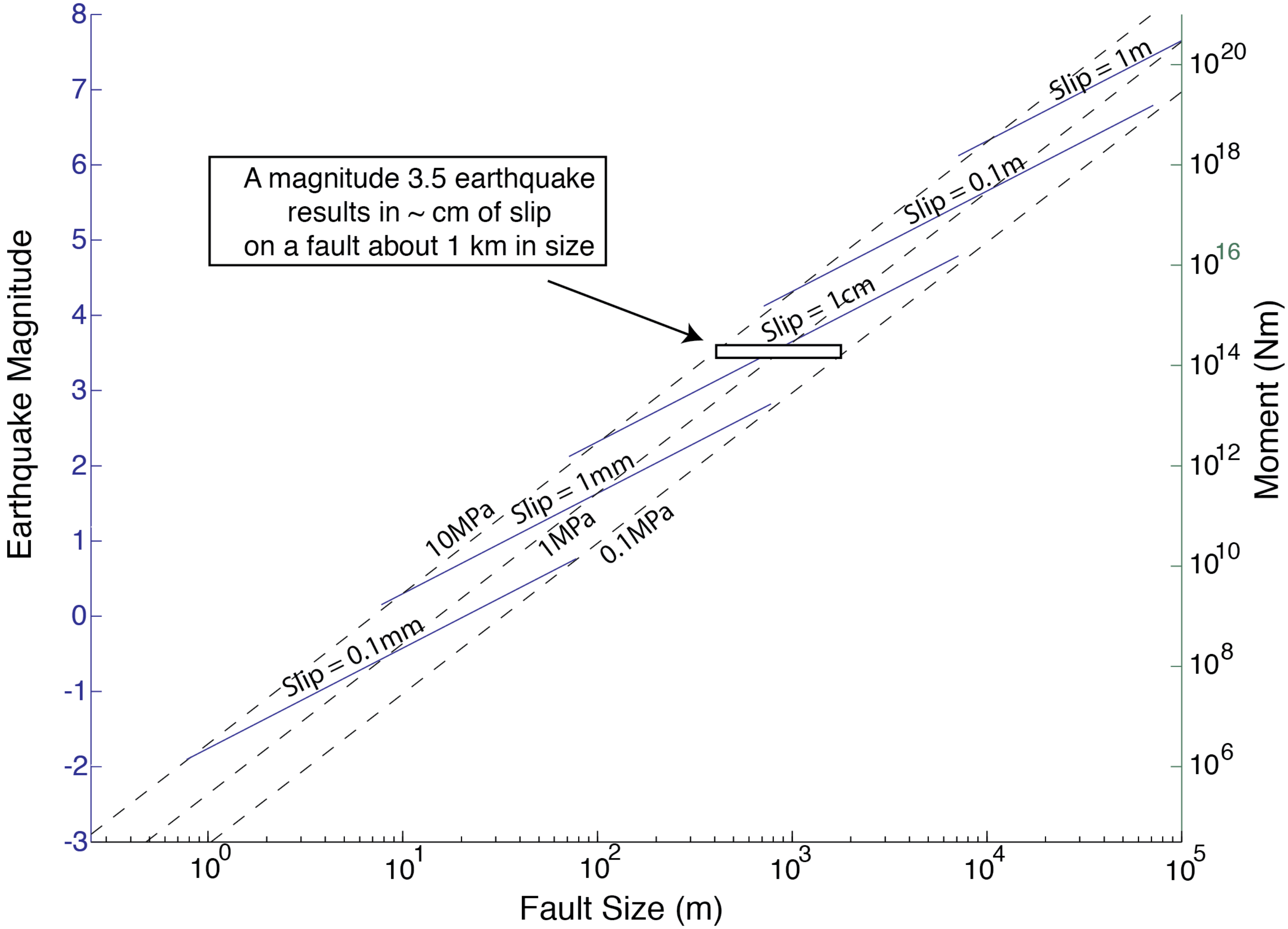
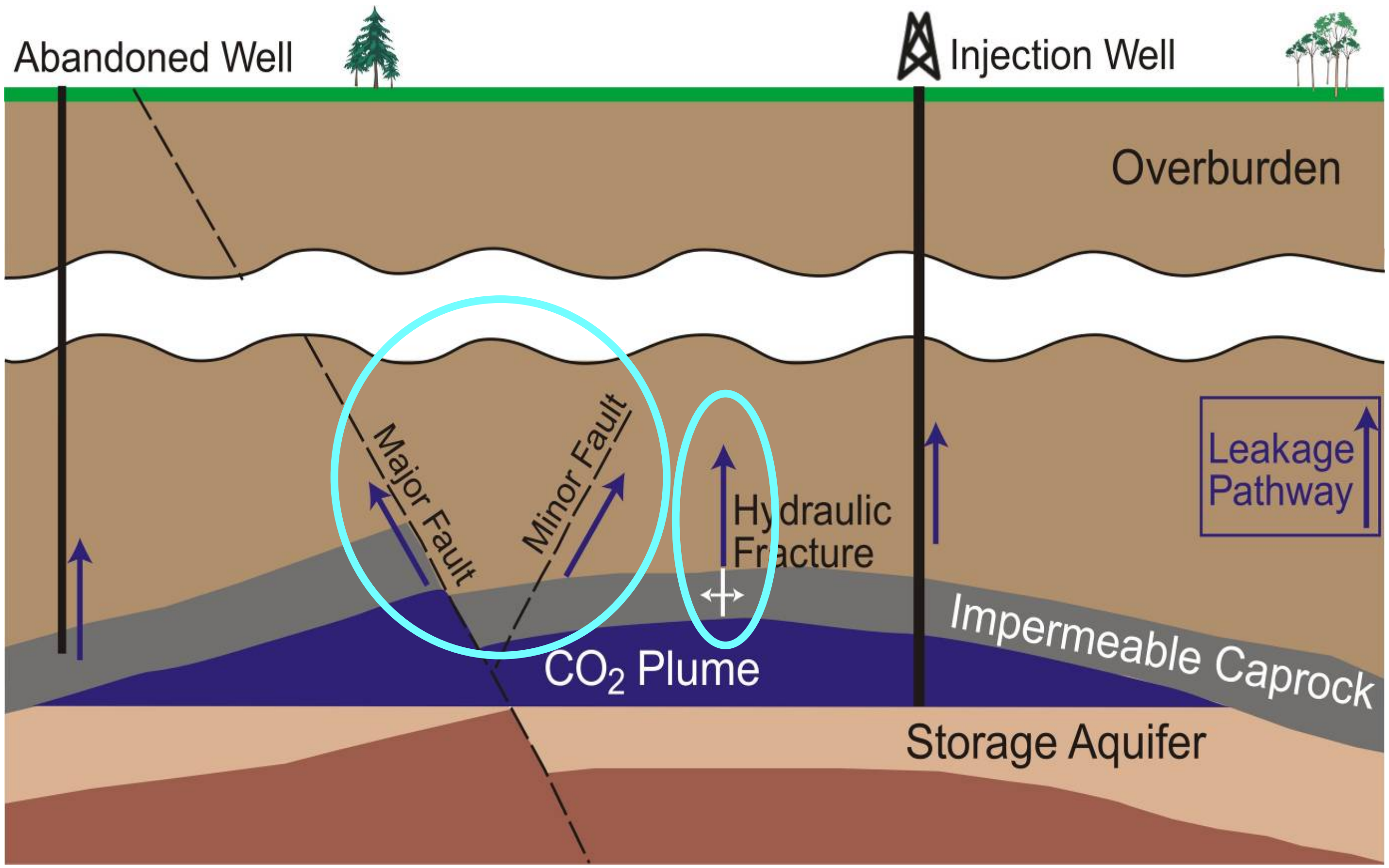
What if a M~3.5 Earthquake Occurred in a CO_2 Reservoir?



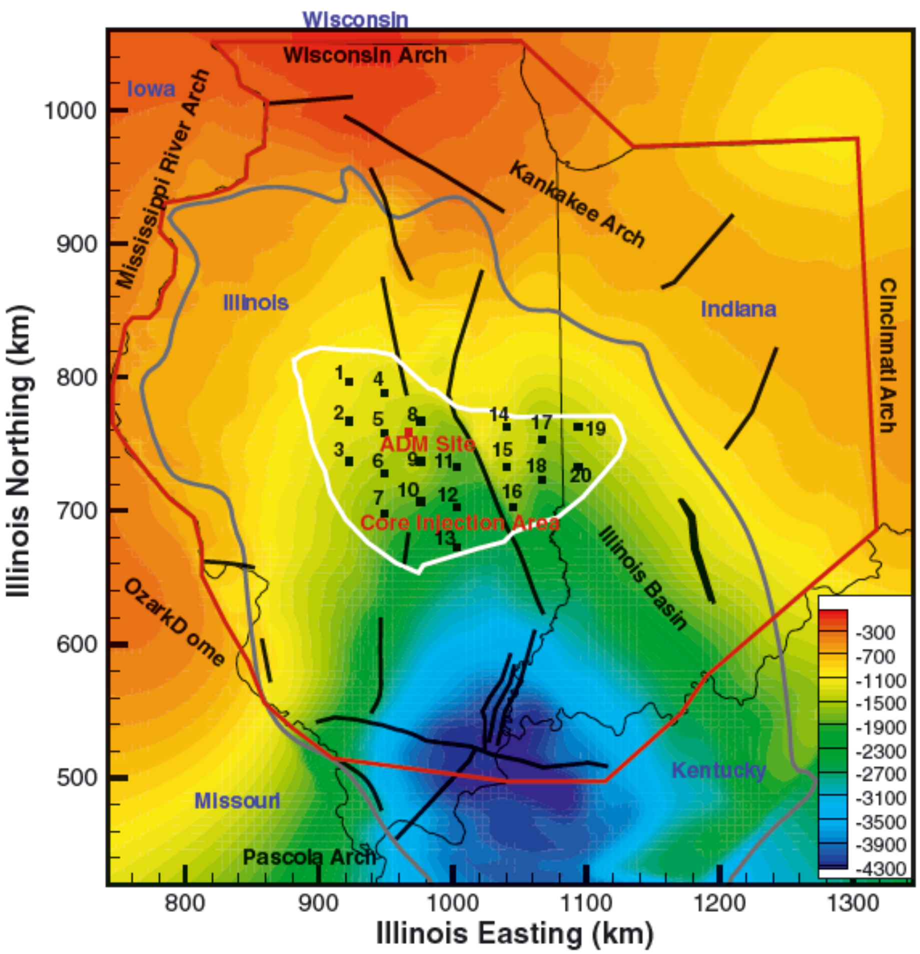
A Magnitude 3 Earthquake Threatens Seal



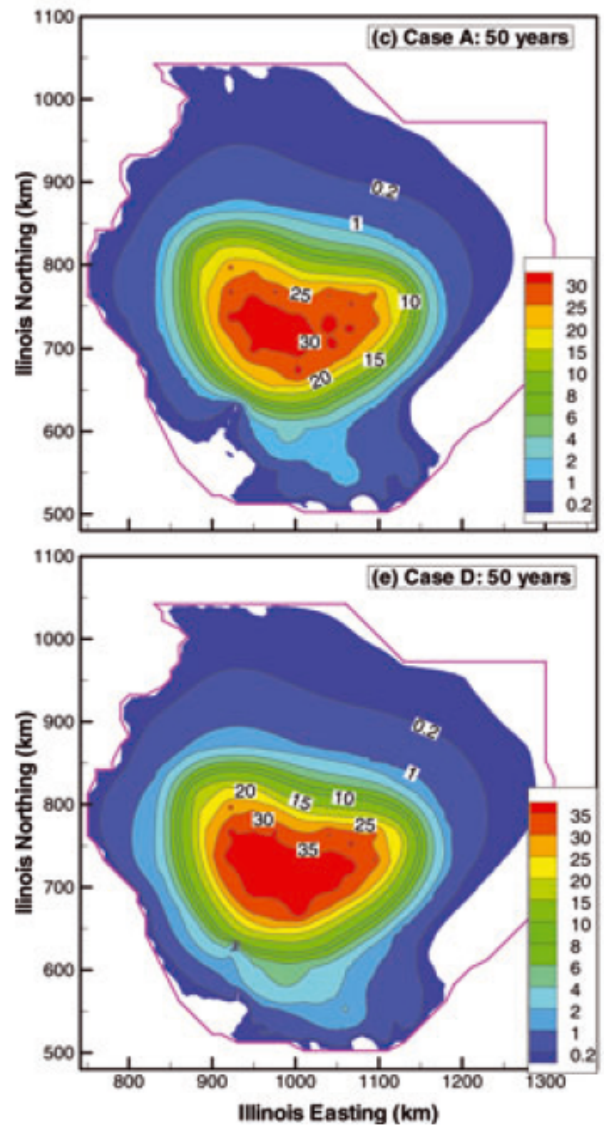
Would it be prudent to leave CO_2 in place even after a small earthquake?

A Regional Solution?

Illinois Basin



Mt. Simon Sandstone

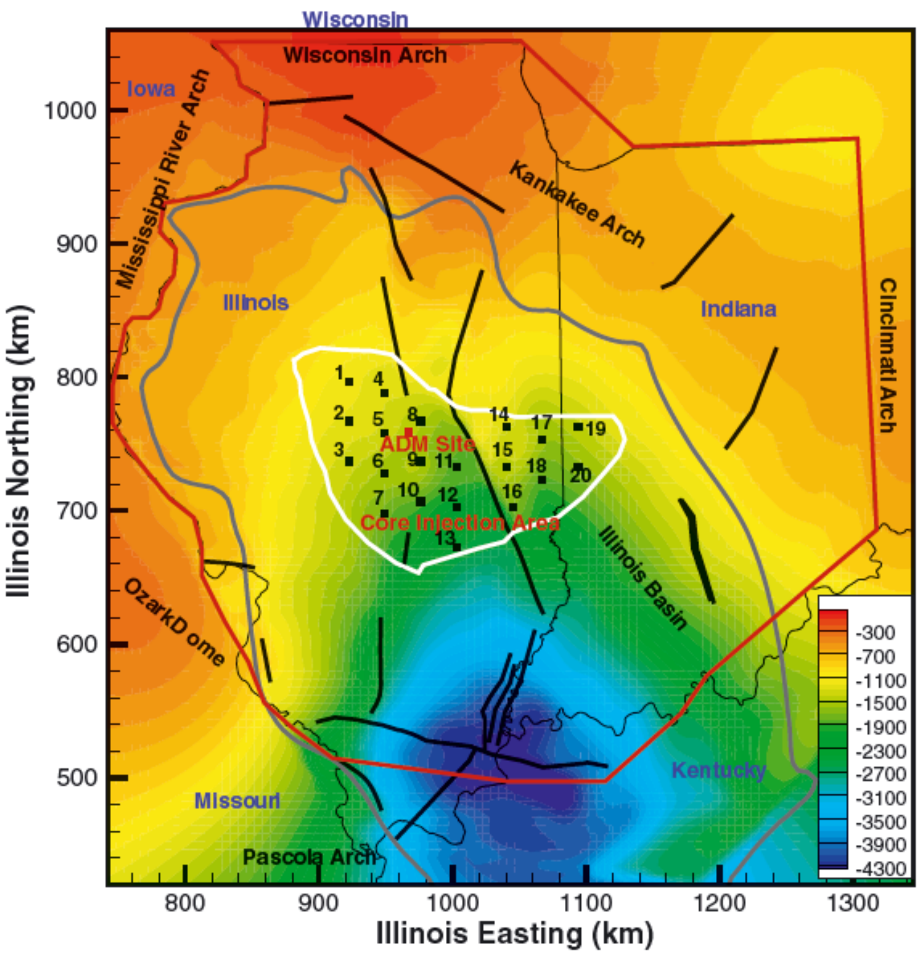


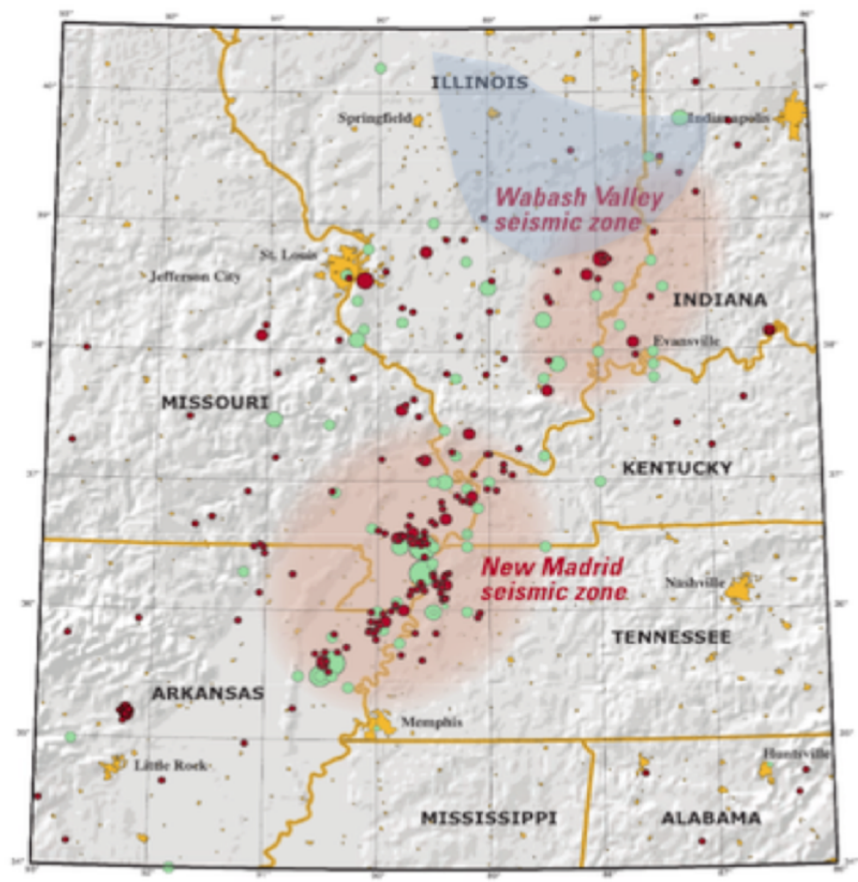
Zhou et al. (2009)

Injection of 100 Mtons/y of CO_2

Regional Perturbations Affect Regional Faults

Illinois Basin





Are the “Seismically Safe” Saline Aquifers?

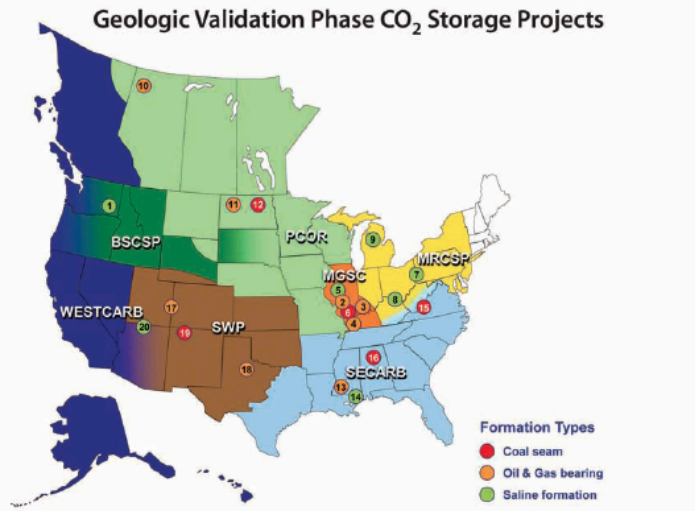
Regional Carbon Sequestration Partnerships

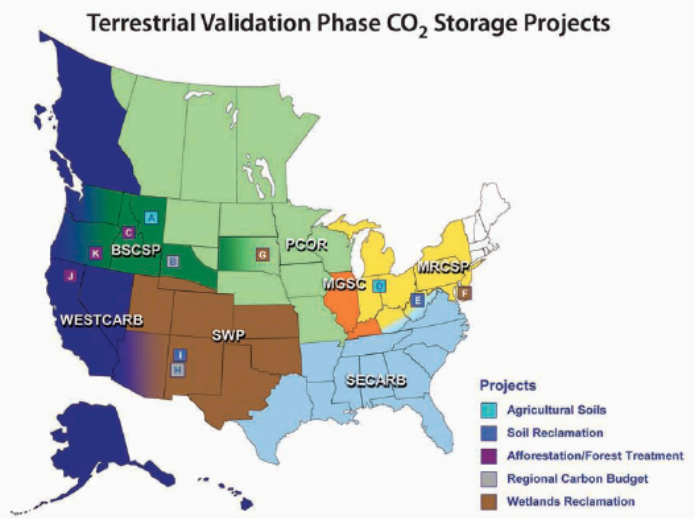
Validation Phase CO_2 Storage Projects

	Partnership	Geologic Province/ Location	Geologic: Total CO_2 Injection (metric tons CO_2)	Geologic: Approximate Depth (feet)	Terrestrial: Estimated CO_2 Storage Potential
1	Big Sky Carbon Sequestration Partnership	Columbia Basin	0	2,500 – 4,000	
A		North Central MT			60 Mt over 20 years
B		Eastern WY			30 Mt over 10 years
C		Region-wide			640–1,040 Mt over 80 years
2	MGSC	Illinois Basin–Loudon Field	< 39	1,550	
3		Illinois Basin–Mumford Hills Field	3,375	1,551	
4		Illinois Basin–Sugar Creek Field	6,500	1,548	
5		Illinois Basin*	*	7,200	
6		Illinois Basin	91	1,000	
7	MRCSP Midwest Regional Carbon Sequestration Partnership	Appalachian Basin	< 50	5,900 – 8,300	
8		Cincinnati Arch	1,000	3,200 – 3,500	
9		Michigan Basin	60,000	3,200 – 3,500	
D		Region-wide			25 Mt over 20 years
E		Region-wide			100 Mt over 20 years
F		Cambridge, MD			TBD
10	PCOR Partnership	Alberta Basin–Zama Field	25,400	4,900	
11		Williston Basin–Northwest Field	400	8,050	
12		Williston Basin	80	1,100	
G		Great Plains wetlands complex (PPR)			14.4 Mt
13	SECARB Southeast Regional Carbon Sequestration Partnership	Gulf Coast–Cranfield	627,744	10,300–10,400	
14		Mississippi Coastal Plain	2,740	8,600	
15		Central Appalachian	907	1,600 – 2,300	
16		Black Warrior Basin	252	1,500 – 2,500	
17	SWP	Paradox Basin–Aneth Field	630,000	5,600 – 5,800	
18		Permian Basin–Sacroc Unit	86,000	5,800	
19		San Juan Basin	16,700	3,000	
H		Region-wide			TBD
I		San Juan Basin Coal Fairway (Navajo City, NM)			TBD
20	West Coast Regional Carbon Sequestration Partnership westcarb.org	Colorado Plateau	0	4,000	
J		Shasta County, CA			4,600 Mt over 80 years (CA)
K		Lake County, OR			900 Mt over 80 years (OR)

* Site was moved to Development Phase injection.

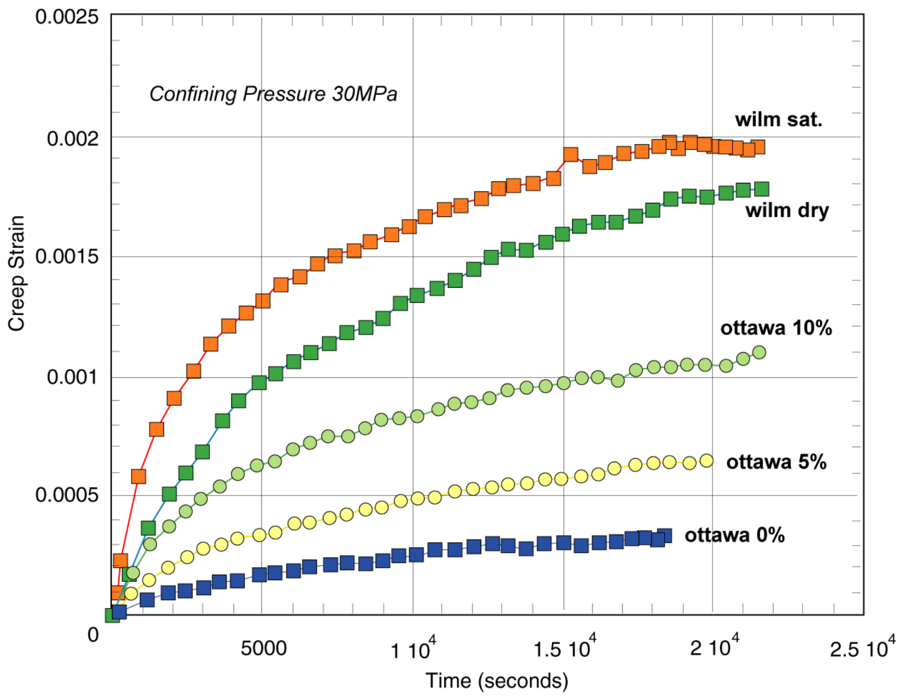
Information current as of June 2010





2010 Carbon Sequestration Atlas of the United States and Canada

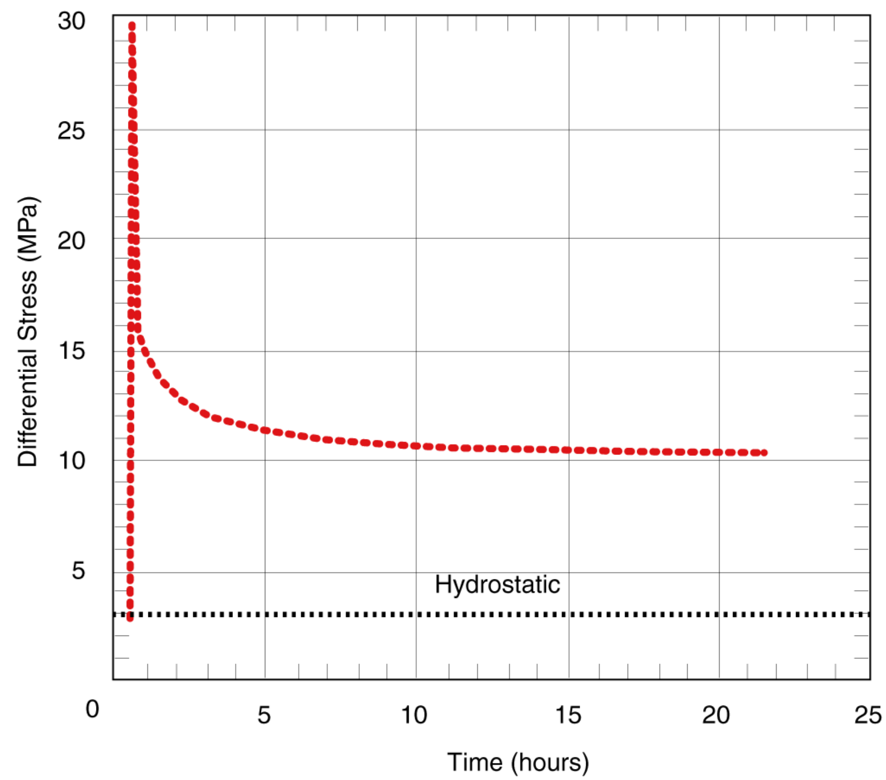
Yes, Poorly cemented Sediments That Deform Viscoplastically



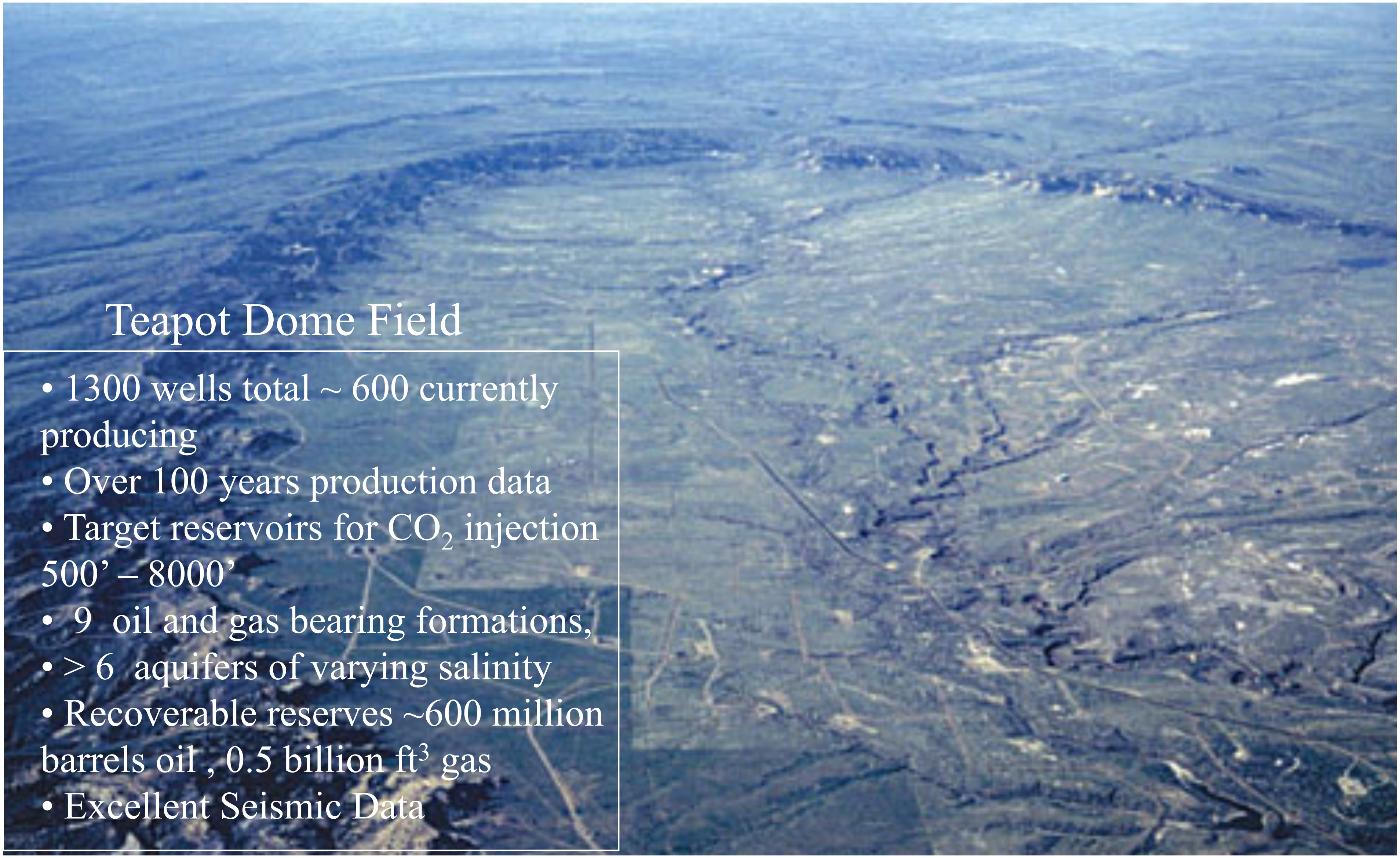
Wilmington Sand Creep Compaction

Chang and Zoback, 1998

Wilmington Sand Stress Relaxation



Teapot Dome Field, Wyoming
Depleted Reservoir/EOR



Teapot Dome Field

- 1300 wells total ~ 600 currently producing
- Over 100 years production data
- Target reservoirs for CO_2 injection 500' – 8000'
- 9 oil and gas bearing formations,
- > 6 aquifers of varying salinity
- Recoverable reserves ~600 million barrels oil , 0.5 billion ft^3 gas
- Excellent Seismic Data

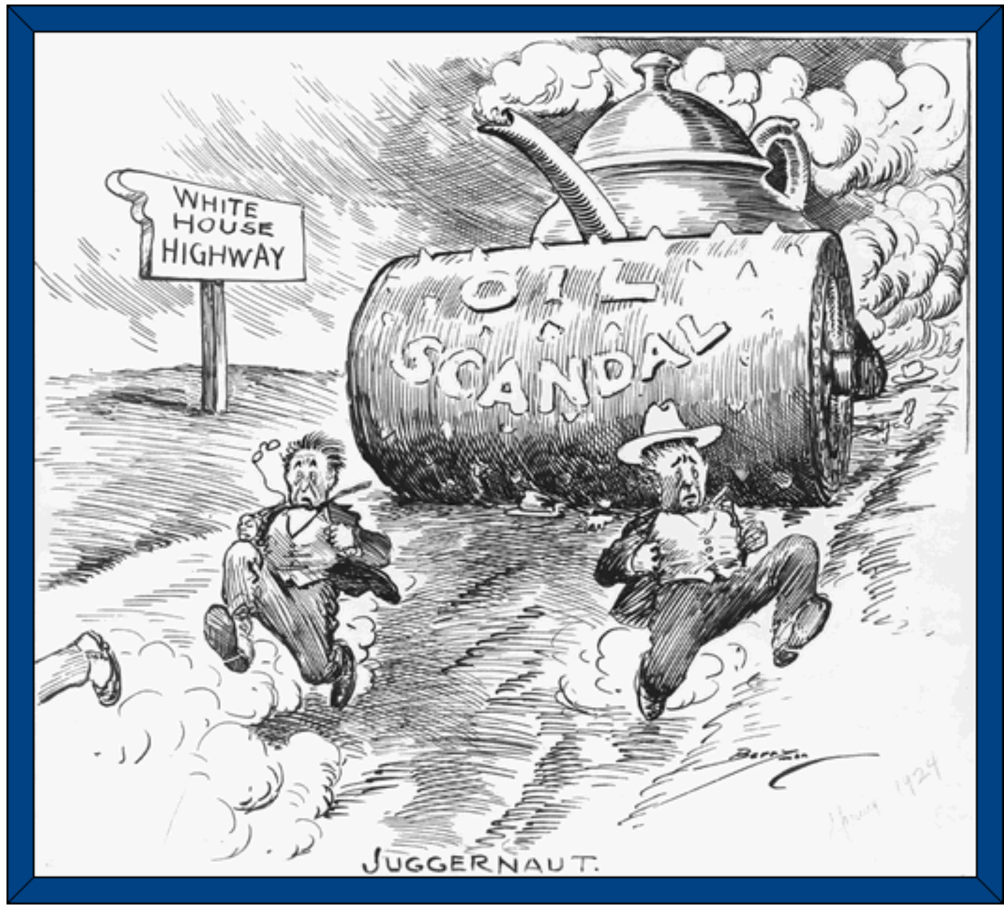
Teapot Dome - History

- **Declared Naval Petroleum Reserve (NPR-3) by Wilson administration in 1915. National scandal shut down of production for ~60 years**

- **Reopened in 1976**

- **1977 became US DOE facility**

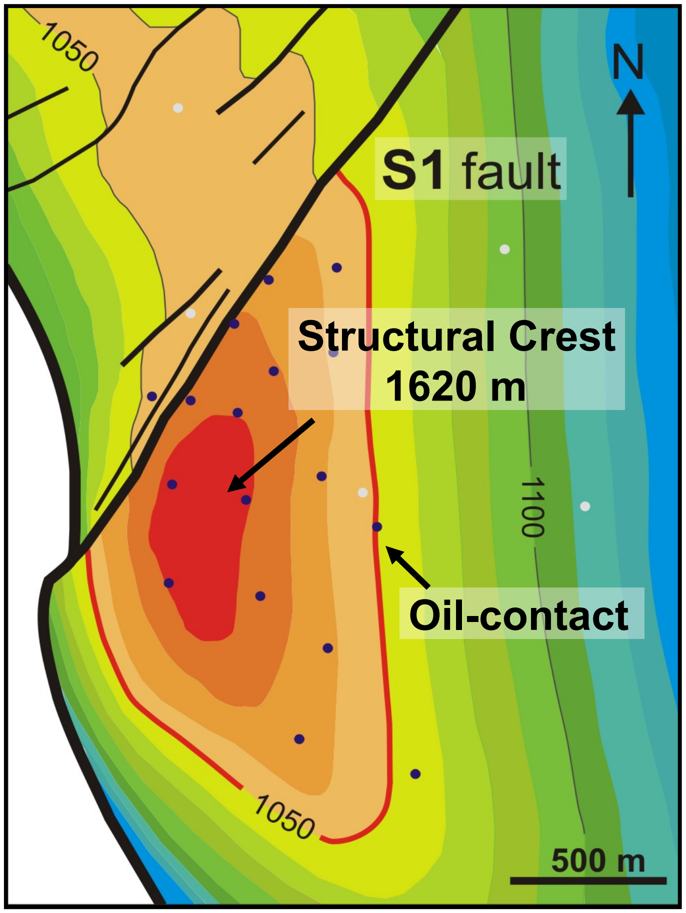
- **October 2003, Teapot Dome designated as the National Geological Carbon Storage Test Center**



Courtesy RMOTC

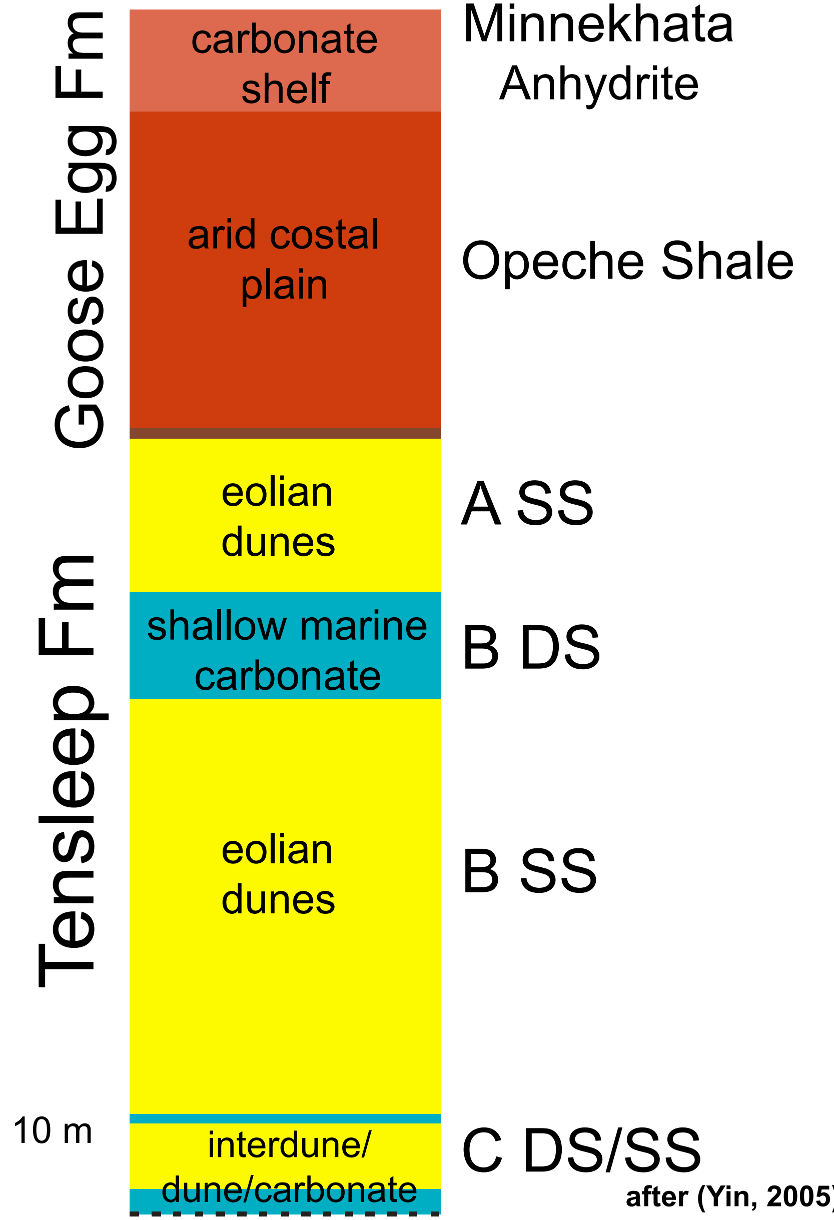
South Teapot Dome – Trap, Reservoir & Seal

3-way closure bounded by S1 fault



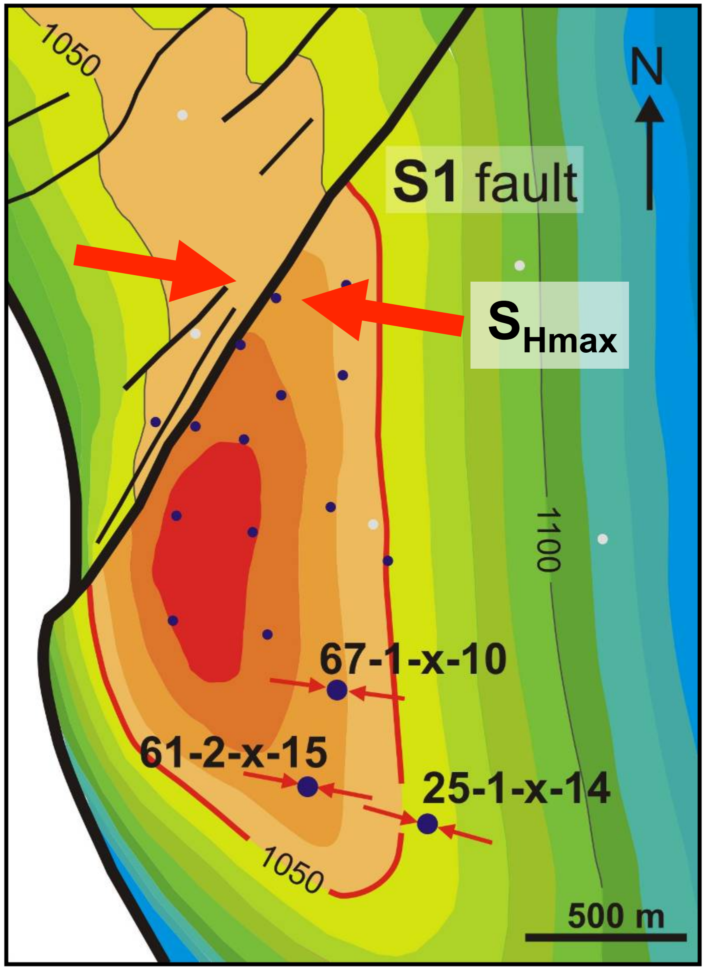
after (McCutcheon, 2003)

Time structure map of Tensleep Fm.



after (Yin, 2005)

S1 Fault area - Stress Data



Chiaramonte, Zoback et al. (2008)

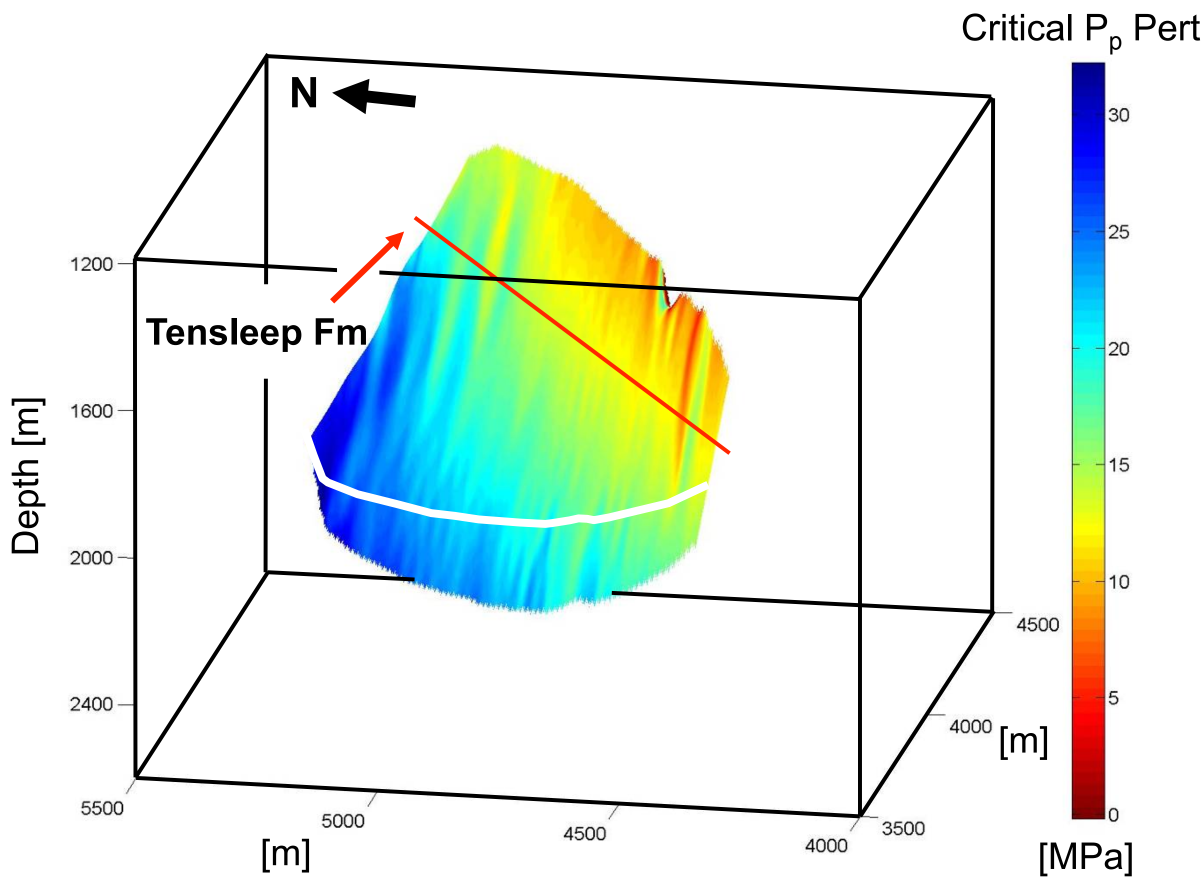
Mean S_{Hmax} orientation
N116°E

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

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

Very Low Slip Potential on S1 Fault

Required Critical Pressure Perturbation ~ 16 MPa



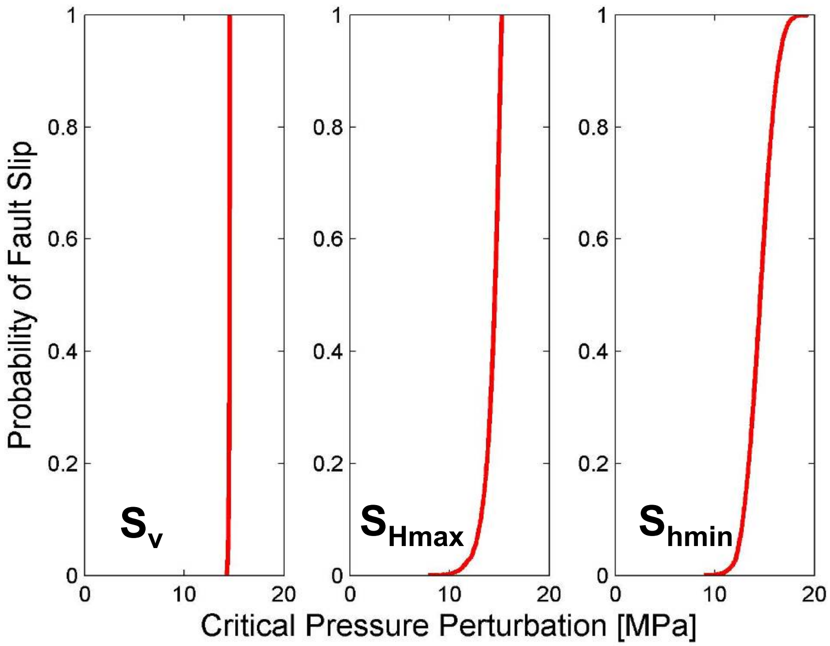
Corresponds to CO_2 column height of ~2300 m (den = 700 kg/m^3)

Tensleep average structural closure ~ 100m

Slip Potential – Sensitivity Analysis

Quantitative Risk Assessment

Normal Faulting Environment

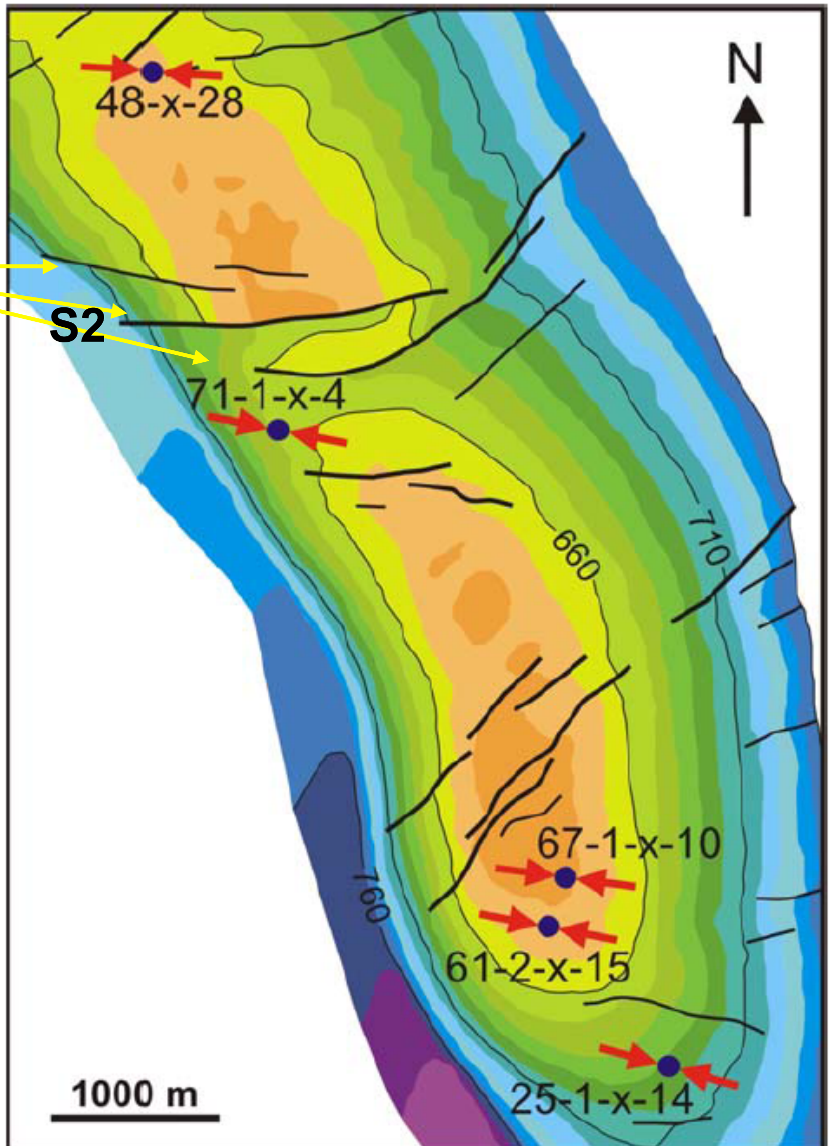


99.9% cases Critical Pressure Pert. > 9 MPa

10,000 Monte Carlo Simulations

S2 Fault Area

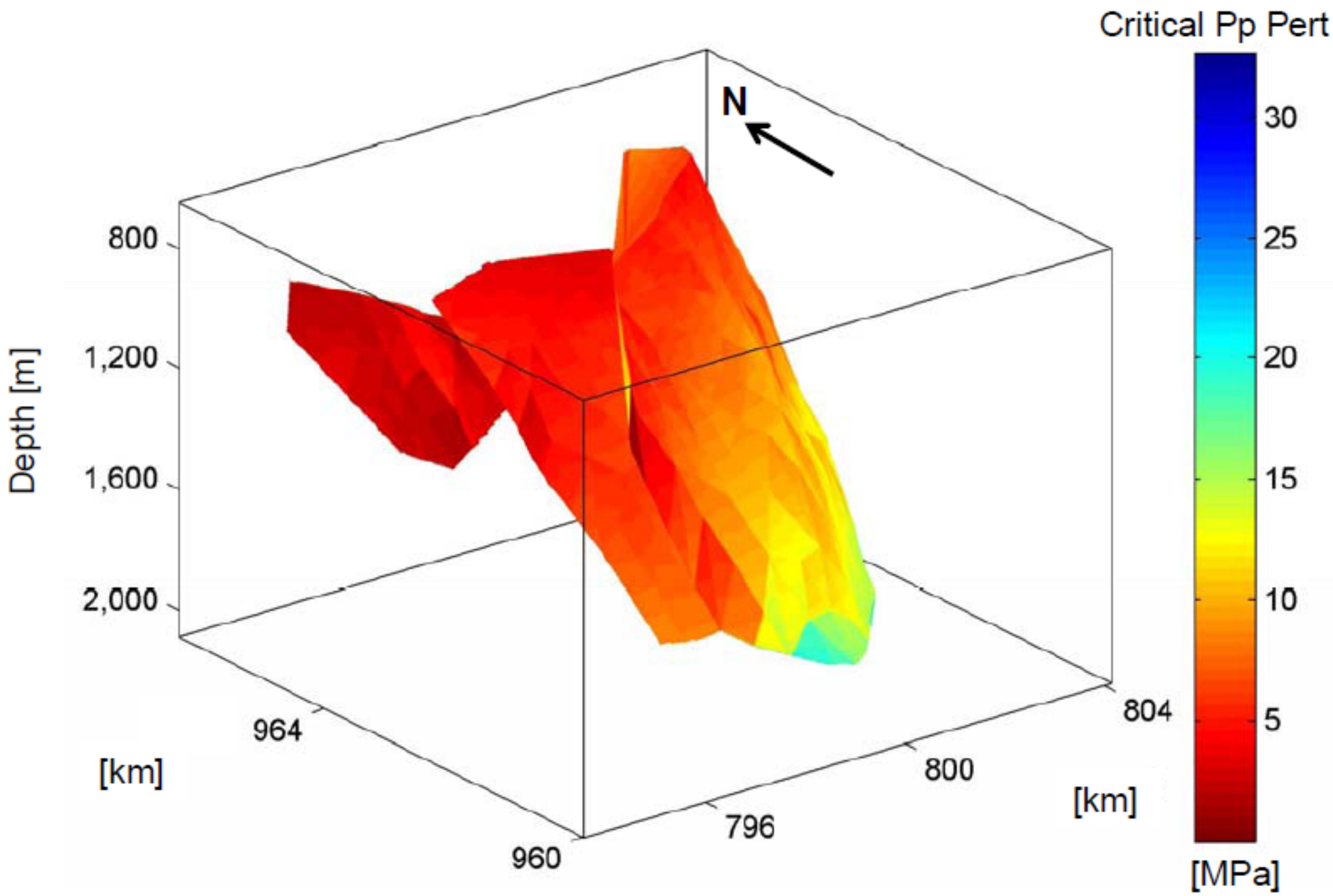
Faults Shown in Next Slide



Time structure map
2^{nd} Wall Creek Fm
(after McCutcheon, 2003)

Slip Potential on S2 Faults

2nd Wall Creek → Critical Pressure Pert. ~ 0 MPa



Corresponds to CO_2 column height of ~0 m

Outline of Presentation

1. Enormous Scale of Carbon Capture and Storage and Shale Gas Development

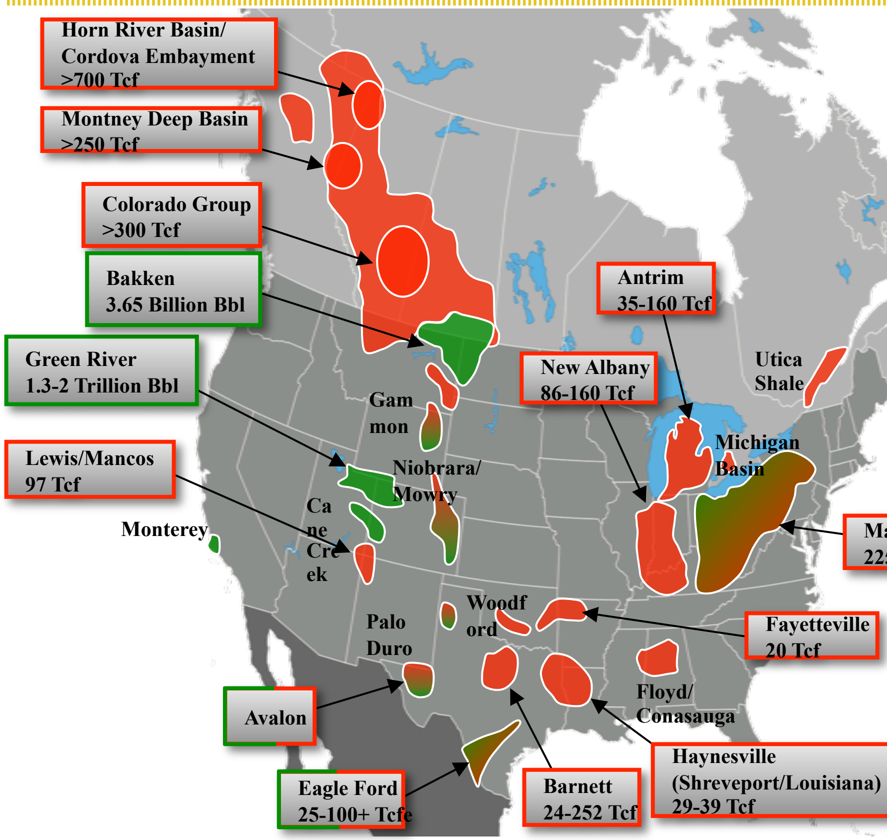
2. The Critically-Stressed Crust and Assessing Fault Stability

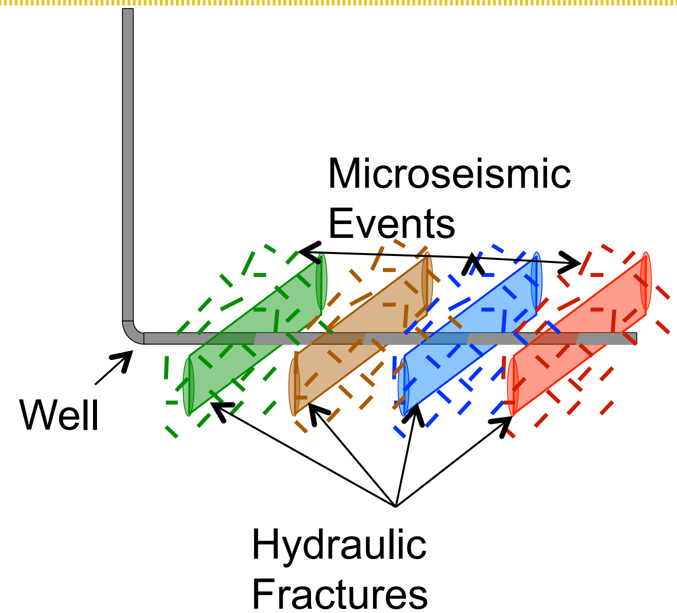
3. CCS and the Potential Triggered Seismicity (Case Studies)

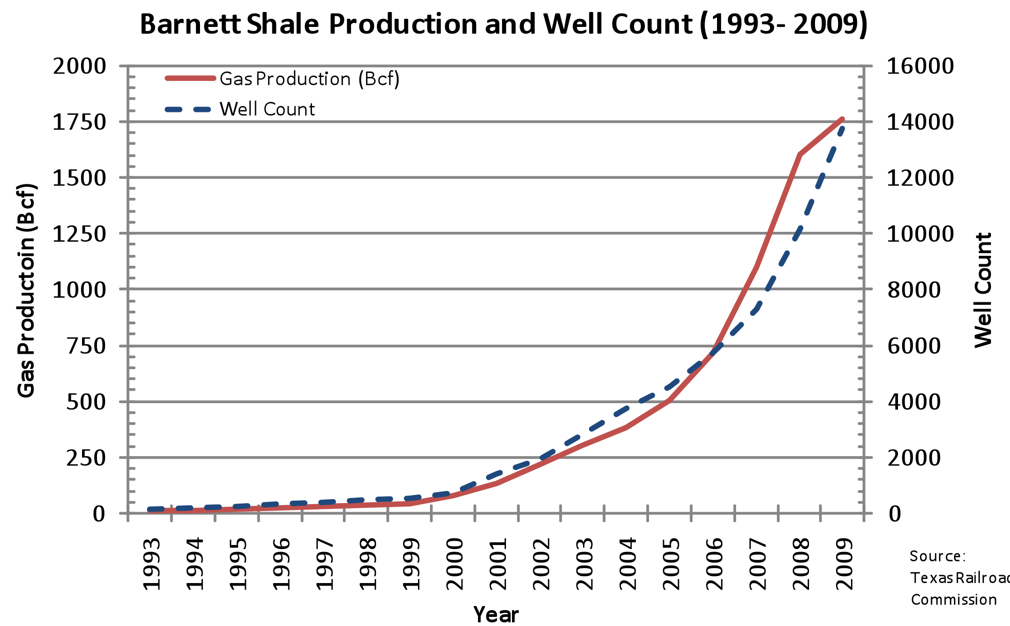
4. Shale Gas and Triggered Seismicity (Case Studies)

5. Assessing and Managing Seismic Risk Associated with CCS and Shale Gas Development

North American Shale Gas Development

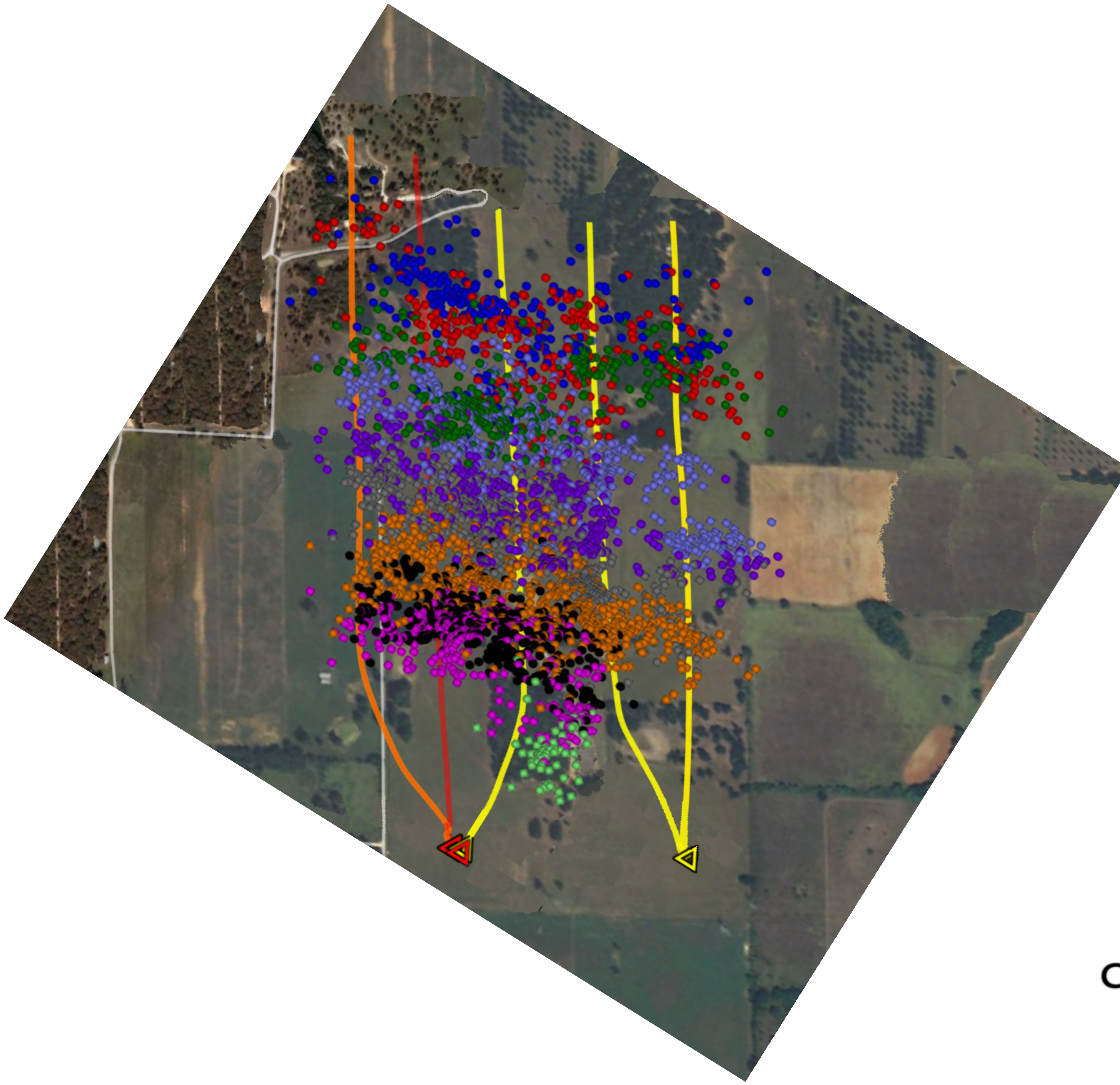






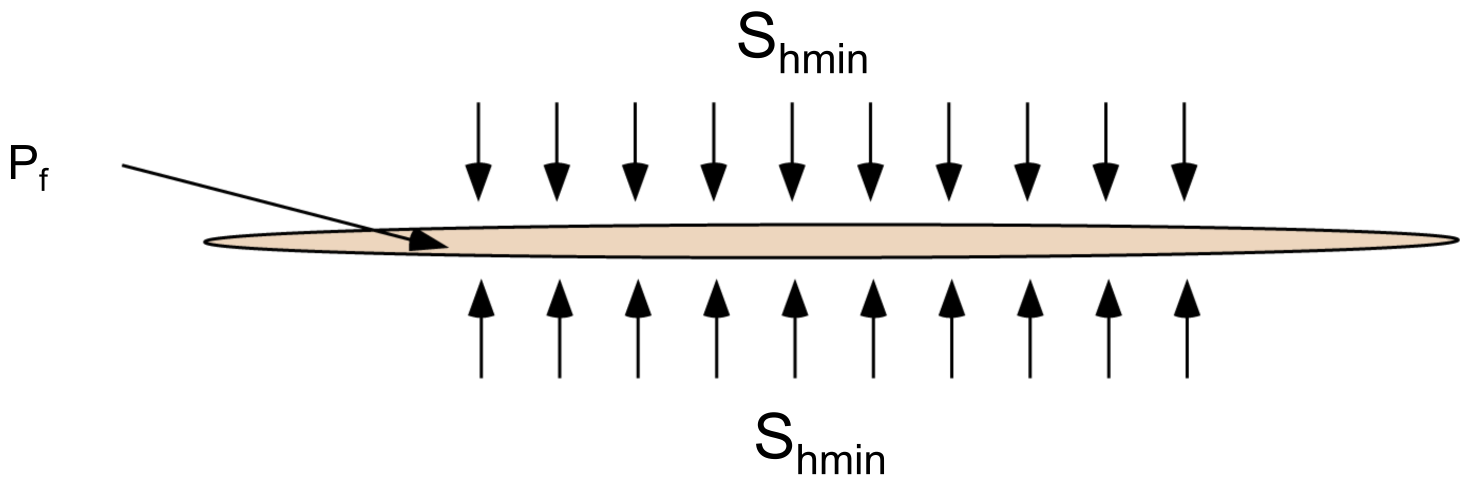
The next 10 years
~ 100,000 wells
~1-2 million hydraulic fractures

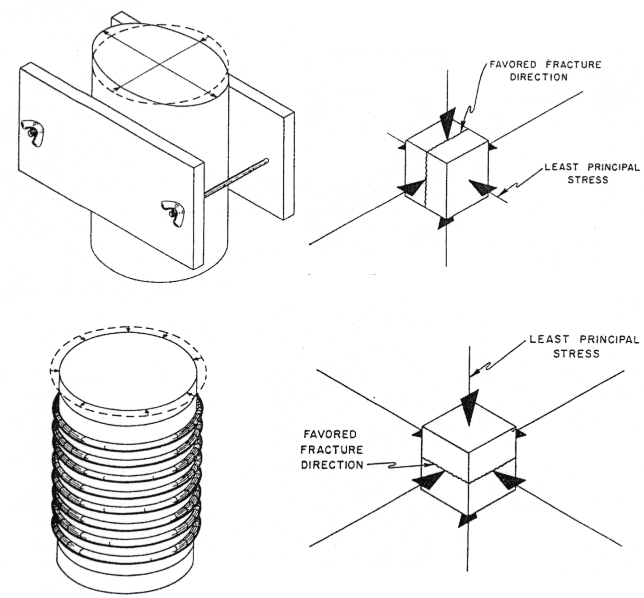
5 Wells – 50 Stages, ~ 100 Microearthquakes/Stage

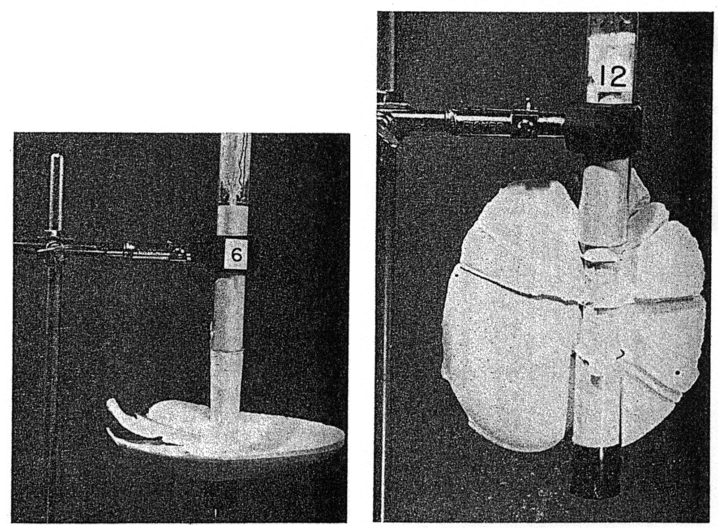


ConocoPhillips

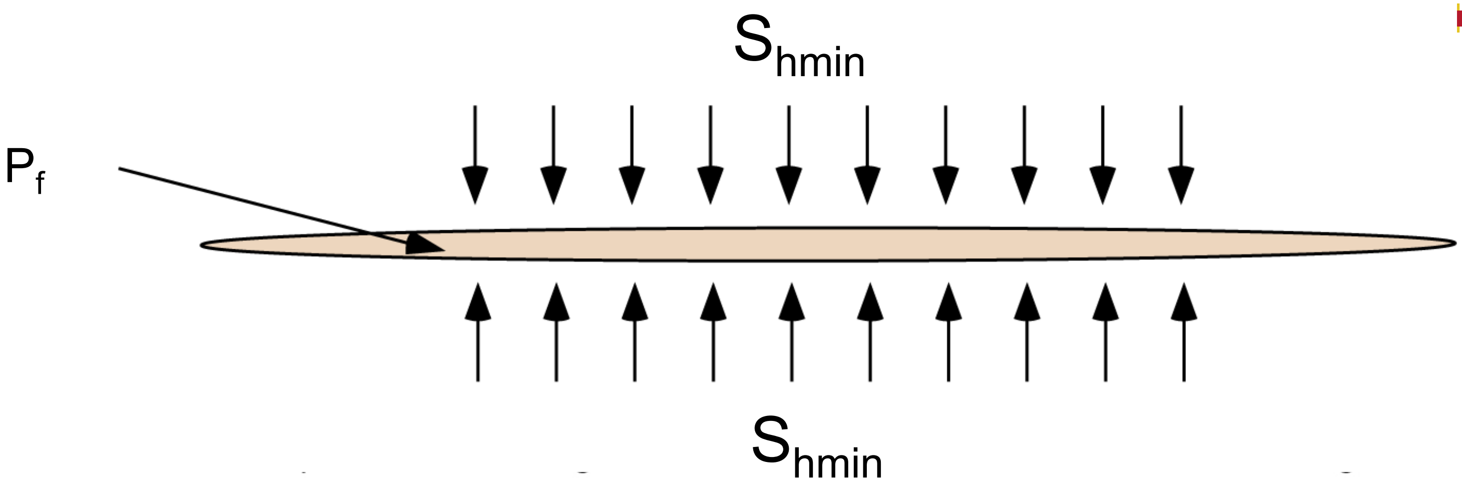
Propagation of a Hydraulic Fracture - 1

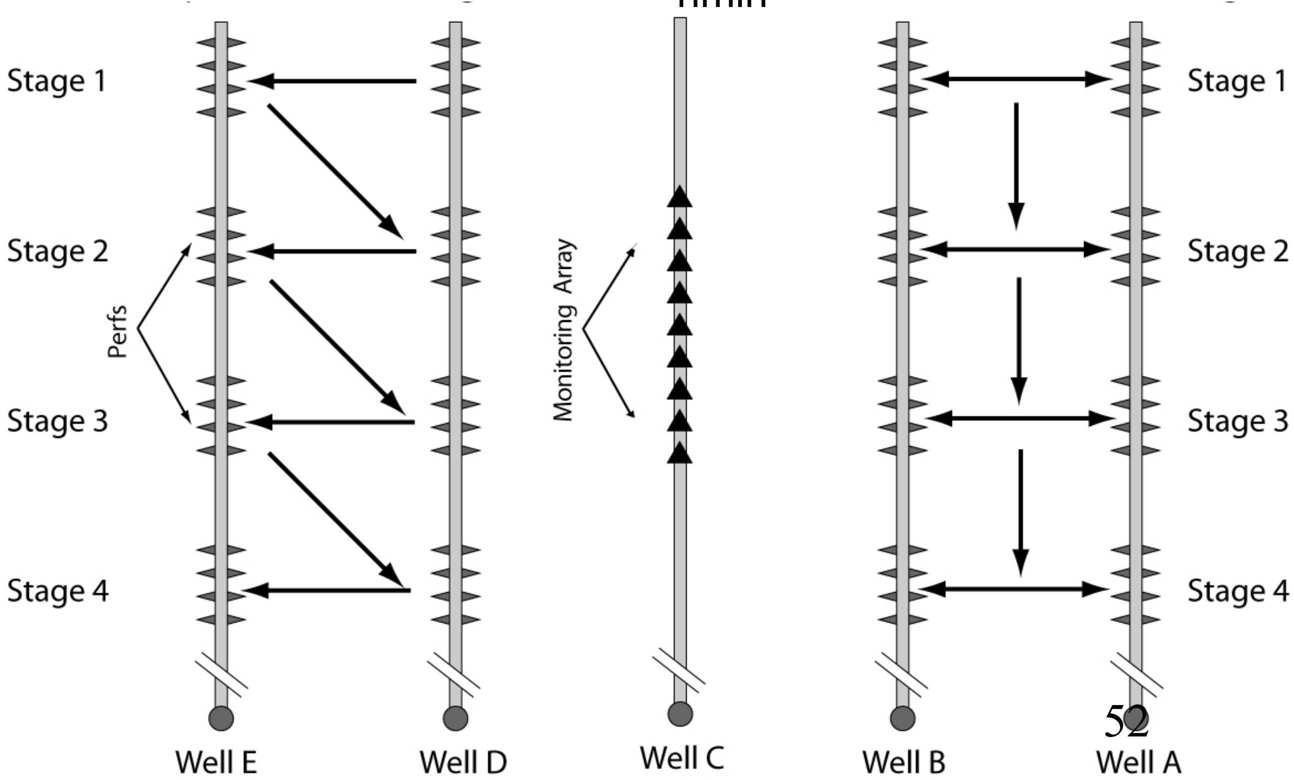




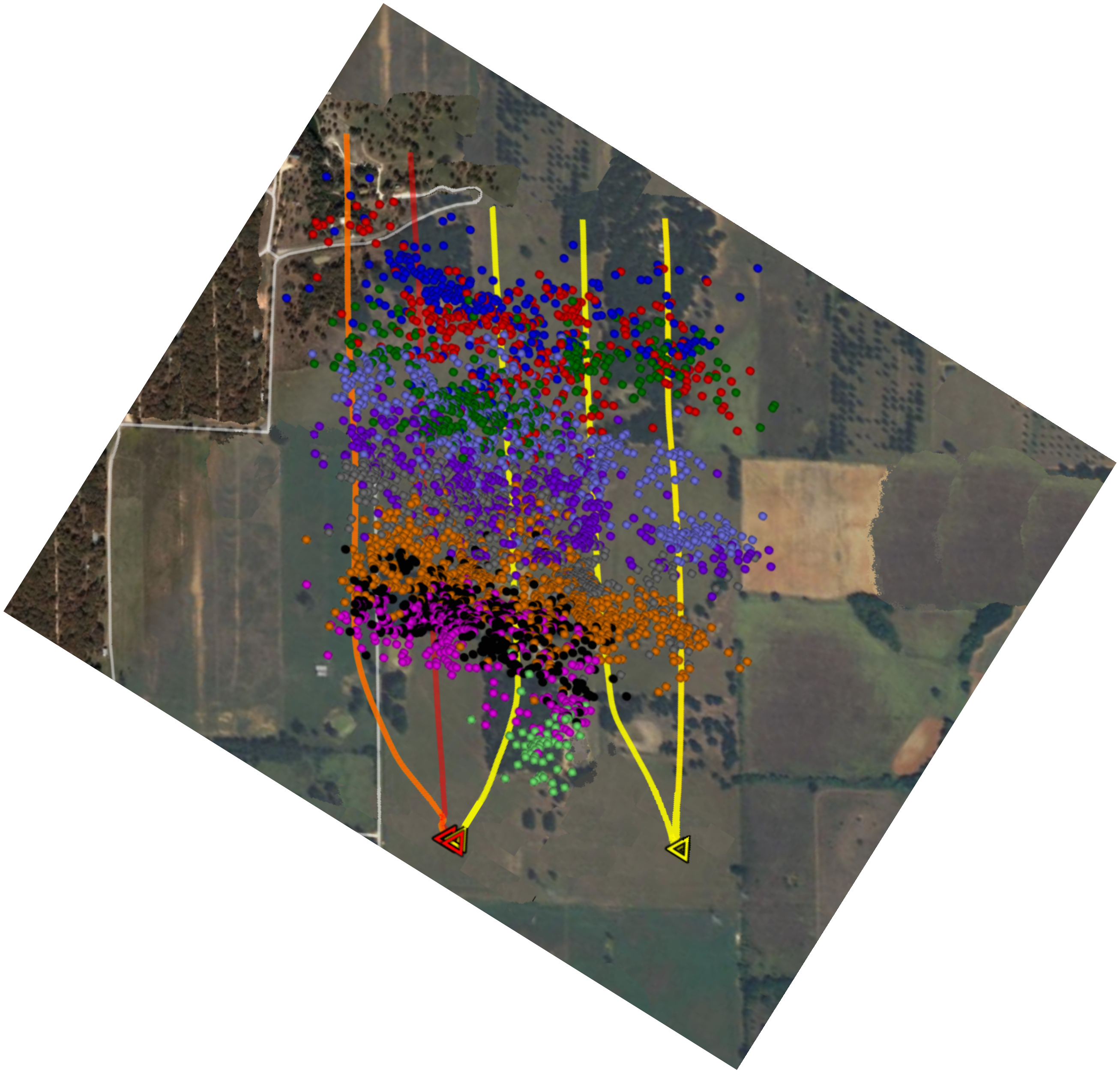


Wells Are Drilled Parallel to S_{hmin}

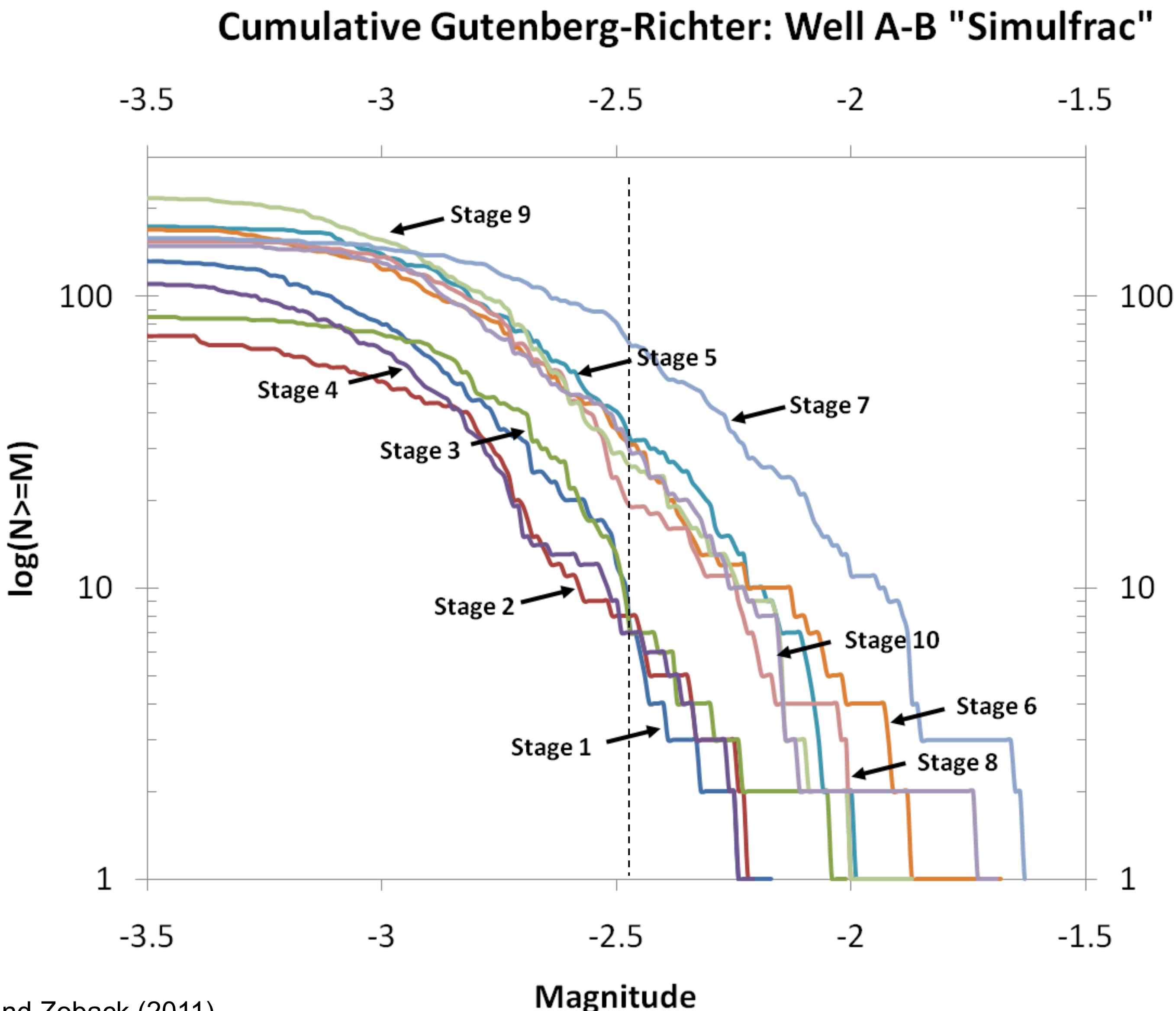




Microearthquakes Increase Permeability of Shale

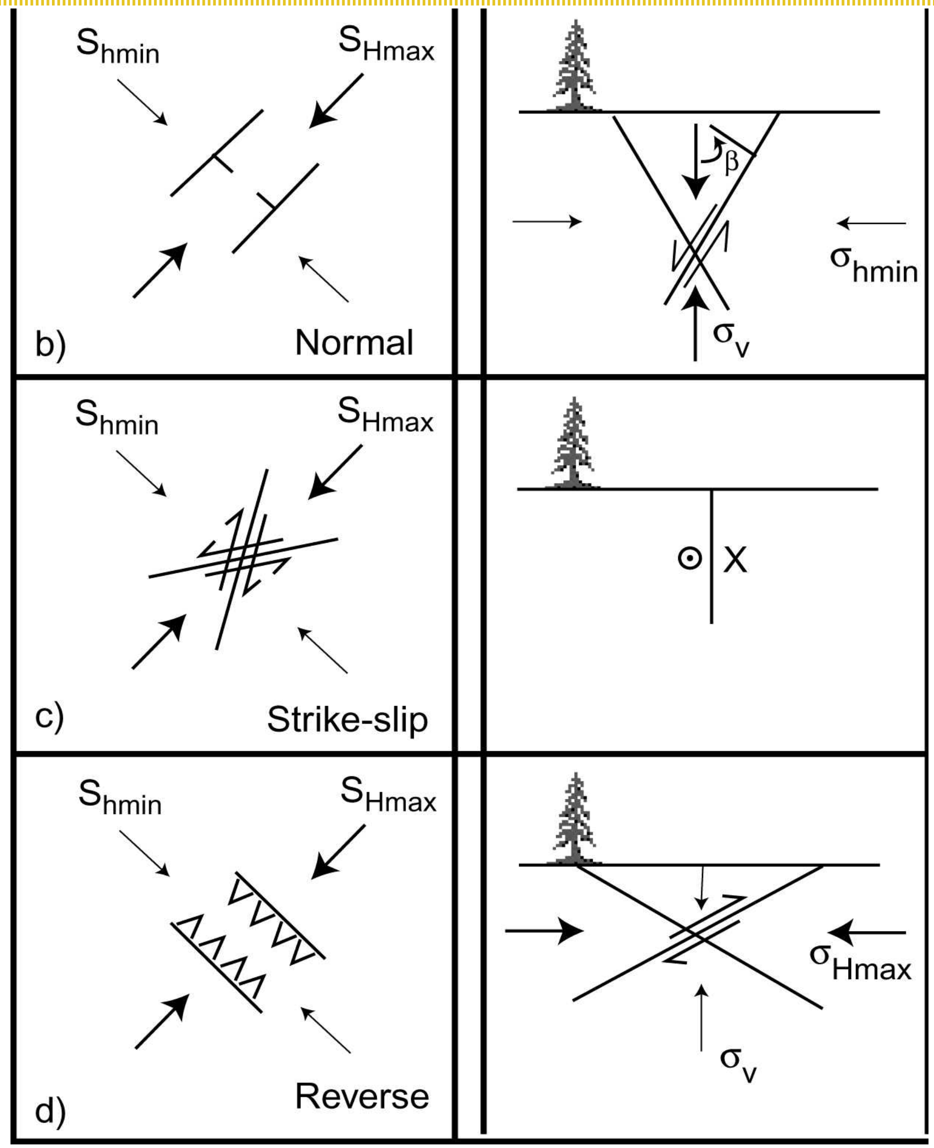


"Typical" Microearthquakes



Vermylen and Zoback (2011)

Relationship Between Stress State and Fault Slip



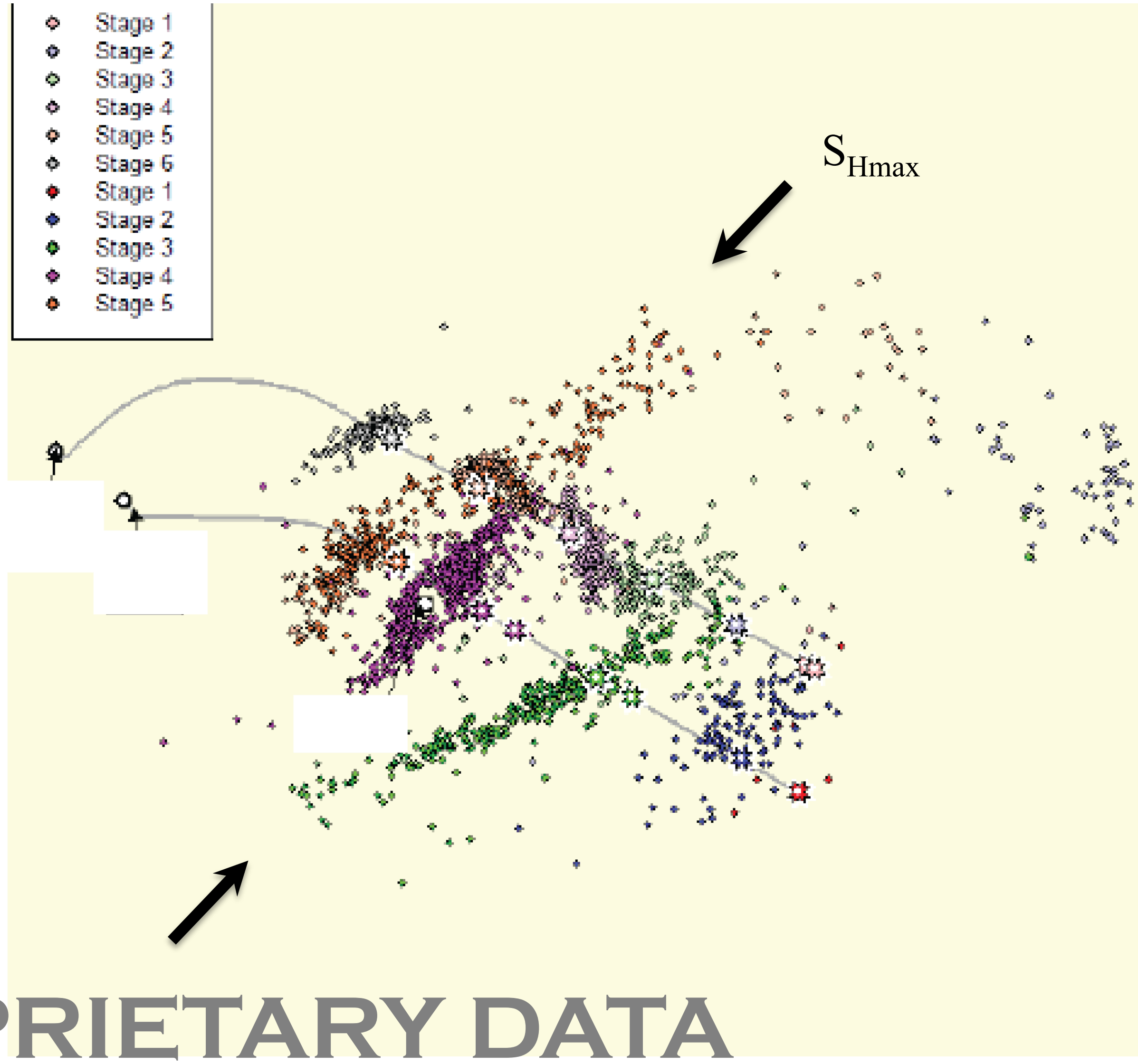
Map View | Cross-section

Normal: Normal faults trend parallel to S_{Hmax}

Strike-Slip: Strike-slip faults trend about ±30° from S_{Hmax}

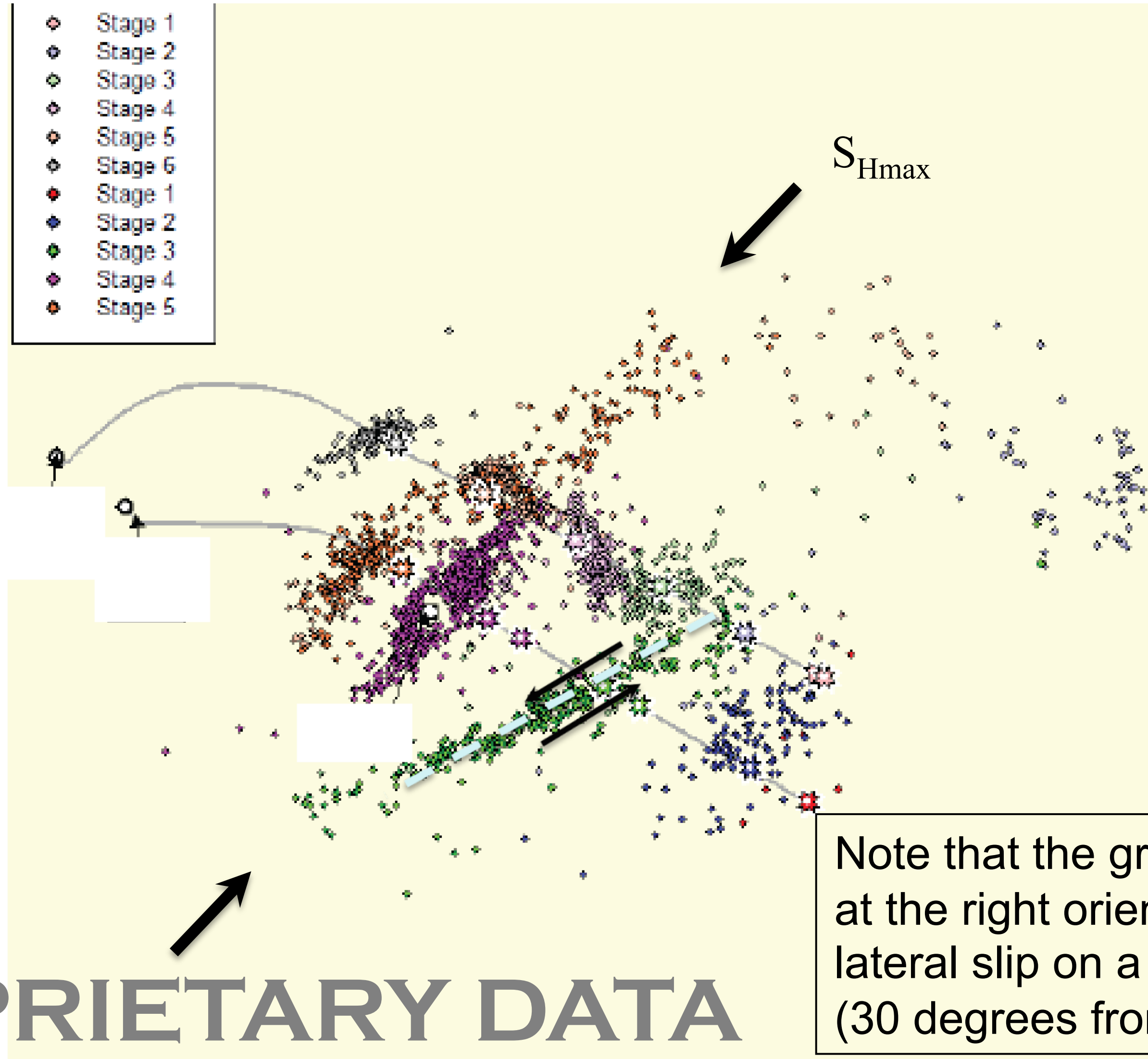
Reverse: Reverse faults trend perpendicular to S_{Hmax}

Unusual Lineations, Distant Evants, Larger Eqs.



PROPRIETARY DATA

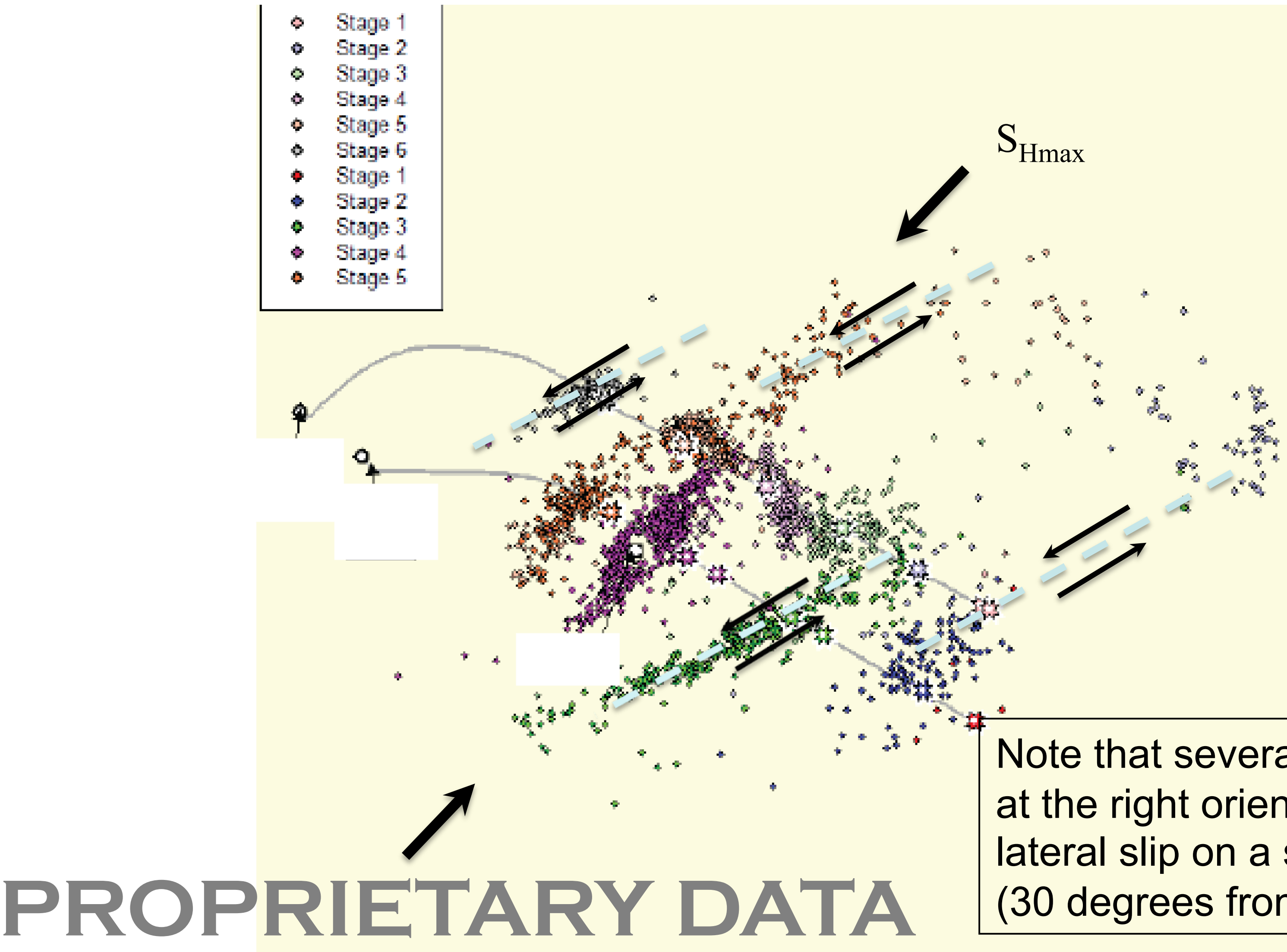
Left-Lateral Strike-Slip Movement



Note that the green lineation is at the right orientation for left-lateral slip on a strike-slip fault (30 degrees from S_{Hmax})

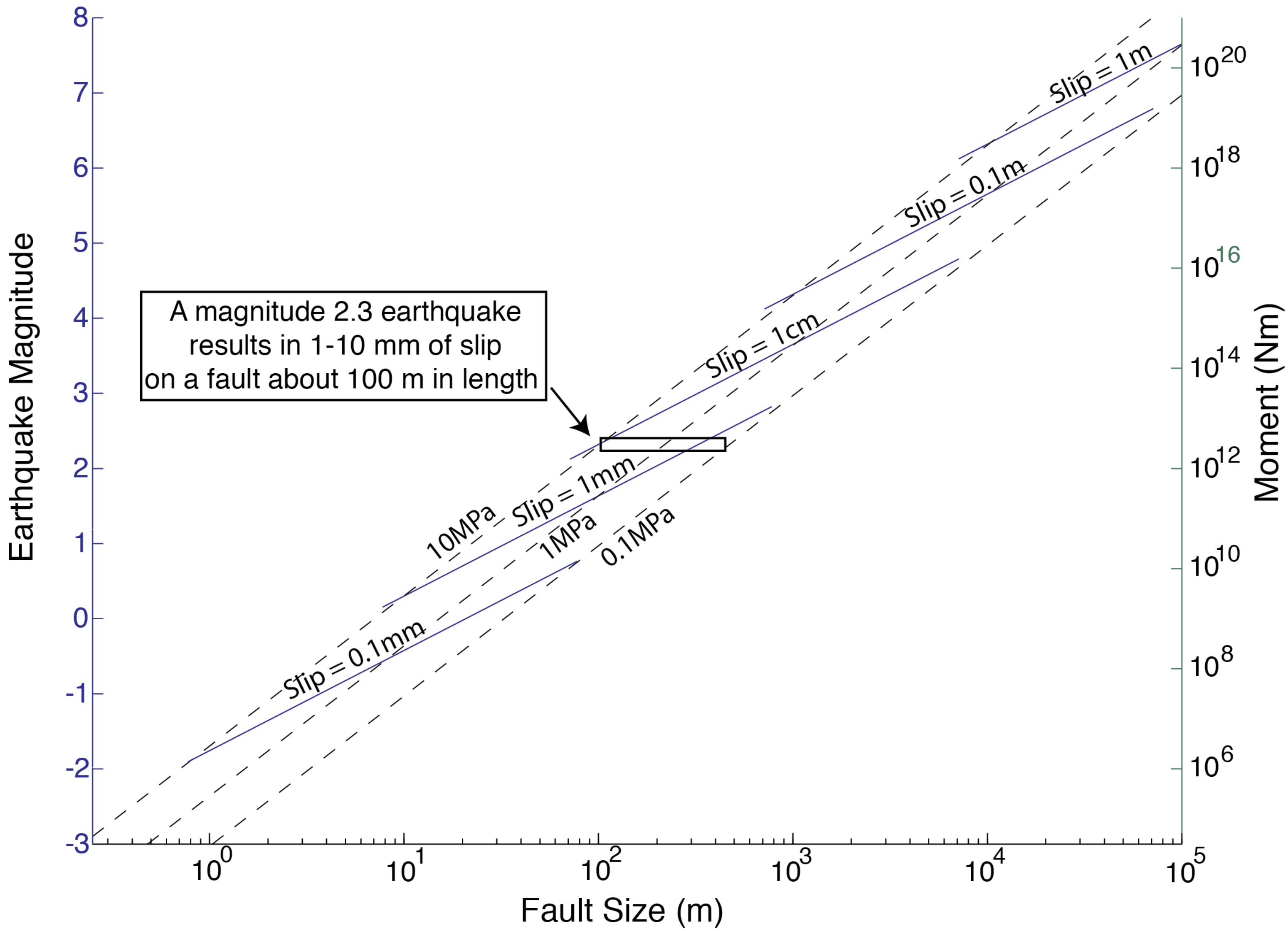
PROPRIETARY DATA

Left-Lateral Strike-Slip Movement



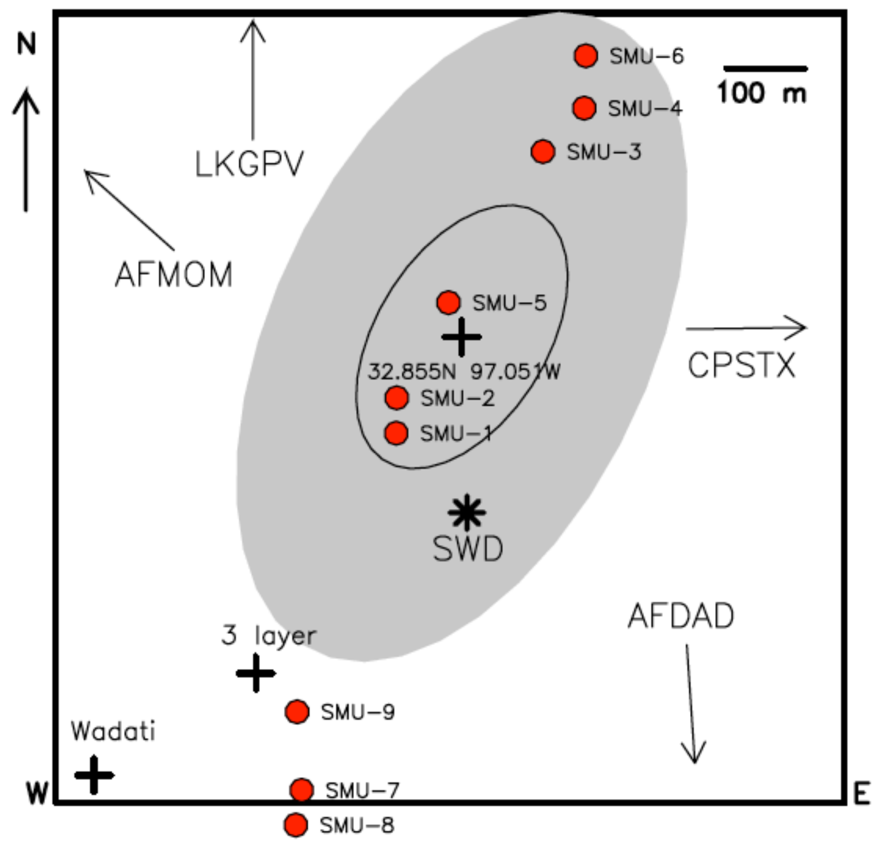
Note that several lineations are at the right orientation for left-lateral slip on a strike-slip fault (30 degrees from S_{Hmax})

The Great Blackpool, England Earthquake of 2011

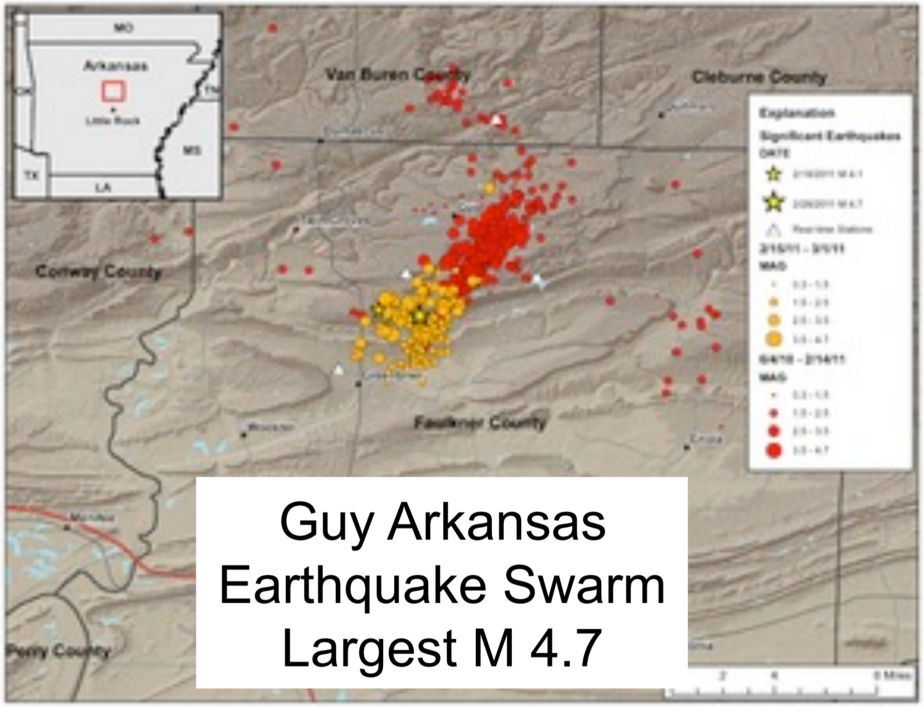


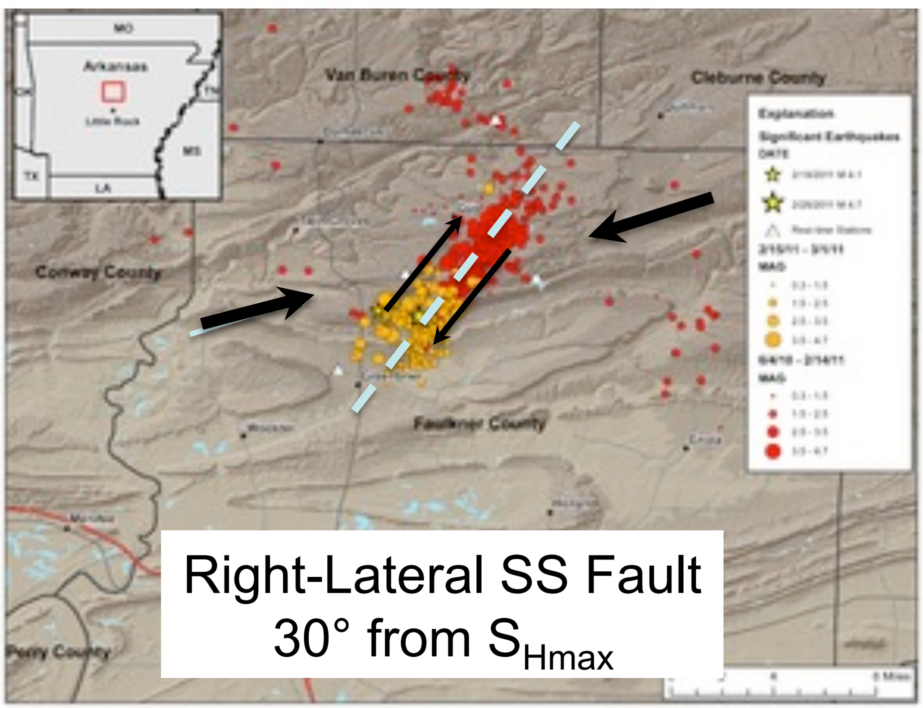
Earthquakes Triggered by Injection of Flow-Back Water After Hydraulic Fracturing

DFW – 2009 Magnitude 2.2-3.3

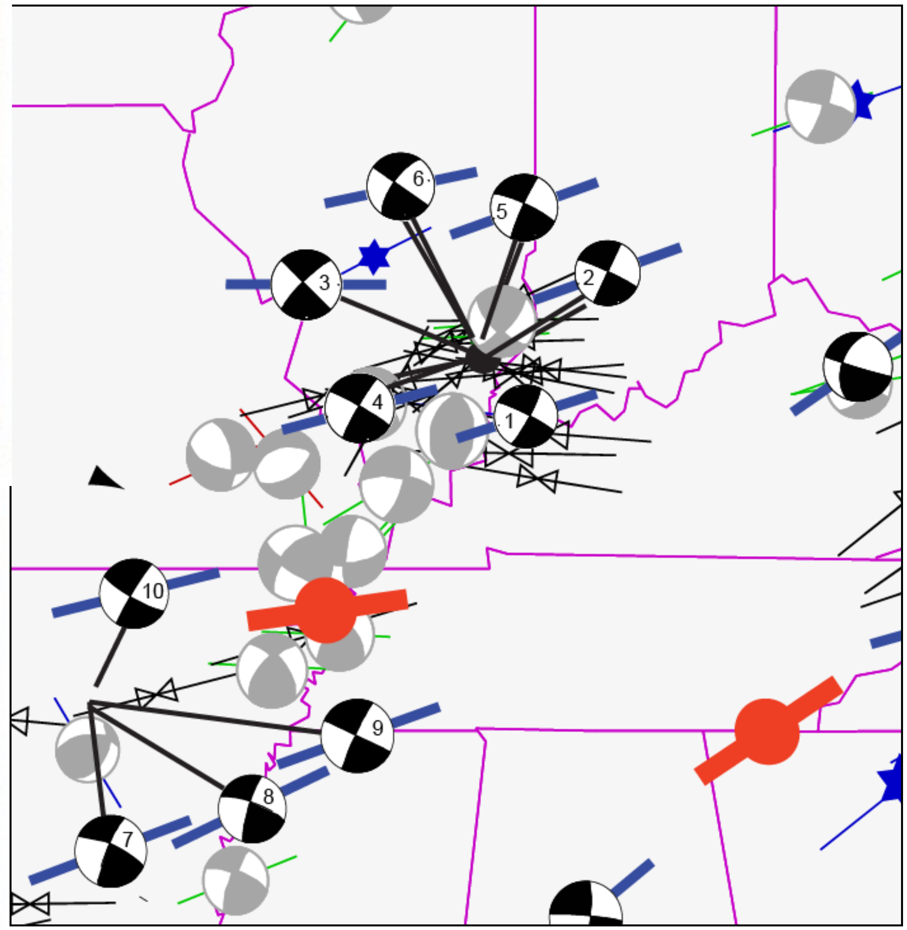


Frohlich et al. (2011)





Stress Map
New Madrid Area



Hurd and Zoback (Submitted)

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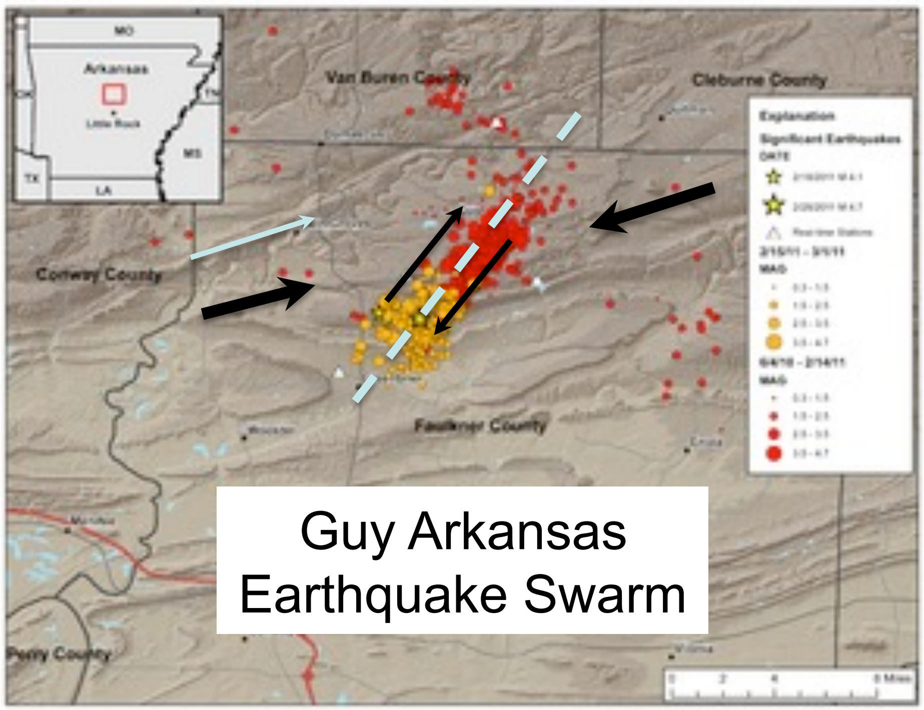
Managing the Risk Associated with Triggered Earthquakes Associated with Shale Gas Development*

1. Monitor Microseismicity
2. Avoid Faults, Limit Pressure Increases
3. Be Prepared to Abandon Some Injection Wells



Primary Need – A Risk Reduction Protocol for Response to Triggered Seismicity

Comprehensive Protocol for Risk Reduction

1. Framework understanding of stress state, pore pressure, pre-existing faults

2. Real-time seismic monitoring

3. Mechanistic understanding of triggered seismicity (triggering of well-oriented, critically-stressed faults or poorly-oriented faults that are slipping only because of the large pressure perturbation)

4. "If…then…" rules. For example, *if an earthquake of M 2 occurs on a well-oriented fault to the stress field, injection should immediately cease.*

Summary

1. Because of the enormous Scale of Carbon Capture and Storage and Shale Gas Development, Triggered Earthquakes Will be a Common Occurrence

2. Even small earthquakes at CO2 storage sites will cause major problems

3.Triggered Seismicity Associated with Shale Gas Development is a Manageable Problem

4.Managing Seismic Risk Associated Shale Gas Development Requires Good Data, Good Understanding and an Established Protocol for Risk Assessment and Response

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