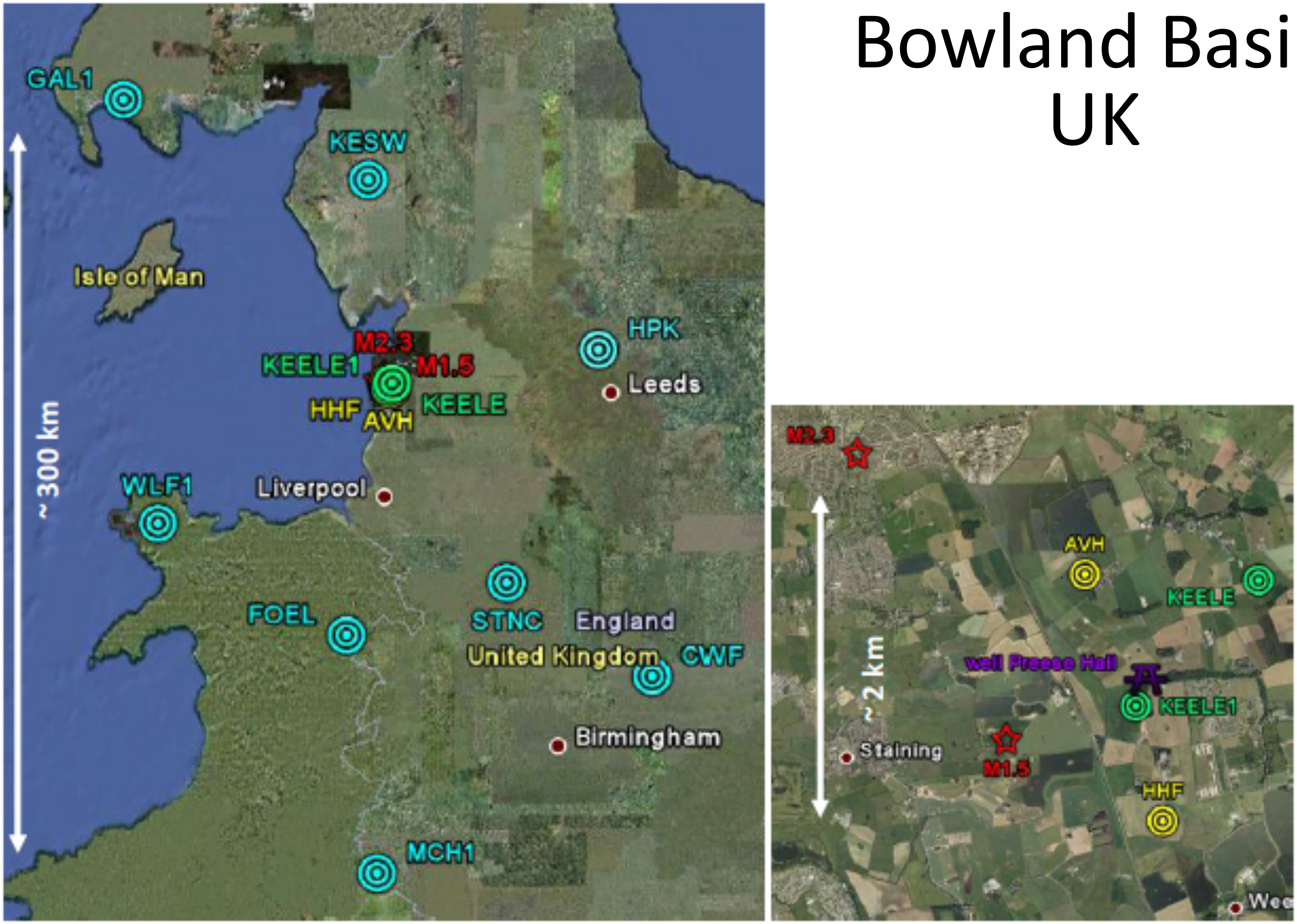
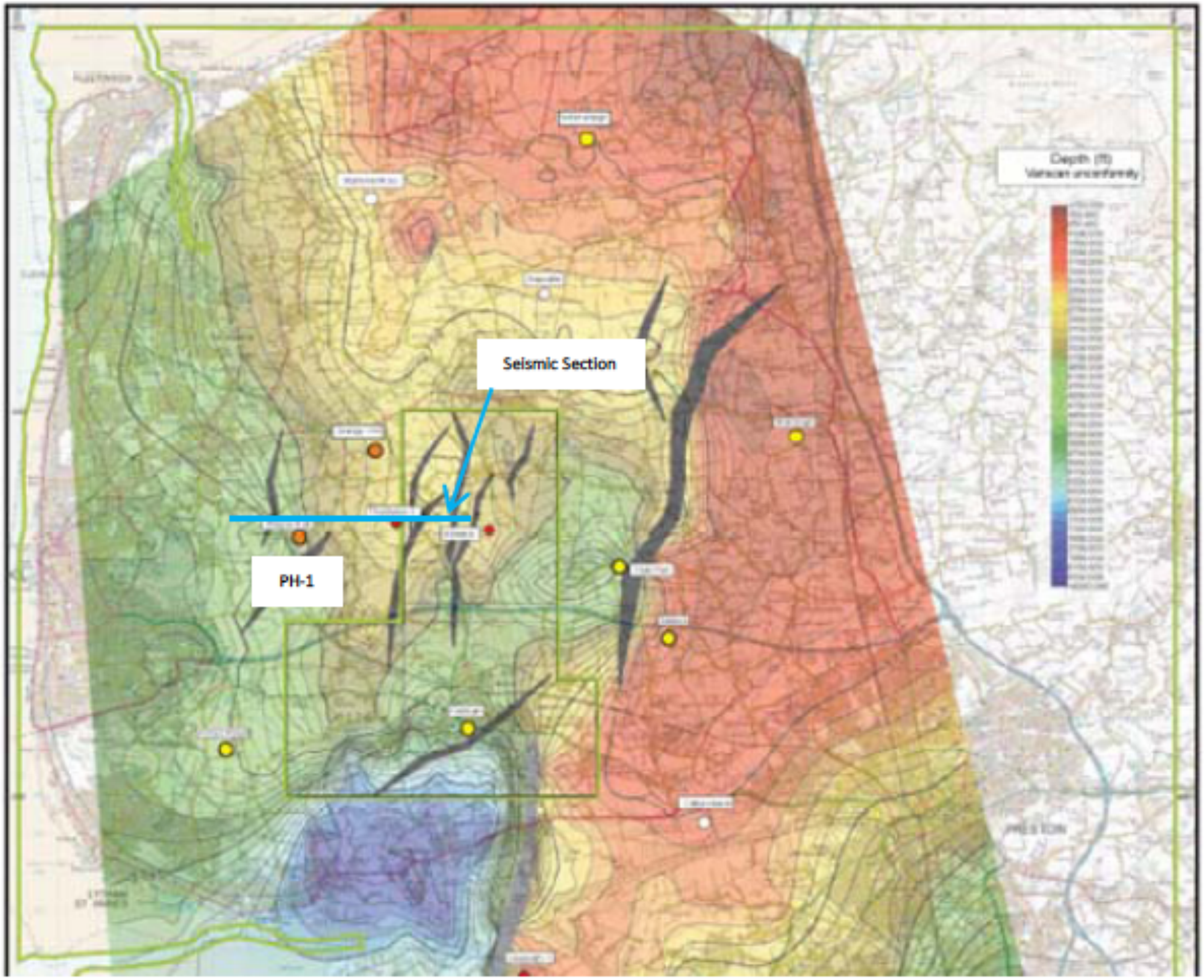


Figure 2. Regional view of stations used in the analysis (left) and local stations (right). Local stations installed only in April (green circles), well position (violet rig symbol), two continuously recording stations HHF and AVH (yellow circles) and BGS reported locations of events (red stars: April 1, 2011 [M2.3] May 27, 2011 [M1.5]).

Bowland Basin, UK



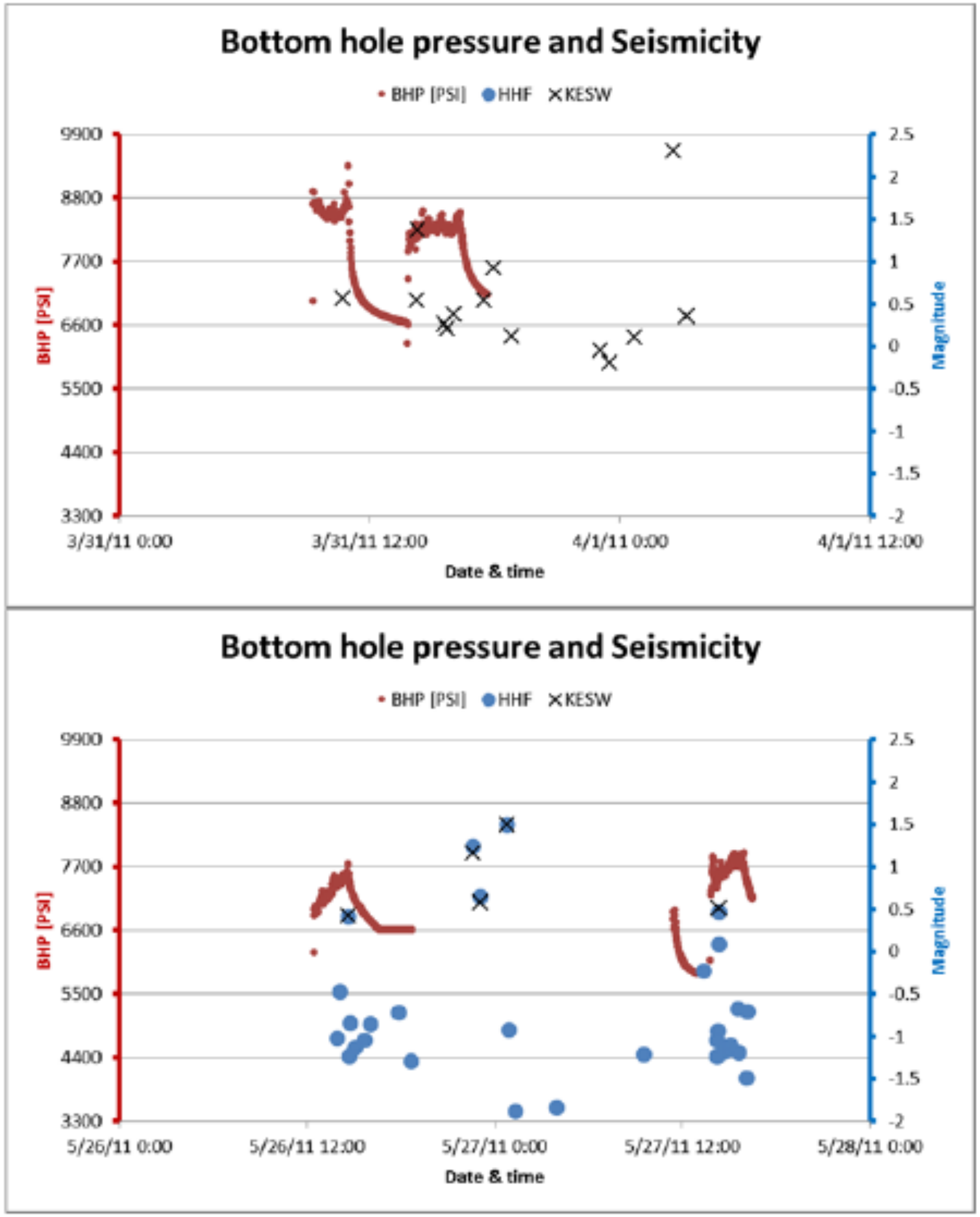
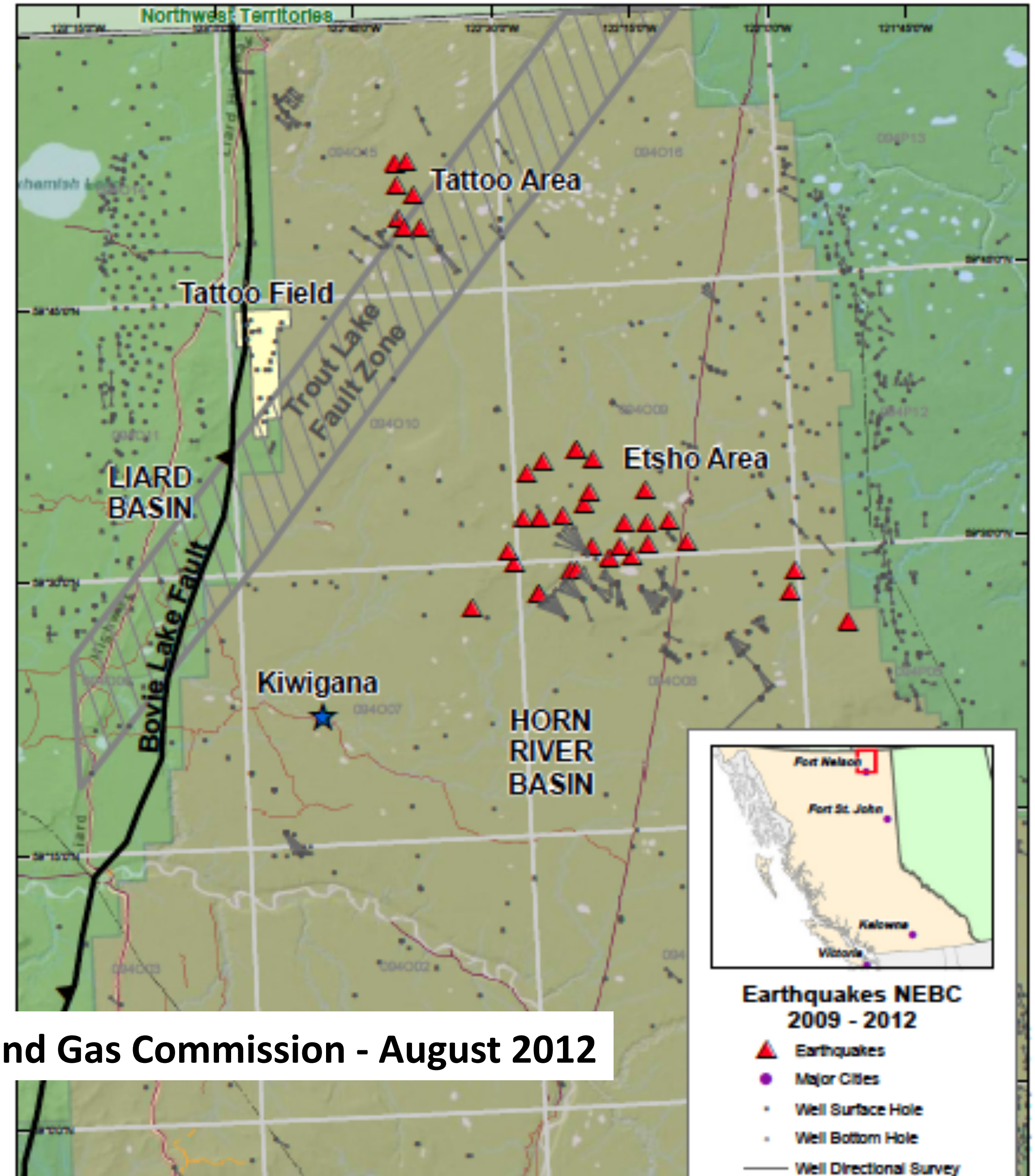


Figure 6. BHP in the exploration well Preese Hall (red line). Events detected by KESW (black crosses) and by HHF (blue dots) are represented by the origin time and magnitude relative to a master event at a given station. The upper plot shows a detailed window of stage 2; the lower plot shows stages 4 and 5. There is no detection by HHF during stage 2 because the local station HHF was not available.

Seismicity Triggered During Hydraulic Fracturing



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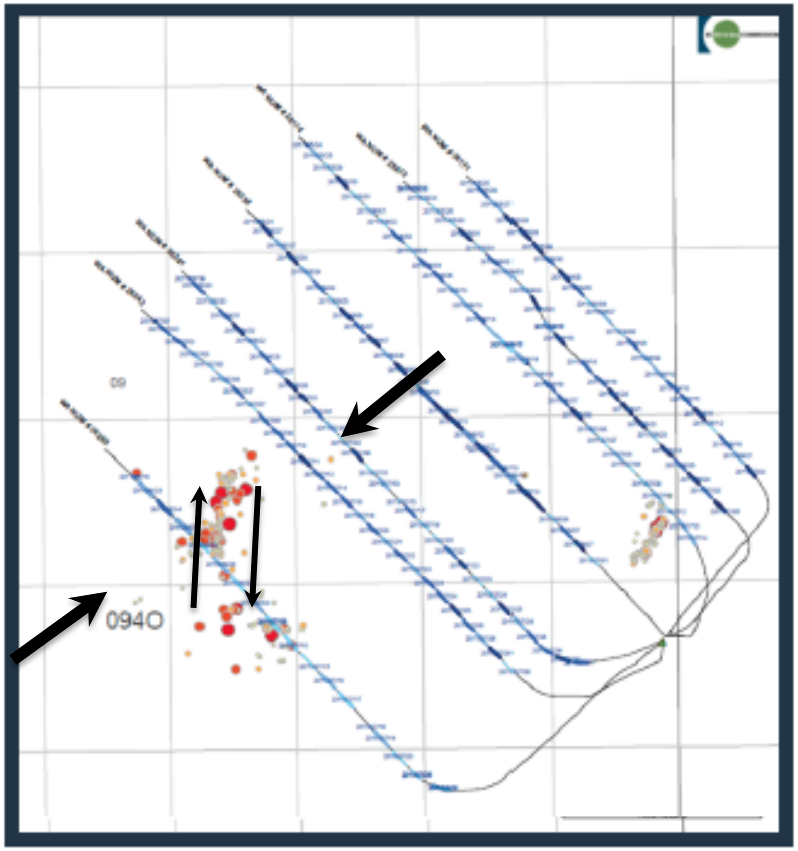
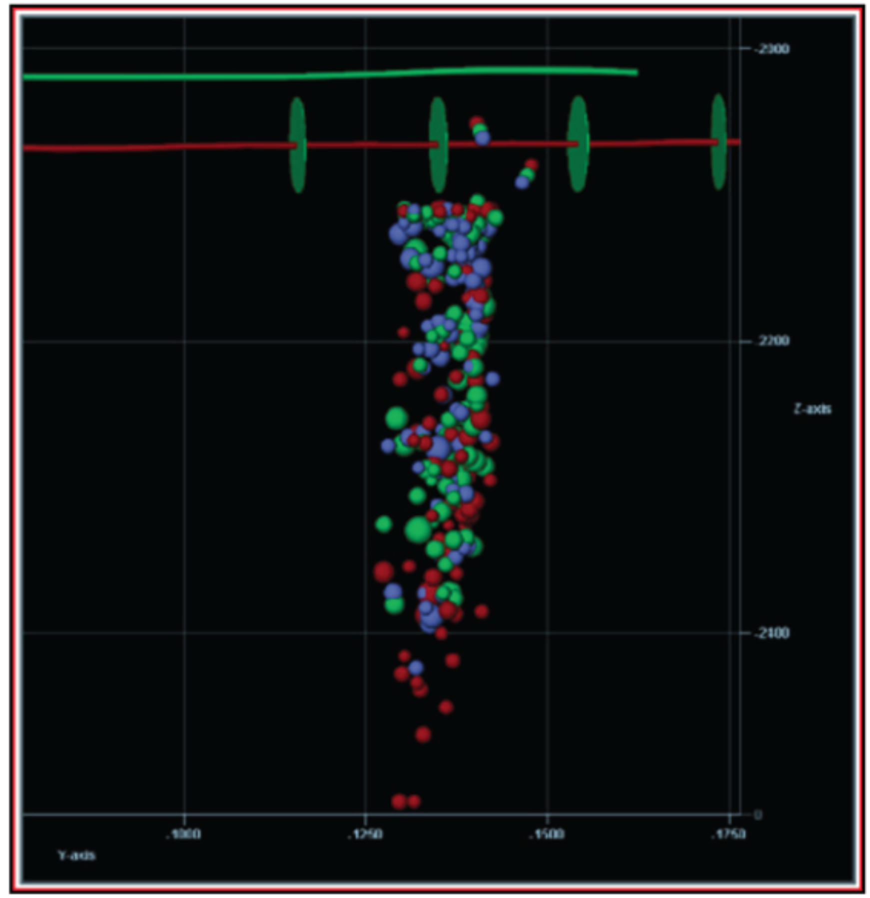
Seismicity Triggered During Hydraulic Fracturing





Earthquakes of unusually large magnitude (1<M<3) on a relatively large pre-existing fault that appears to be active in current stress field

Earthquakes rapidly propagating down Into crystalline basement

BC Oil and Gas Commission - August 2012

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Induced Seismicity Potential in Energy Technologies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

Risk Associated with Injection and Triggered Seismicity

Microseismic Events Associated with Hydraulic Fracturing

- Very Low Risk to Public
  - Limited rock volume, limited pumping volume/time
  - Very few events > M 2 in 100,000's of frac stages

Seismic Events Associated with Wastewater Injection

- Low Risk to Public
  - Much Larger Pumping Volumes
  - Can be Effectively Managed by Effective Site Characterization, Monitoring and Proactive Planning
  - Minimize Injection by Water Recycling

Potential of Triggered Seismicity with Large Scale CCS

- Injection of extremely large volumes pose considerable risk of triggering "larger" earthquakes

Managing Triggered Seismicity

Liquid carbon dioxide has been injected into the Sleipner gas- and oilfield in the North Sea for 15 years without triggering any seismicity. It serves as a good example of how fluid injection can be done safely.

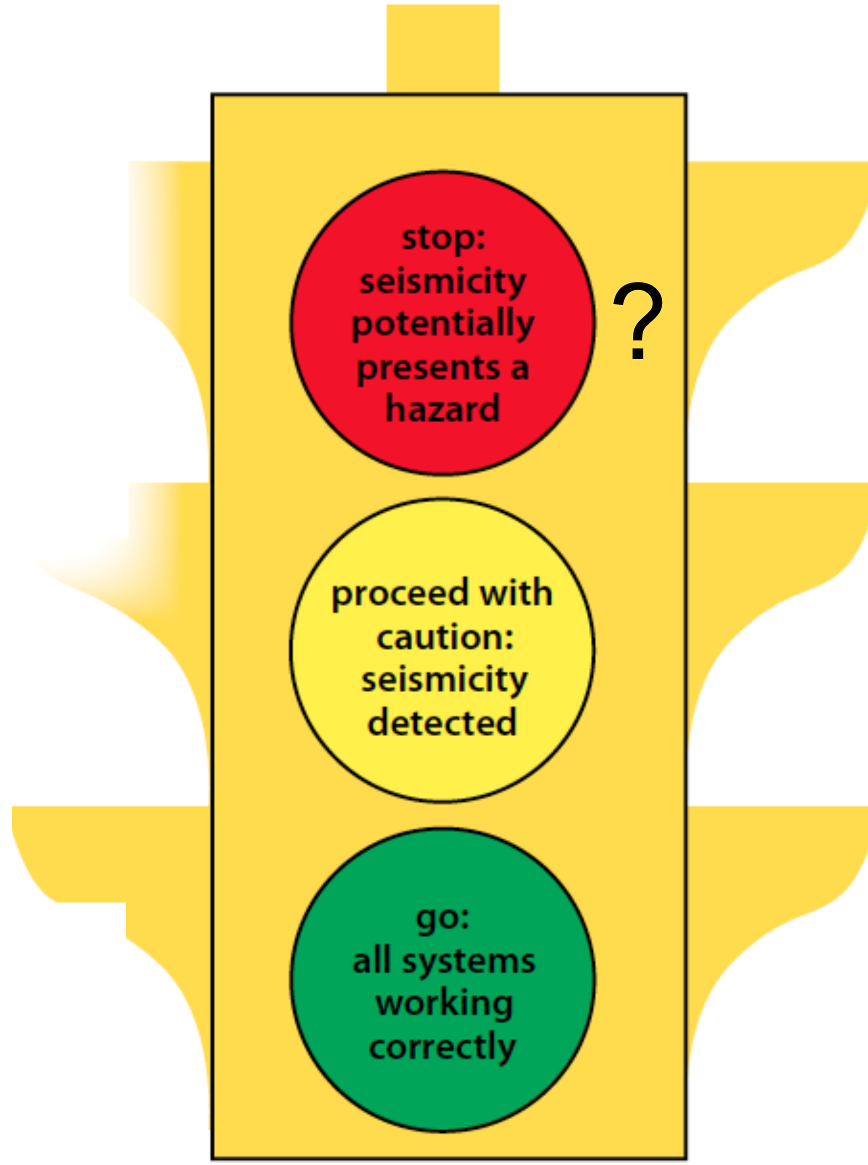
Managing the Seismic Risk Posed by Wastewater Disposal

Mark D. Zoback

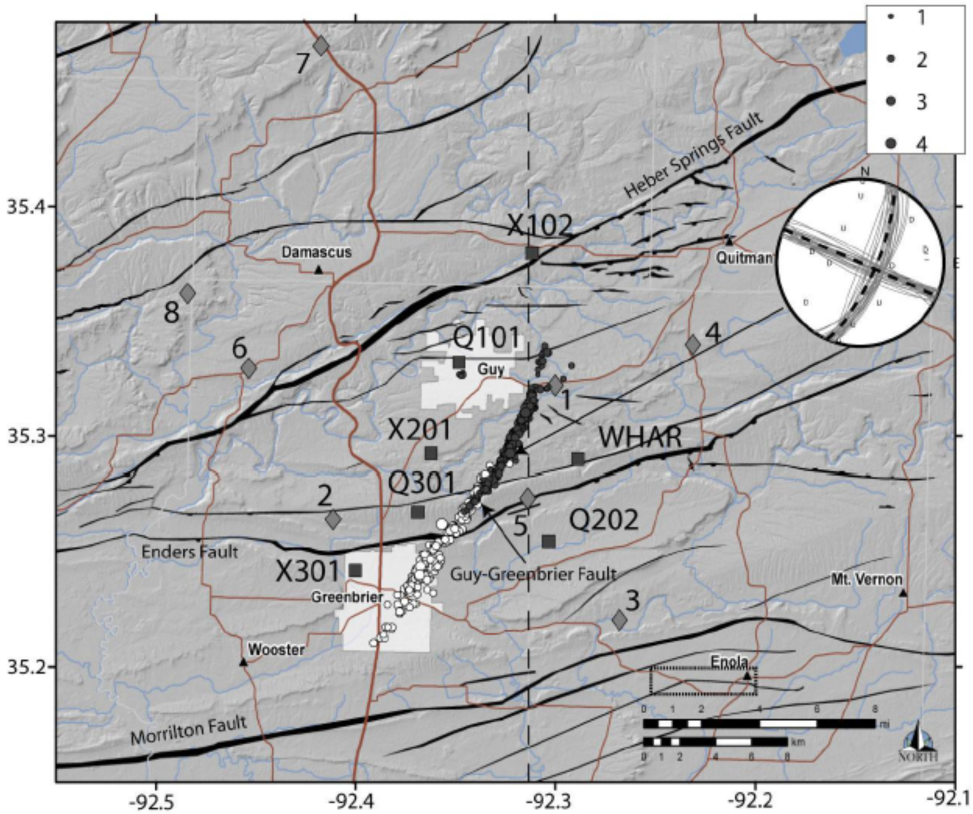
From an earthquake perspective, 2011 was a remarkable year. While the devastation accompanying the magnitude-9.0 Tohoku earthquake that occurred off the coast of Japan on March 11 still captures attention worldwide, the relatively stable interior of the U.S. was struck by a somewhat surprising number of small-to-moderate earthquakes that were widely felt. Most of these were natural events, the types of earthquakes that occur from time to time in all intraplate regions. For example, the magnitude 5.8 that occurred in central Virginia on Aug. 23 was felt throughout the northeast, damaged the Washington Monument, and caused the temporary shutdown of a nuclear power plant. This earthquake occurred in the Central Virginia Seismic Zone, an area known to produce relatively frequent small earthquakes.

However, a number of the small-to-moderate earthquakes that occurred in the U.S. interior in 2011 appear to be associated with the disposal of wastewater, at least in part related to natural gas production. Several small earthquakes were apparently caused by injection of wastewater associated with shale gas production near Guy, Ark.; the largest earthquake was a magnitude-4.7 event on Feb. 27. In the Trinidad/Raton area near the border of Colorado and New Mexico, injection of wastewater associated with coalbed methane production seems to be associated with a magnitude-5.3 event that occurred on Aug. 22, and small earthquakes that appear to have been triggered by

EARTH April, 2012

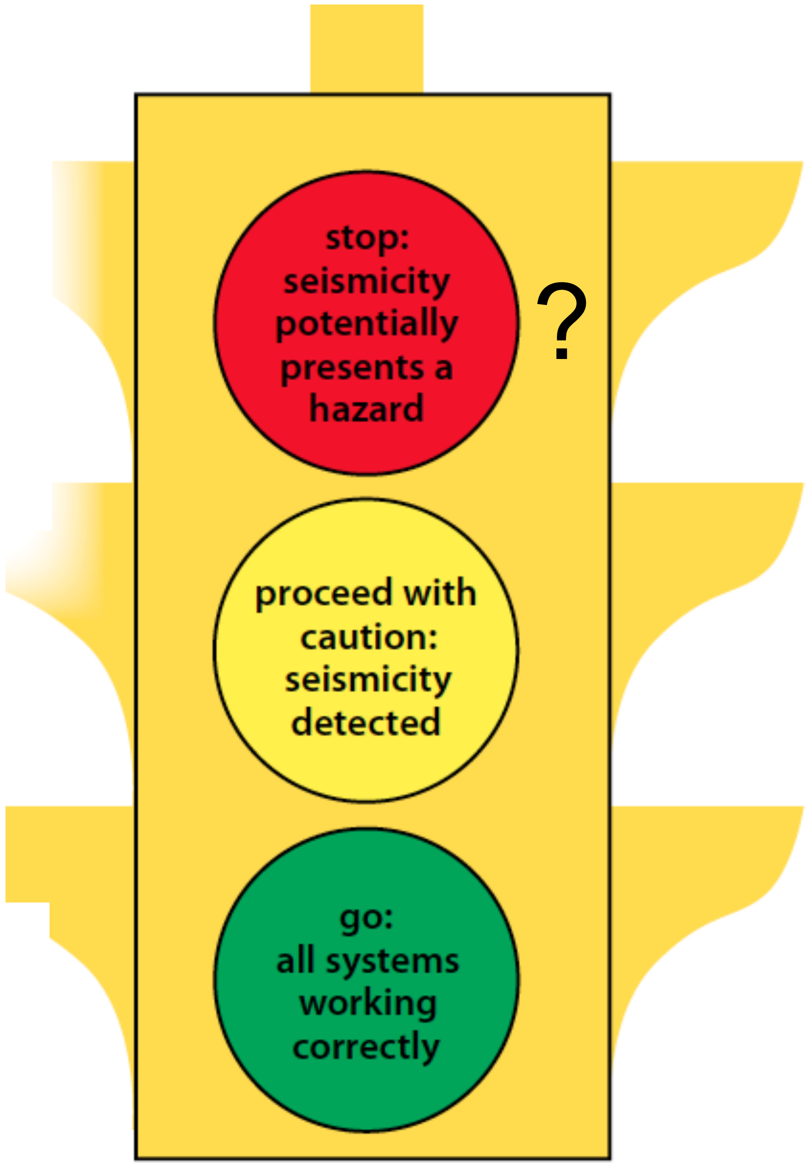


Seismicity Triggered by Injection

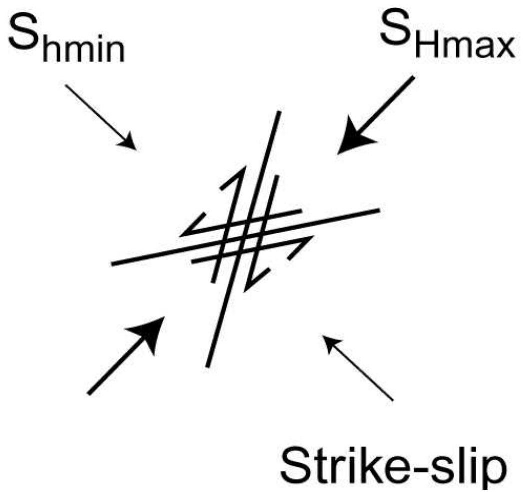


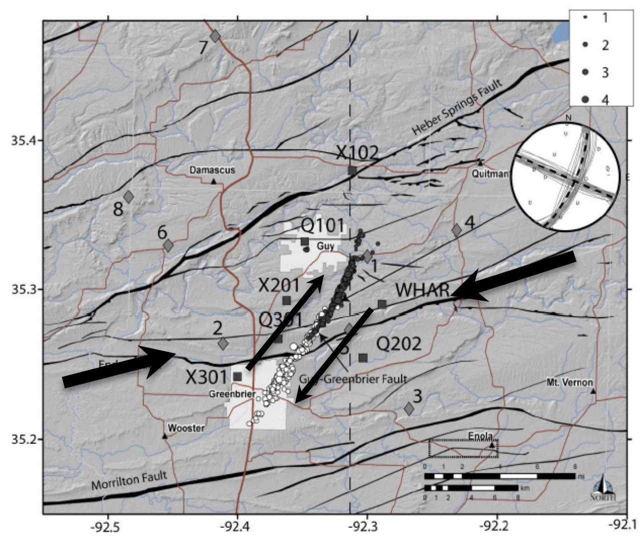
Guy Arkansas
Earthquake Swarm

Horton (2012)



Earthquakes Spreading Out Along an Active Fault





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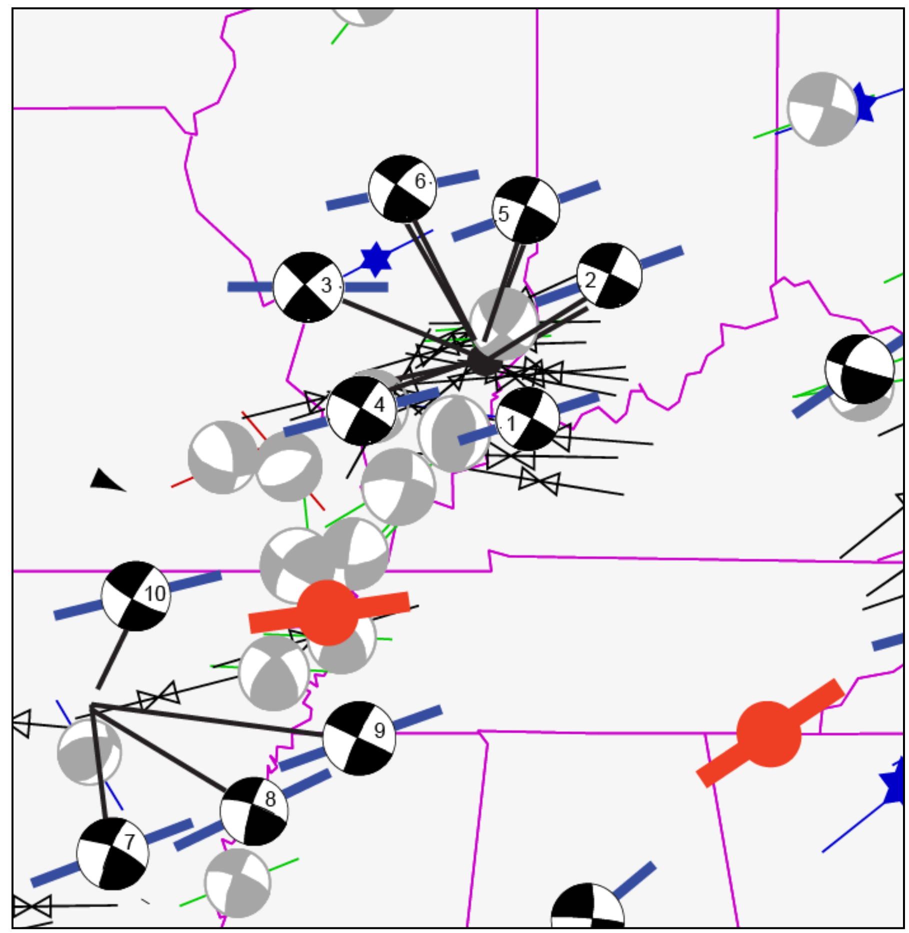

Hurd and Zoback (2012)

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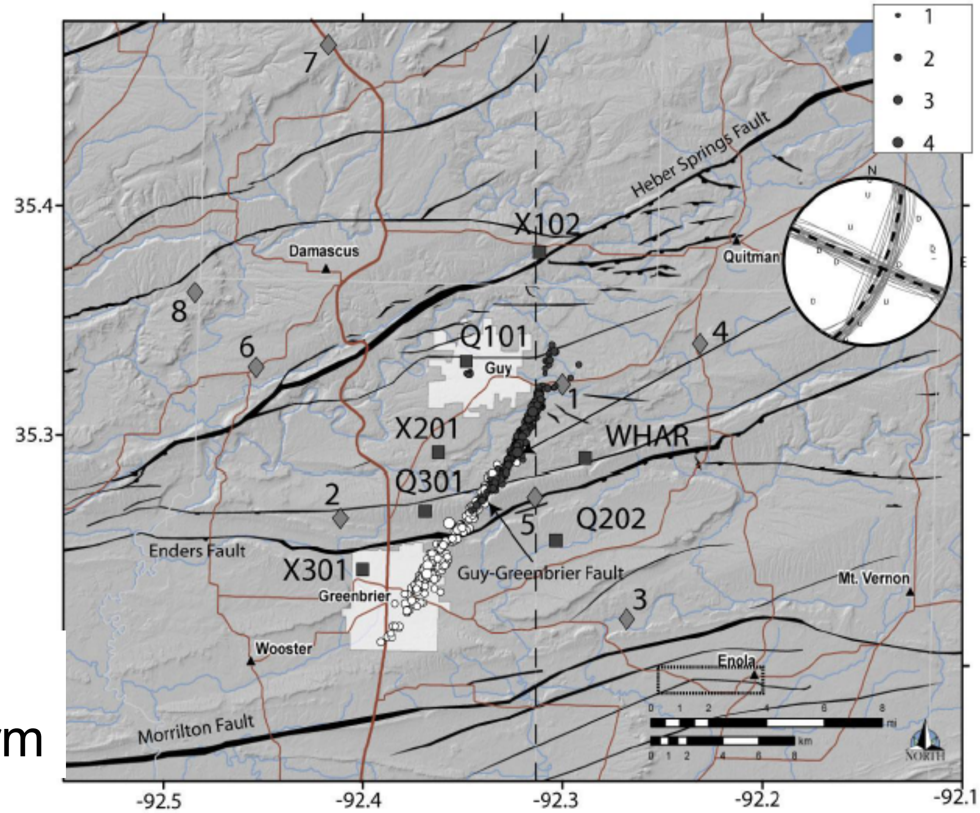
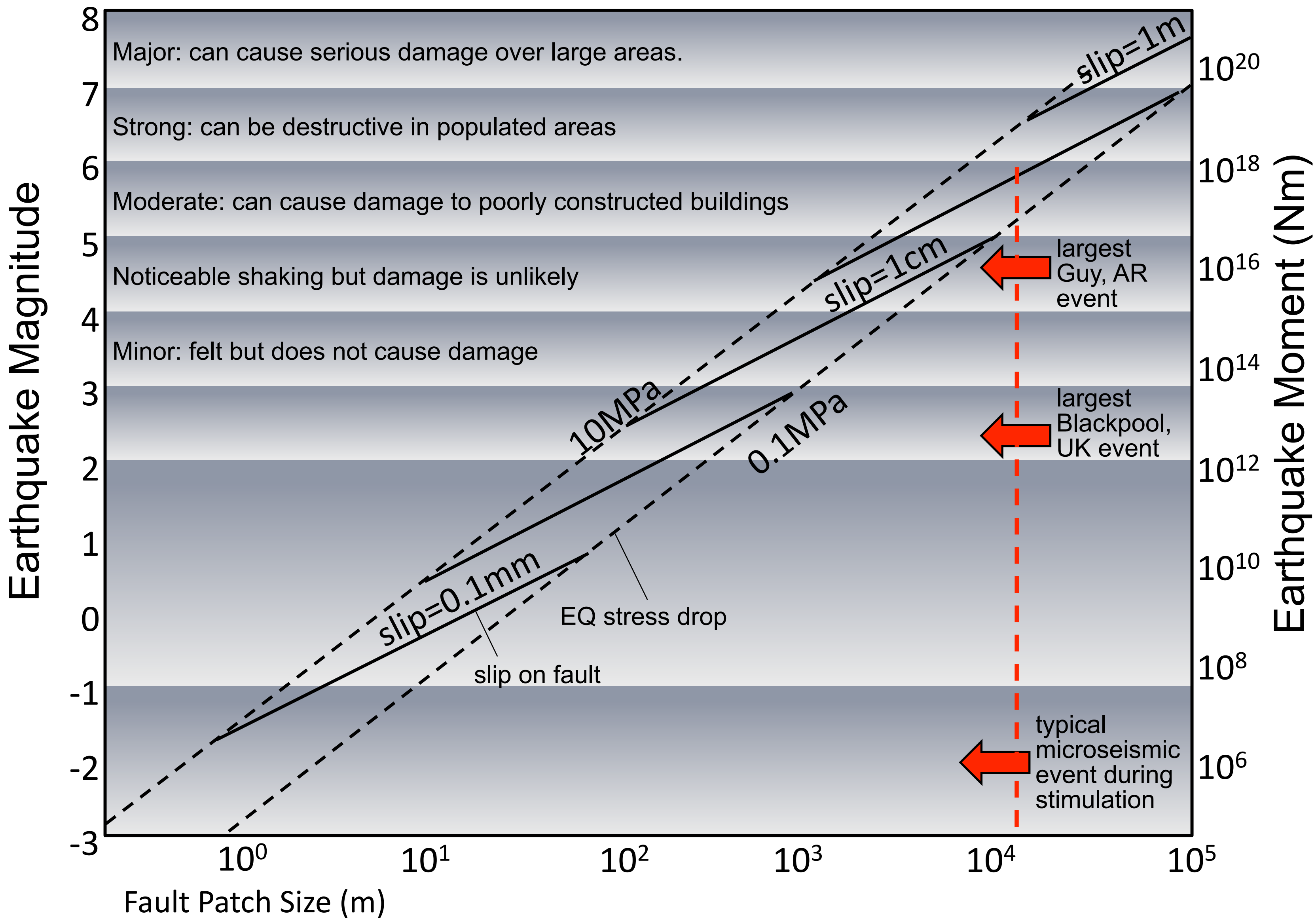


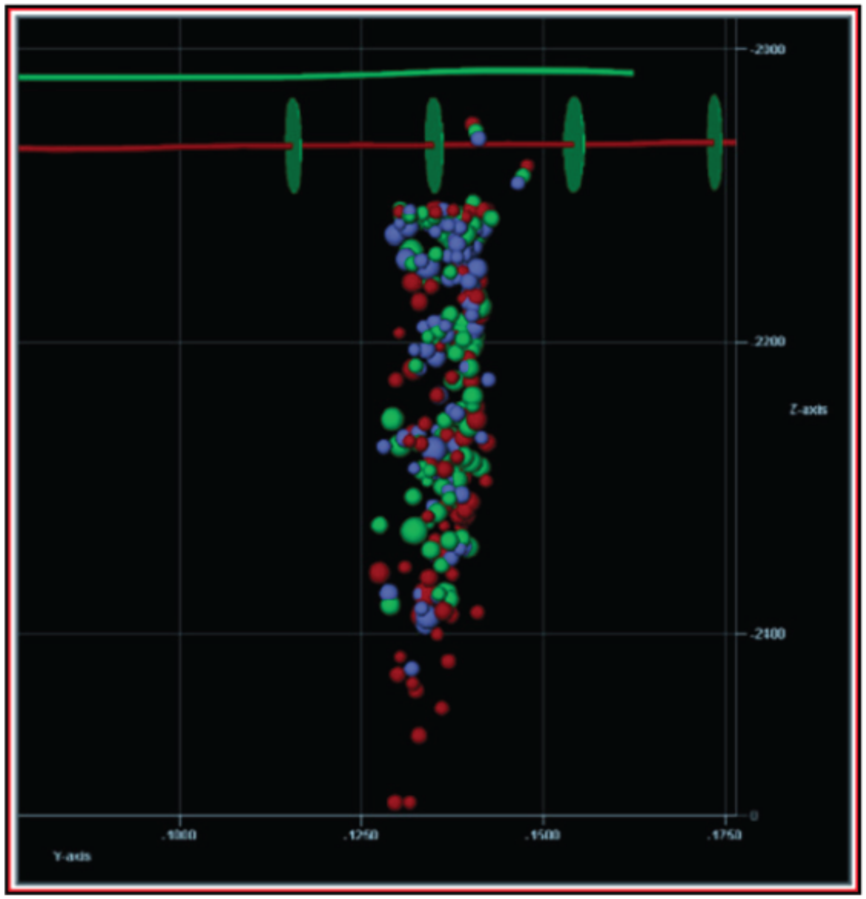
Guy Arkansas
Earthquake Swarm

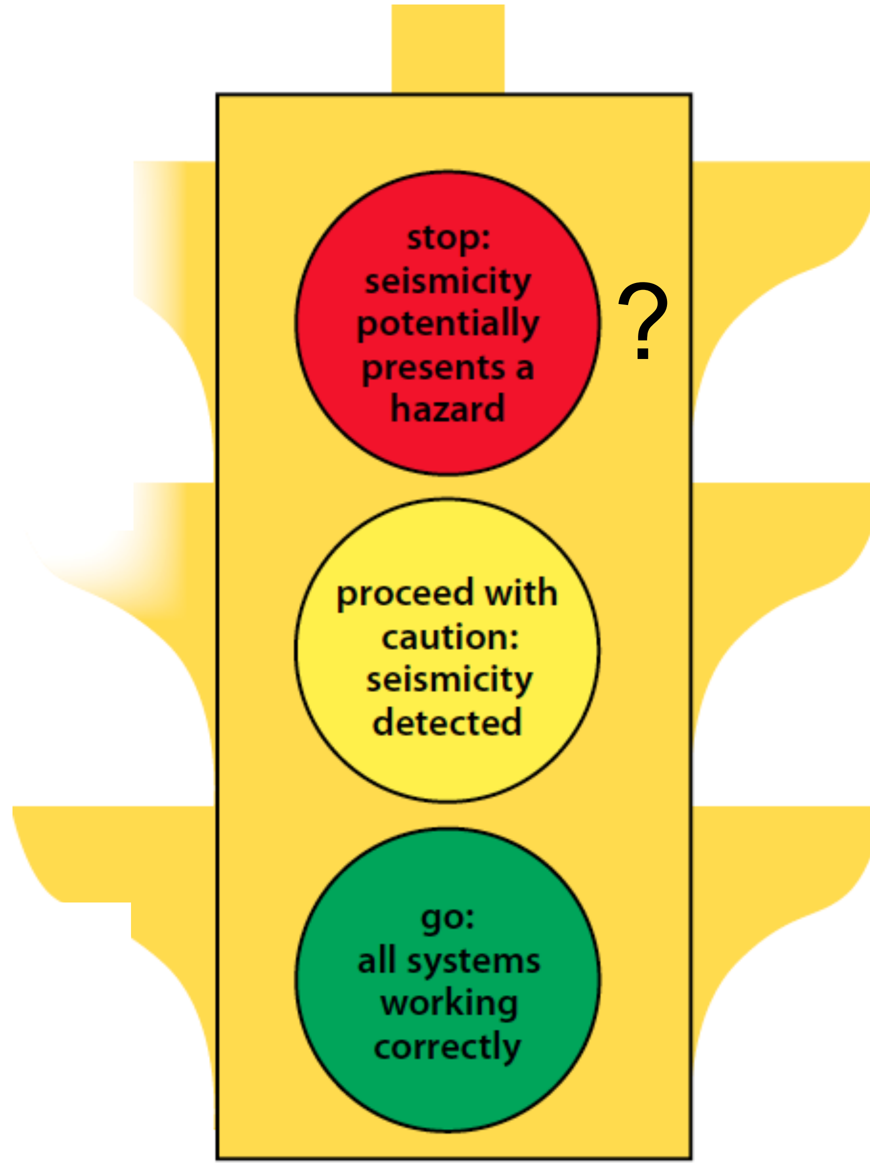
- Avoid Injection into Potentially Active Faults
- Limit Injection Rates (Pressure) Increases
- Monitor Seismicity (As Appropriate)
- Assess Risk
- Be Prepared to Abandon Some Injection Wells

Was a Potentially Larger Eq. Avoided?

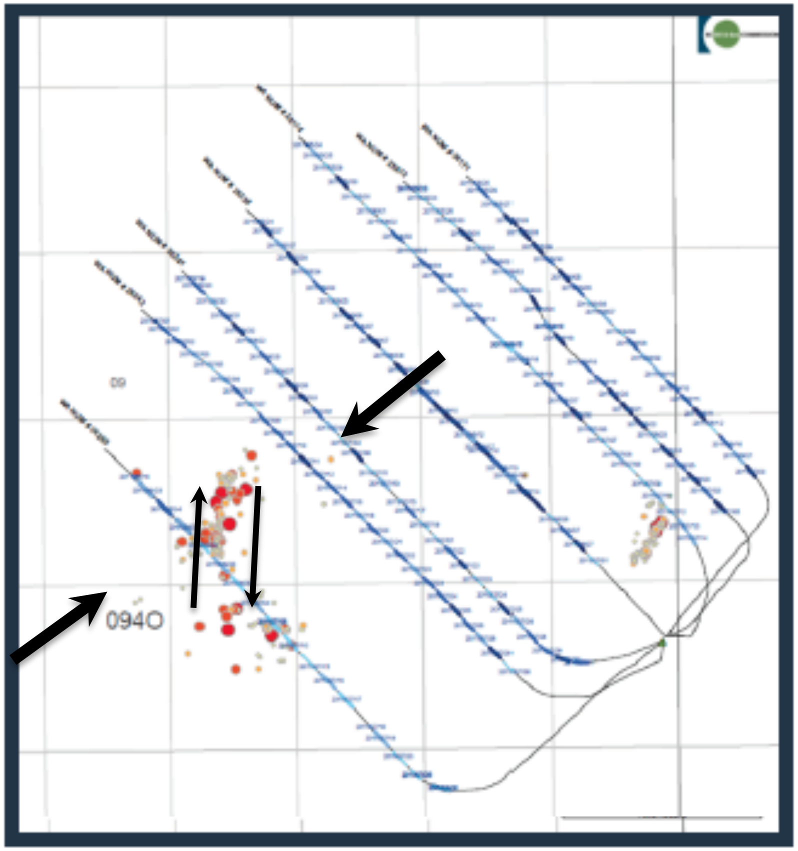


Seismicity Triggered by Hydraulic Fracturing





Seismicity Triggered During Hydraulic Fracturing



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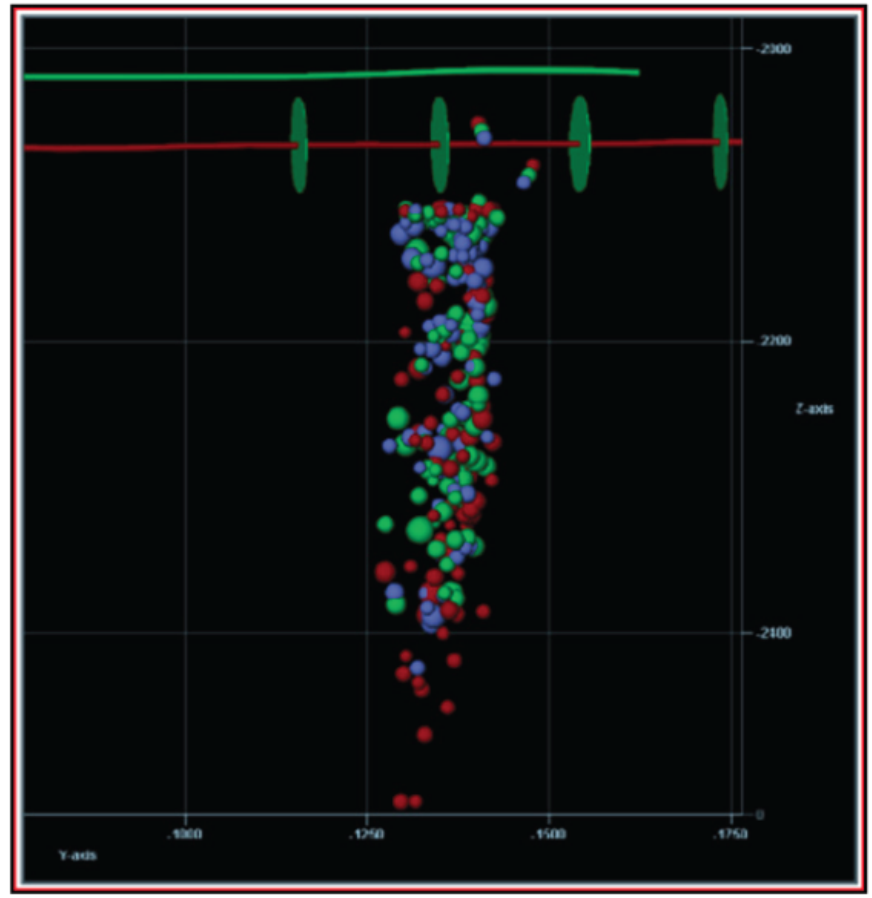

Earthquakes rapidly propagating down Into crystalline basement

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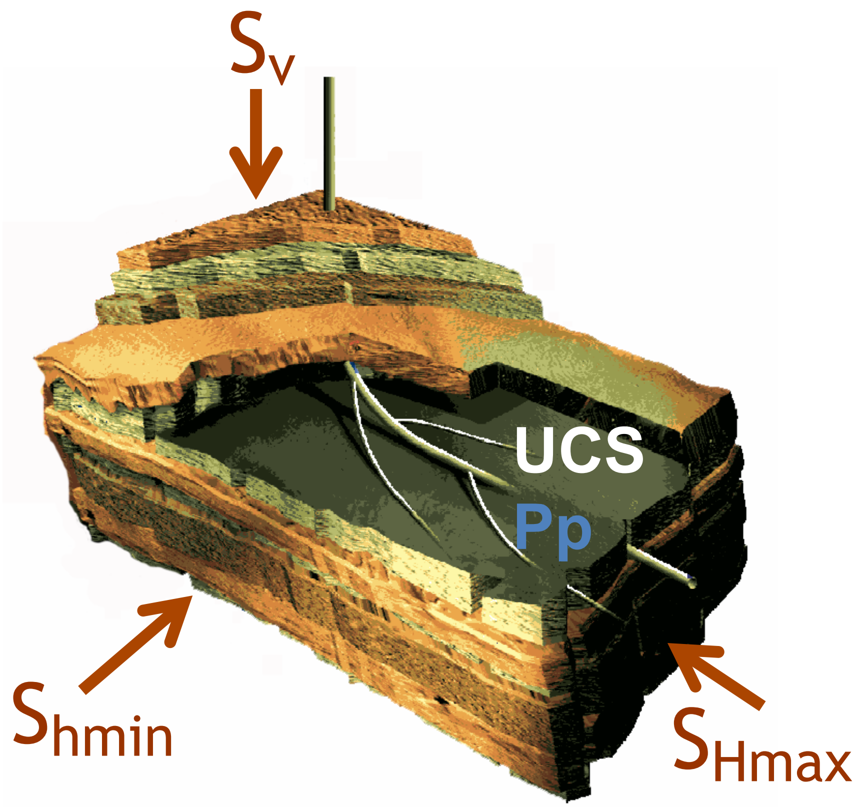
Step 1 - Develop a Geomechanical Model



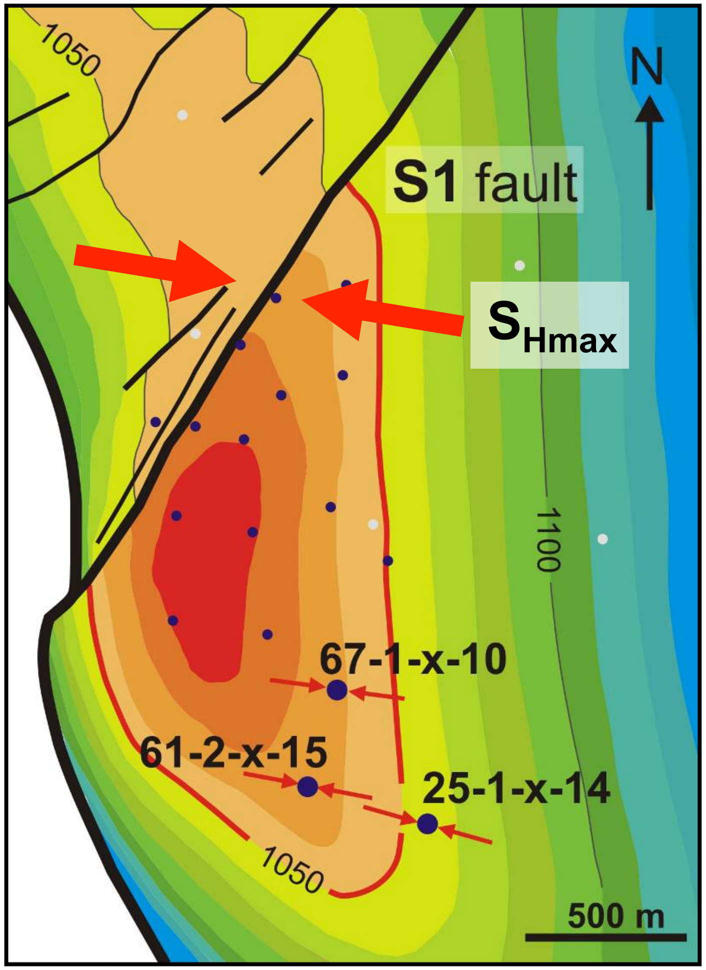
Principal Stresses at Depth

S_v – Overburden
S_{Hmax} – Maximum horizontal principal stress
S_{hmin} – Minimum horizontal principal stress

Additional Components of a Geomechanical Model

P_p – Pore Pressure
UCS – Rock Strength (from logs)
Fractures and Faults (from Image Logs, Seismic, etc.)

Step 2 – Evaluate Potentially Faults



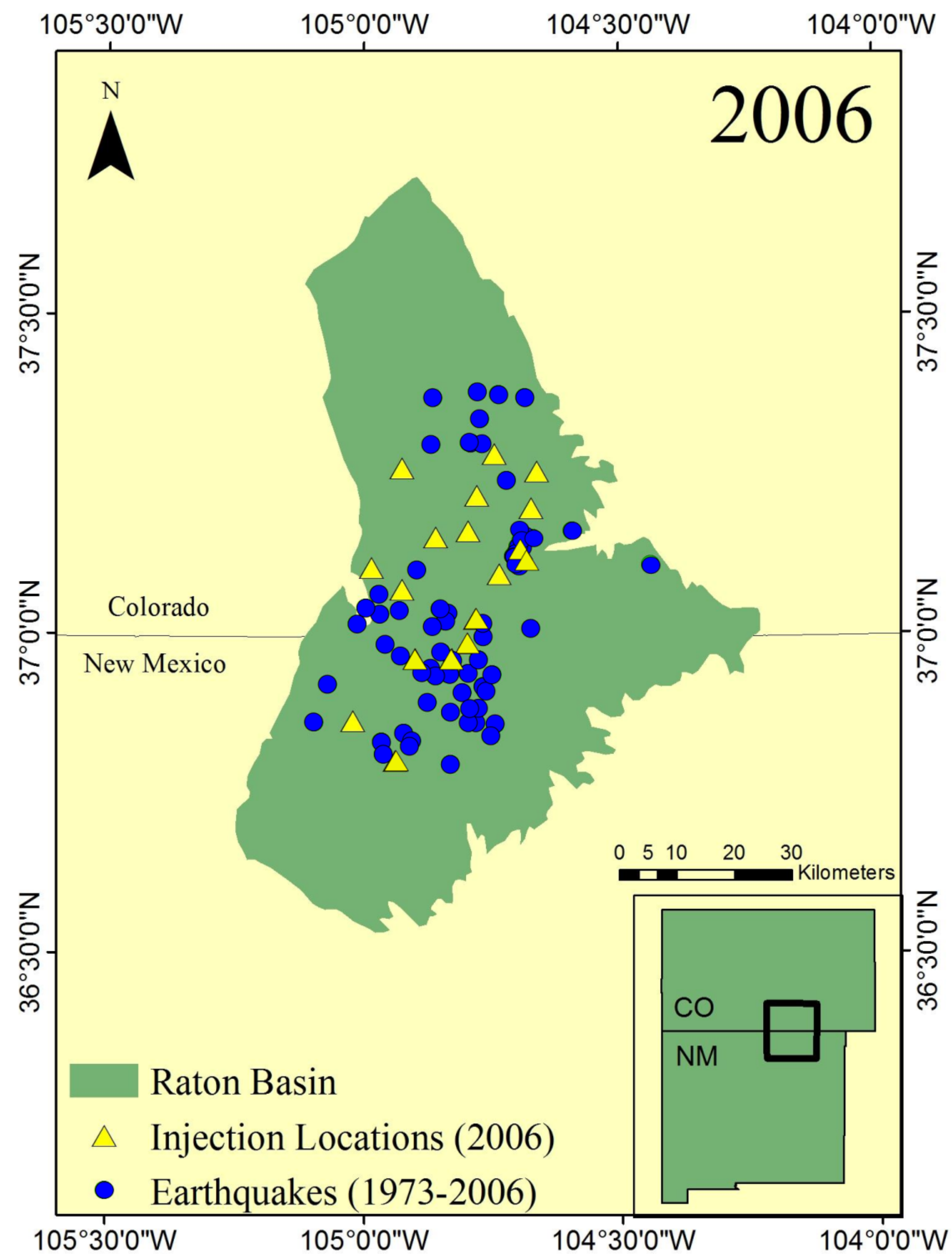
Mean S_{Hmax} orientation
N116°E

- 420 Consistent Observations of Stress Orientation
- Range of depths: 400 – 1800 m
- Tensleep Fm. ~1650 m

Strike-Slip/Normal
Stress Magnitudes
$S_{Hmax} \approx S_v > S_{hmin}$

3. Monitor Seismicity

- Several NM waste fluid wells report injection activities
- Seismicity increases in NM portion of Raton Basin



Weingarten and Ge (in preparation)

Spatial Correlation

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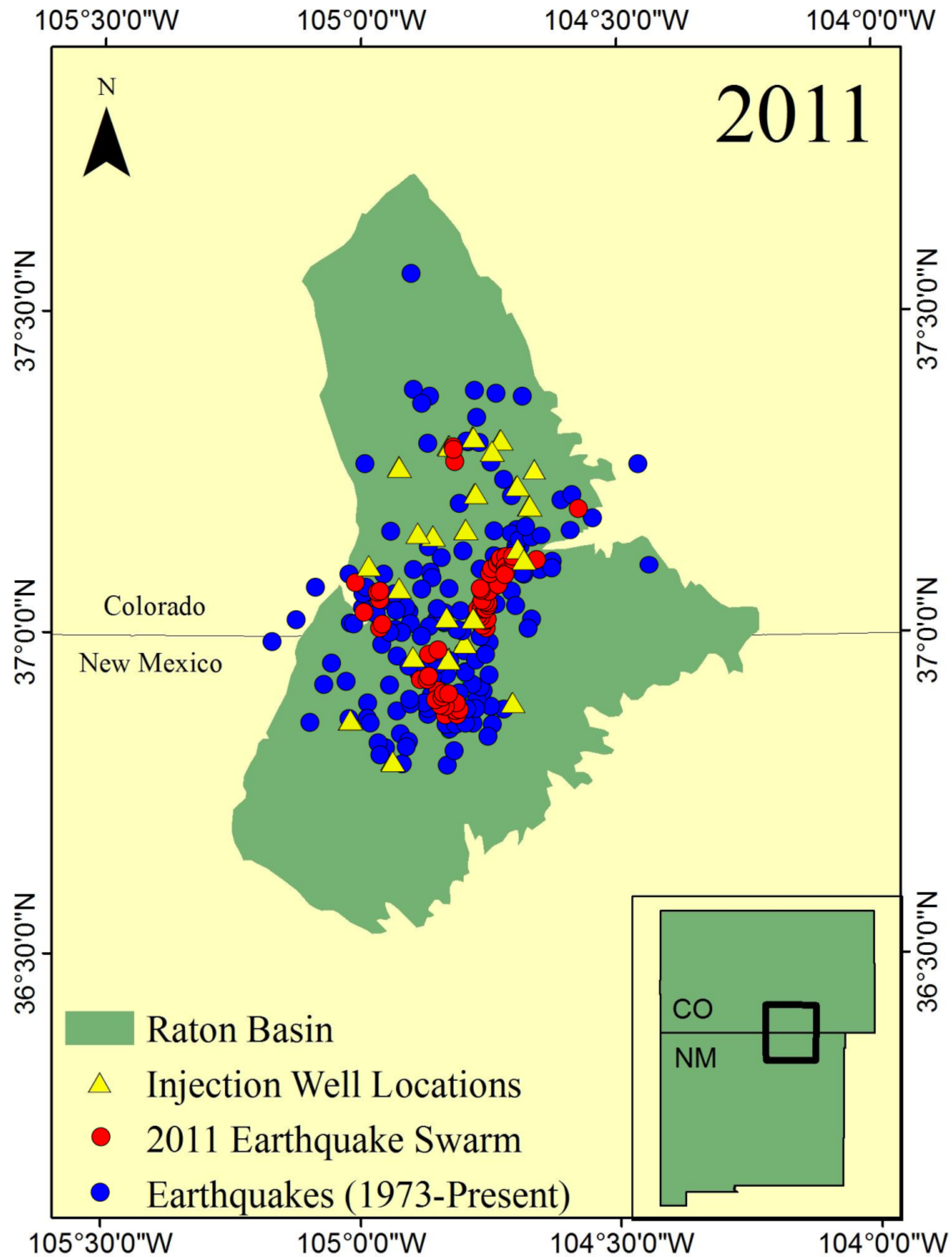
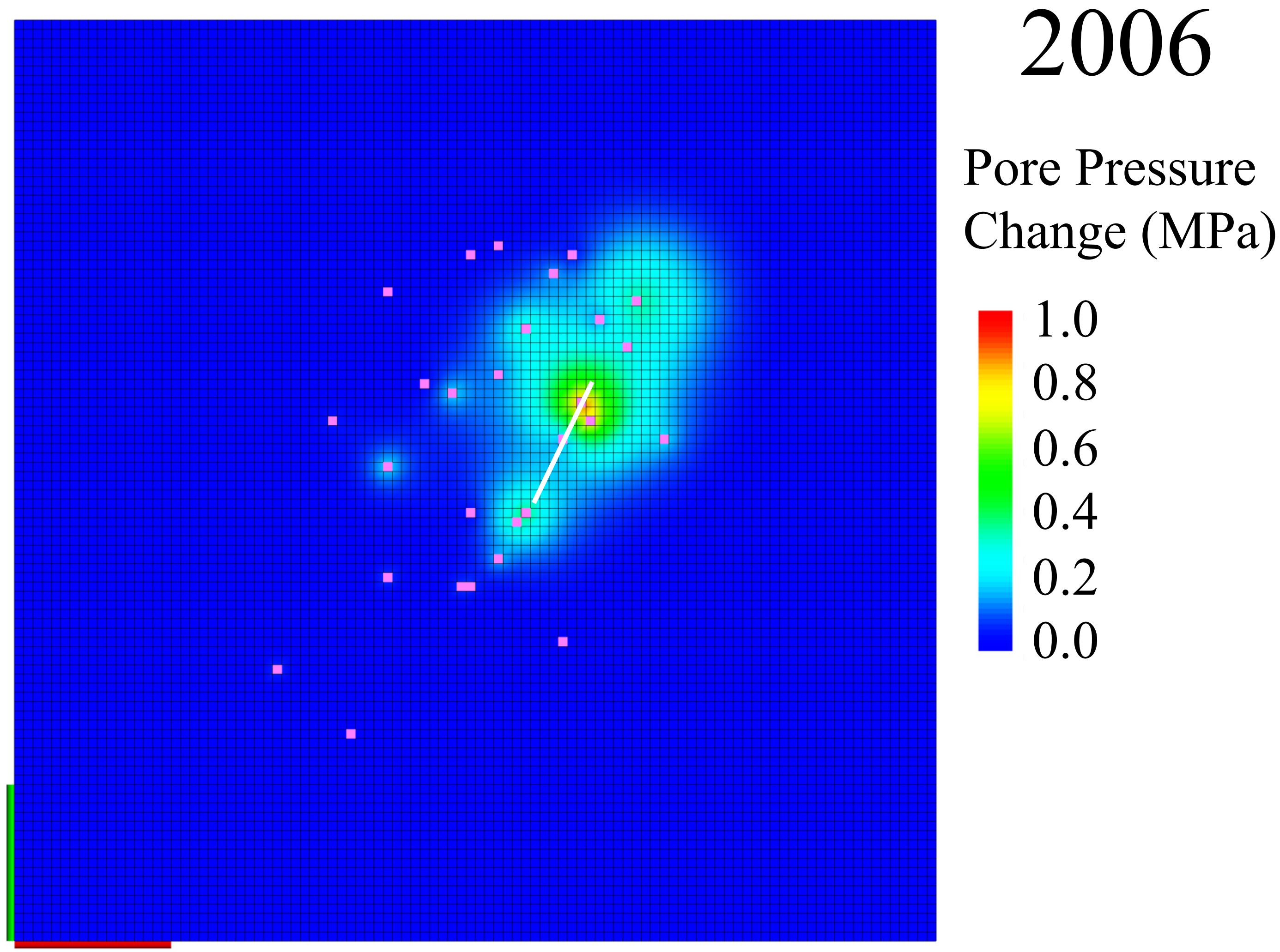
  - Largest EQ M5.3 on NE trending basement fault

Seismicity Results from Increased Injection Volumes With Time



Low Hydraulic Conductivity Model



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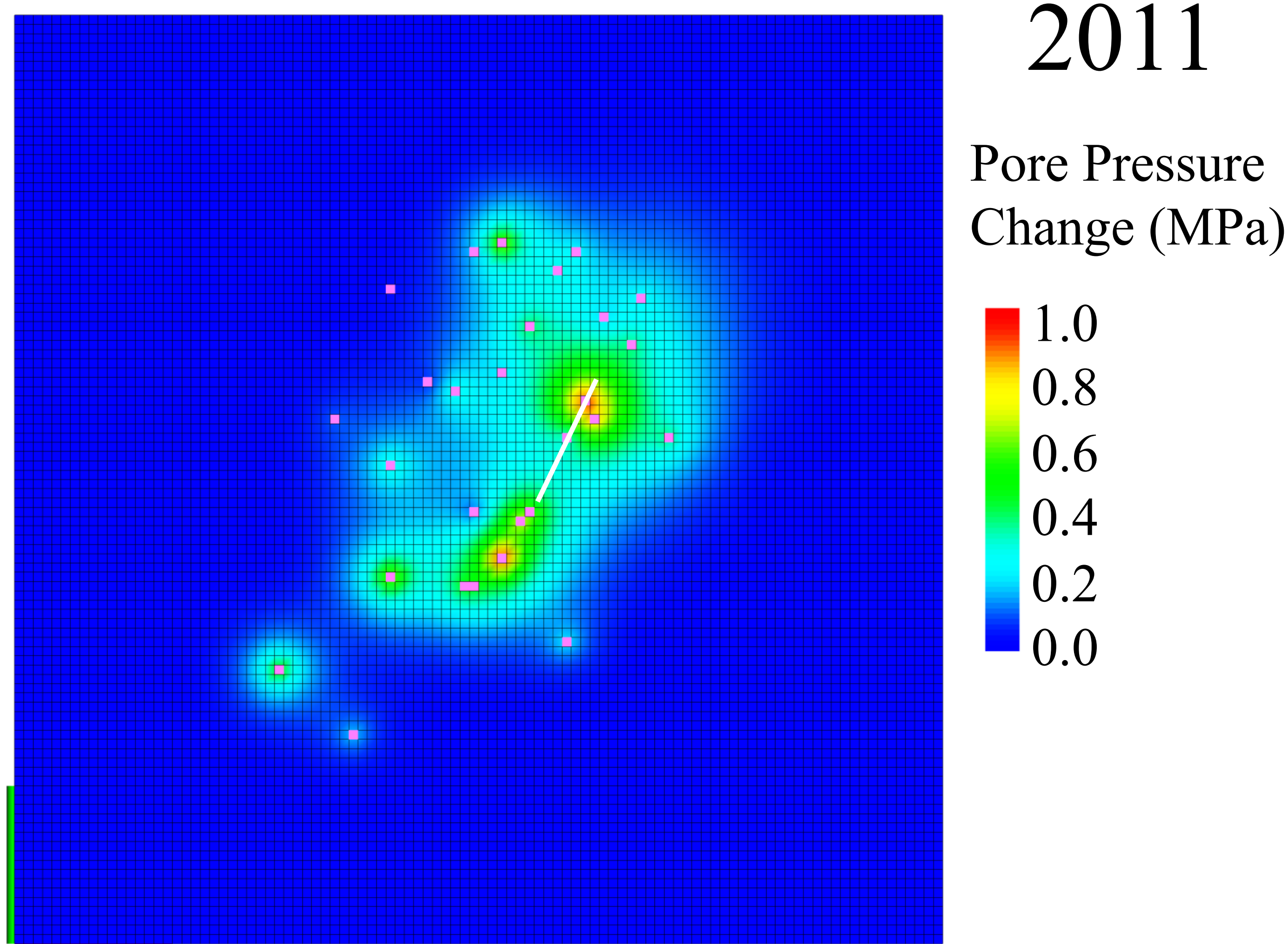
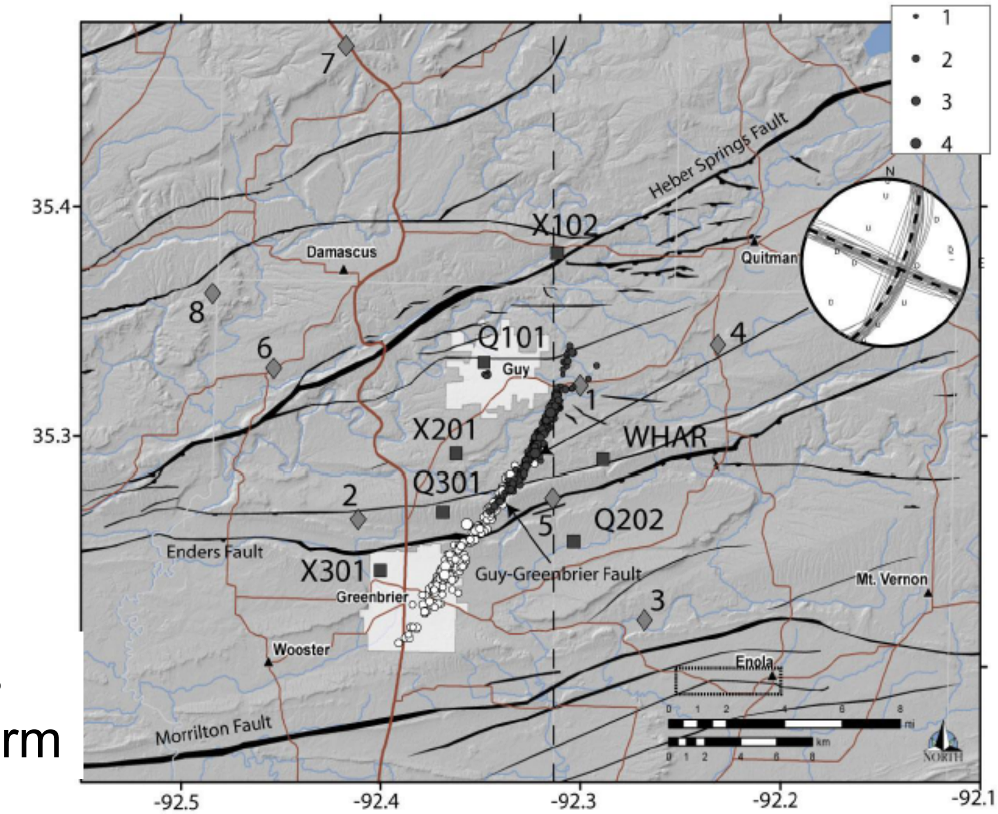


Injection Rate?
Injection Volume?
Presence of Potentially Active Faults?
Hydraulic Modeling of Injection Strategies?

Be Prepared to Abandon Some Injection Wells



Guy Arkansas
Earthquake Swarm

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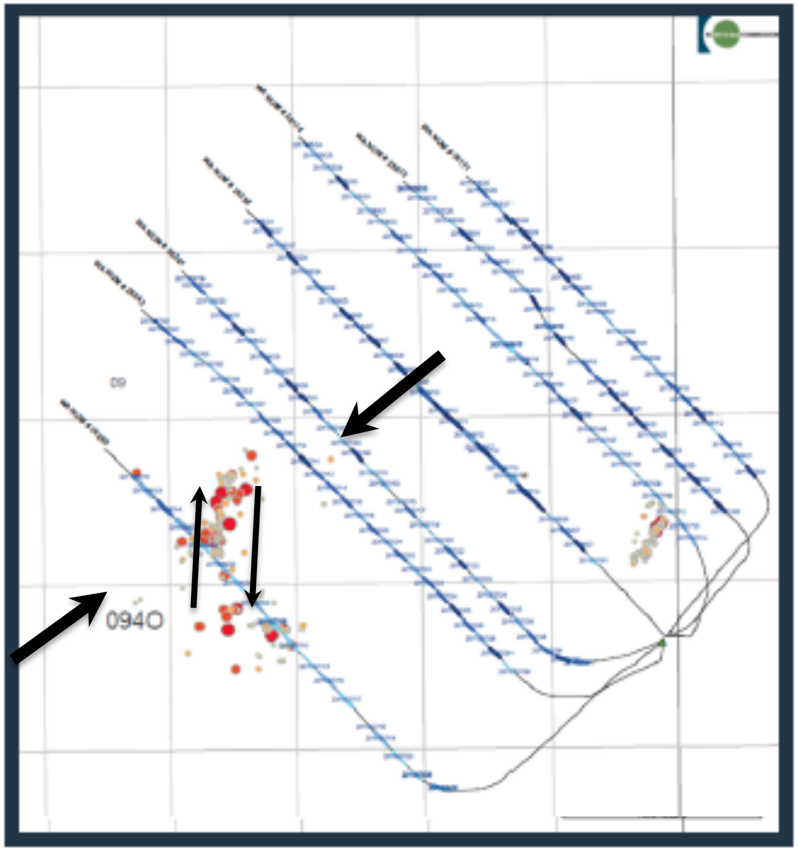
Real-Time Monitoring of Hydraulic Fracturing



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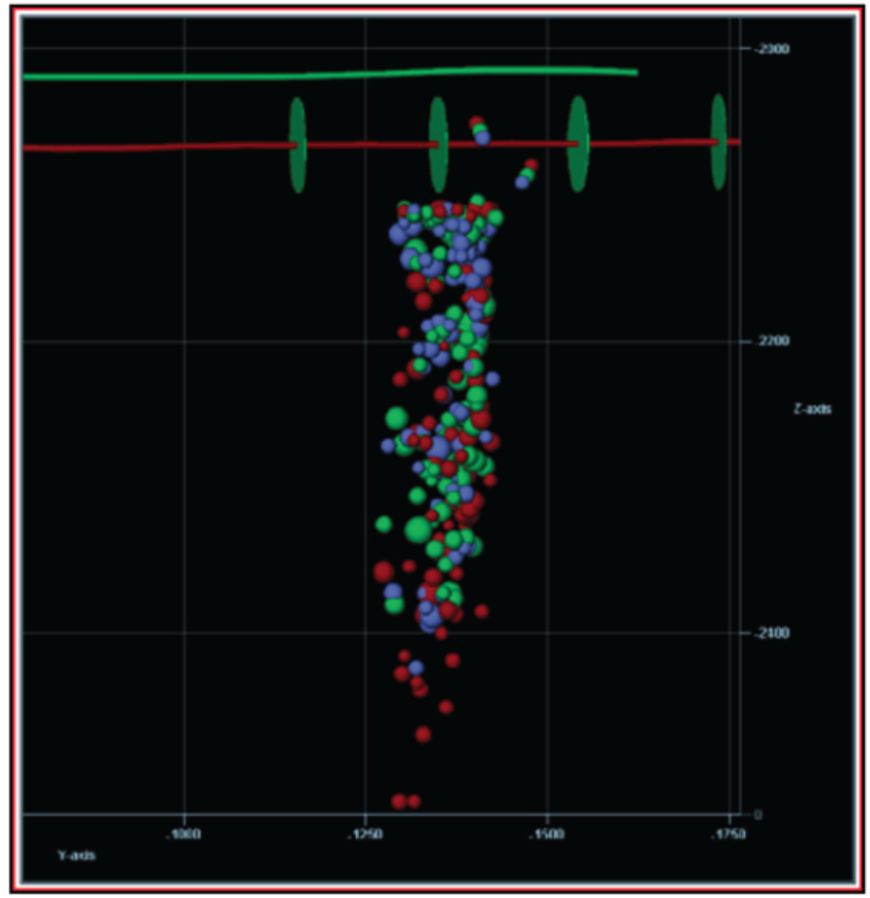

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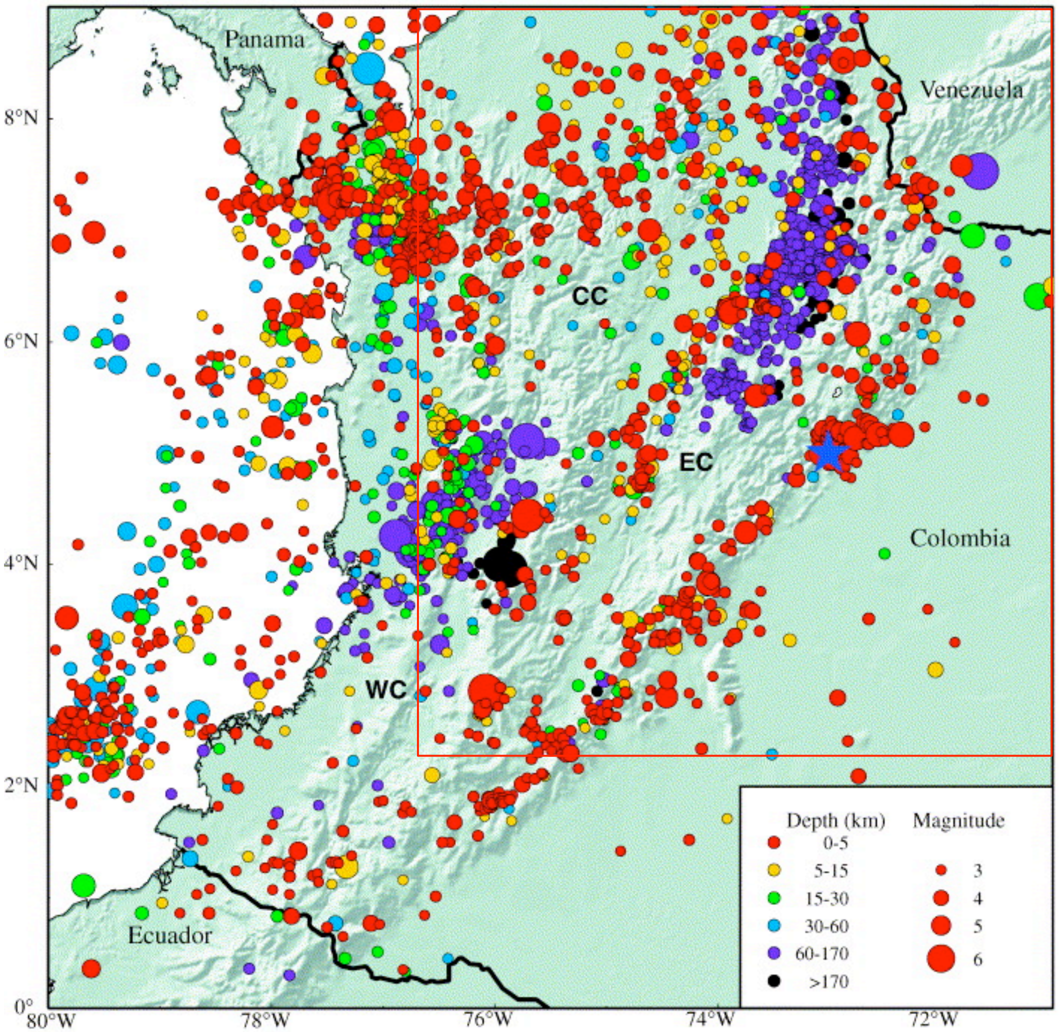
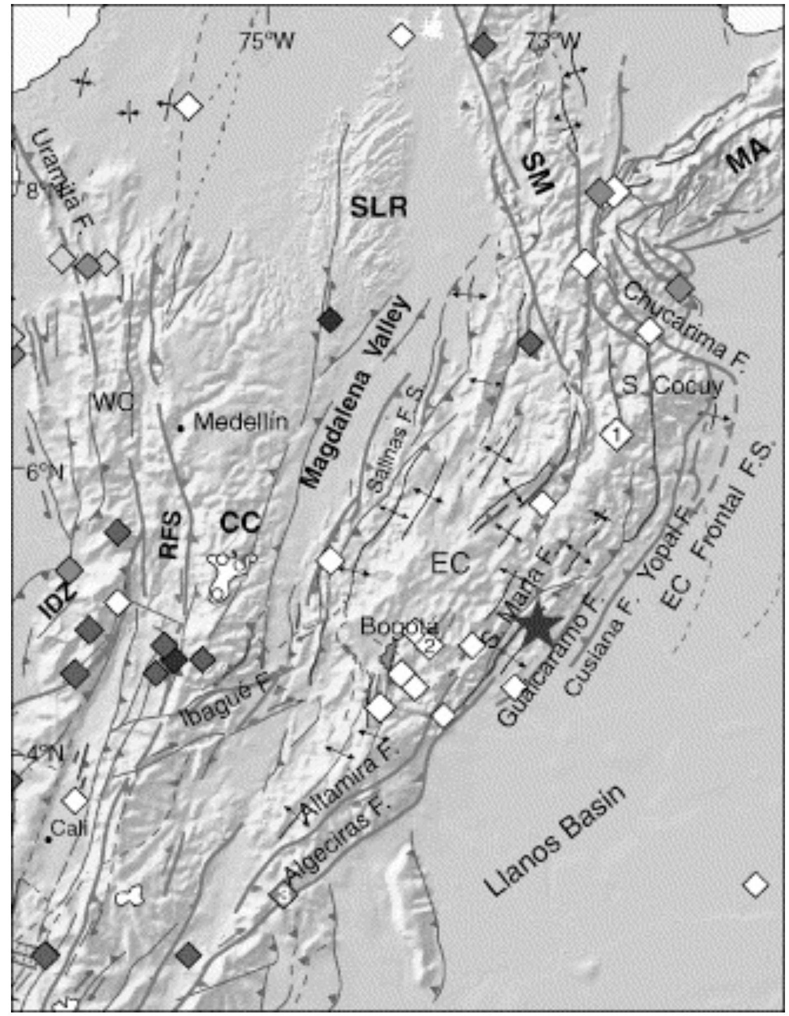
Baseline Data Requirements

- Historical Seismicity
- Active Faulting
- Geomechanical Model
- Utilize Optimal Formations for Injection
- Seismic and Pressure Monitoring

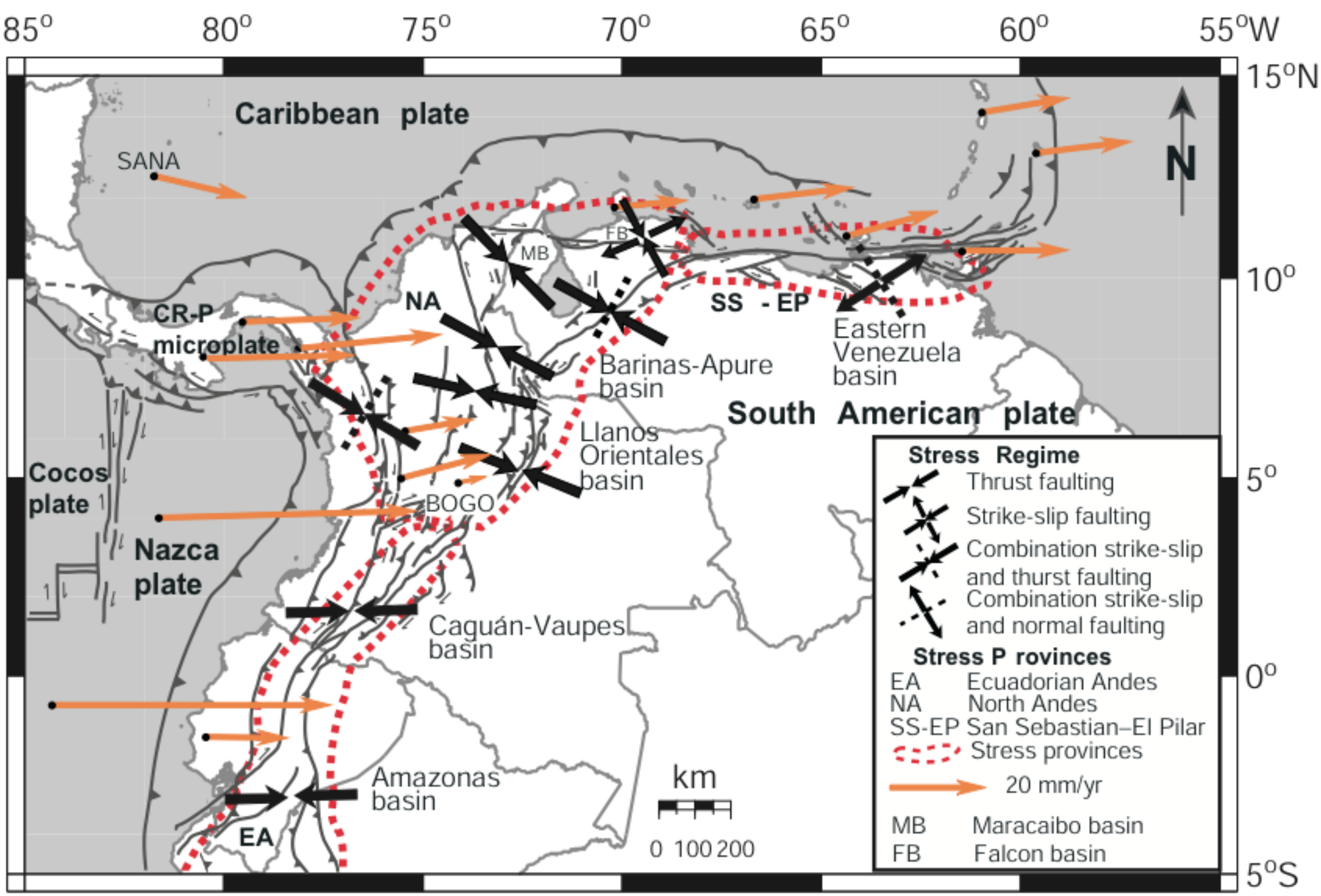
Earthquakes in Colombia





Diamate et al. (2003)

Seismotectionics of Northern South America



Colmenares and Zoback (2003)