The Potential for Triggered Seismicity Associated with CO_2 Sequestration and Shale Gas Development

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Outline of Presentation

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

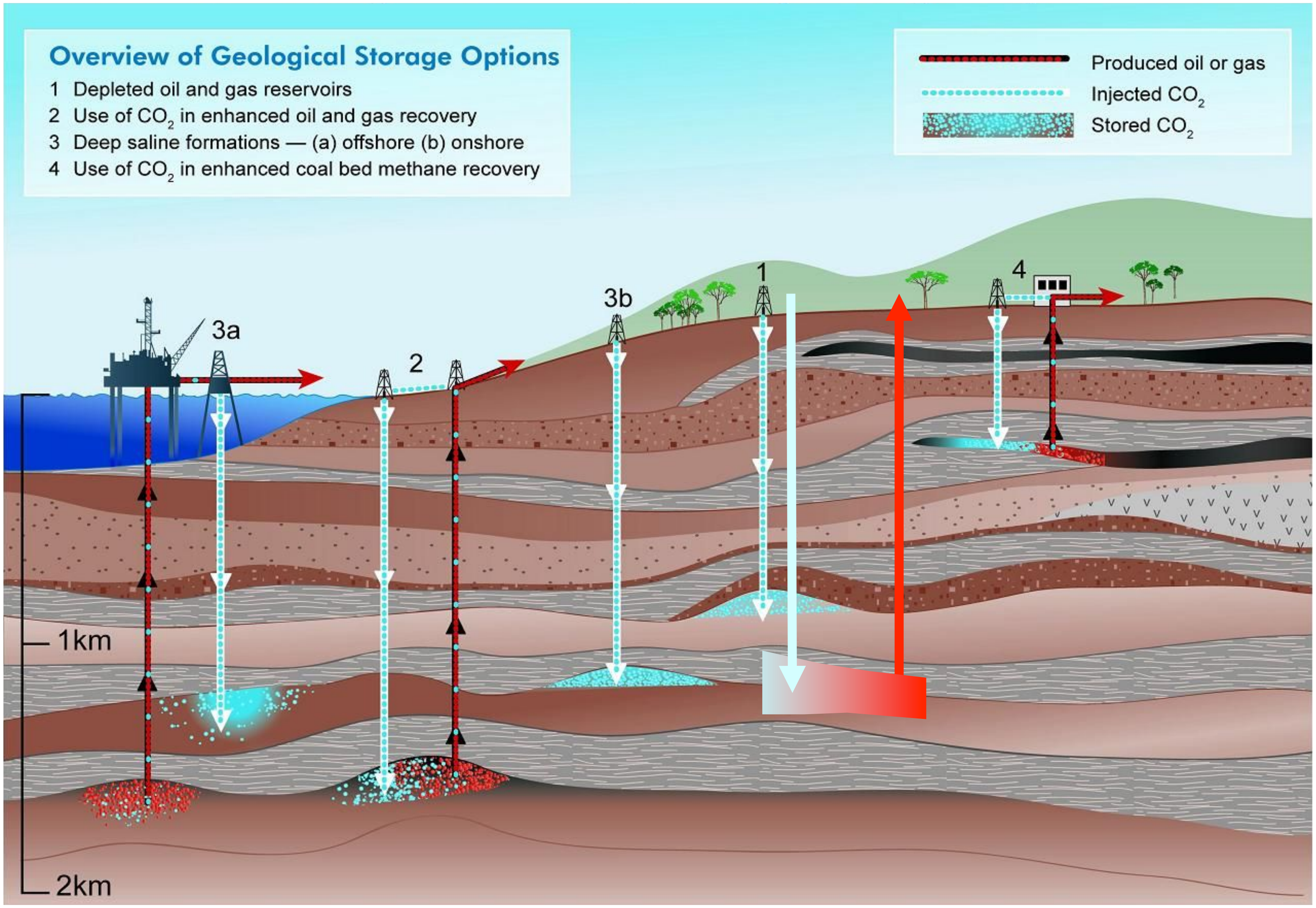
2. The Critically-Stressed Crust and Assessing Fault Stability

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

4. Shale Gas and Triggered Seismicity (Case Studies)

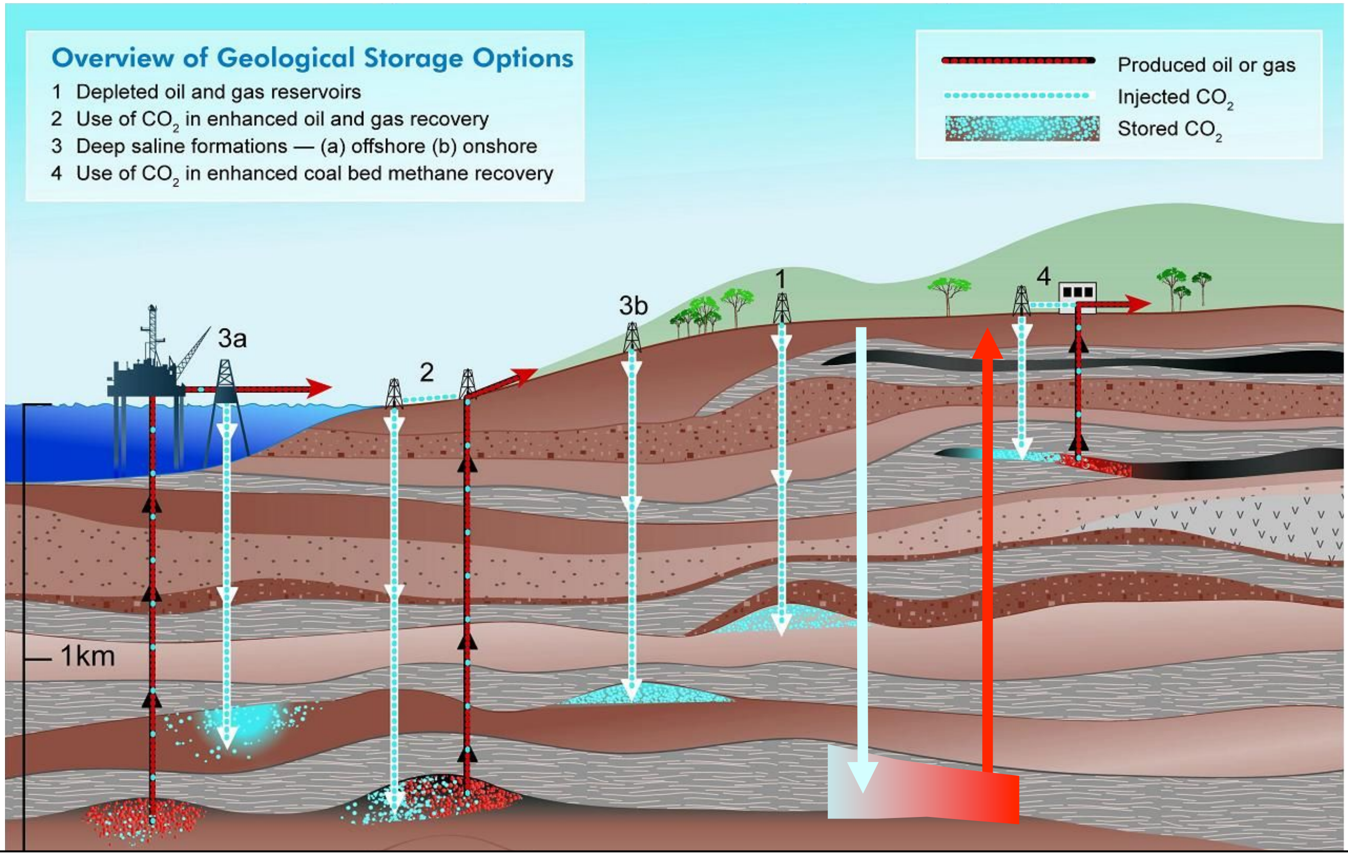
5. Assessing and Managing Seismic Risk Associated with CCS and Shale Gas Development

Strategies for Geologic Sequestration of CO_2



IPCC (2005)

Most Common Concern About CO_2 Sequestration

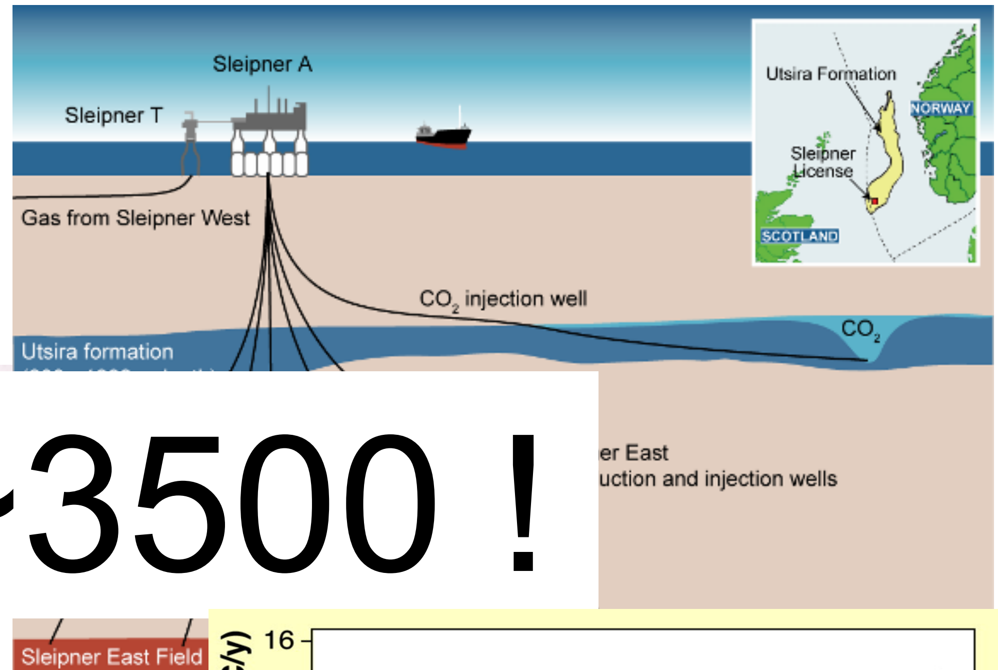


HUGE SCALE – Comparable to volumes oil and gas produced annually

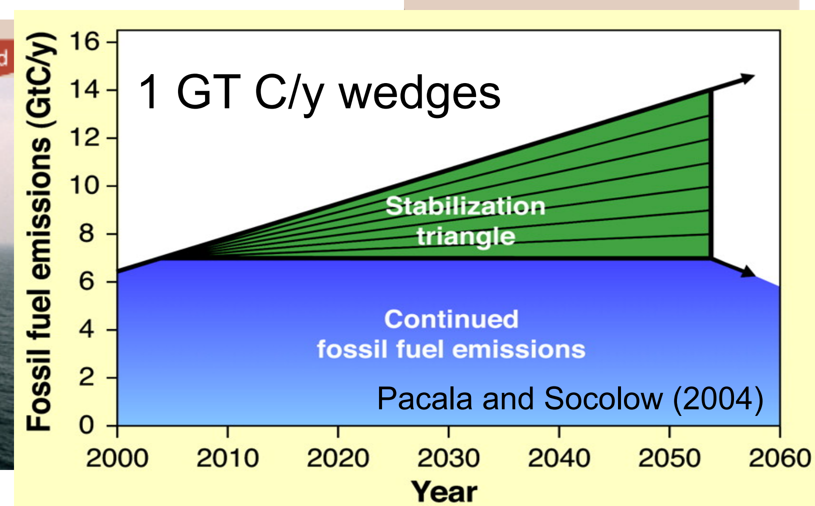
HUGE COSTS – Carbon capture, pipelines, injection wells, monitoring systems

Sleipner Field

- 1996 to present
- 1 Mt CO_2 injection/yr
- Seismic monitoring



X ~3500 !



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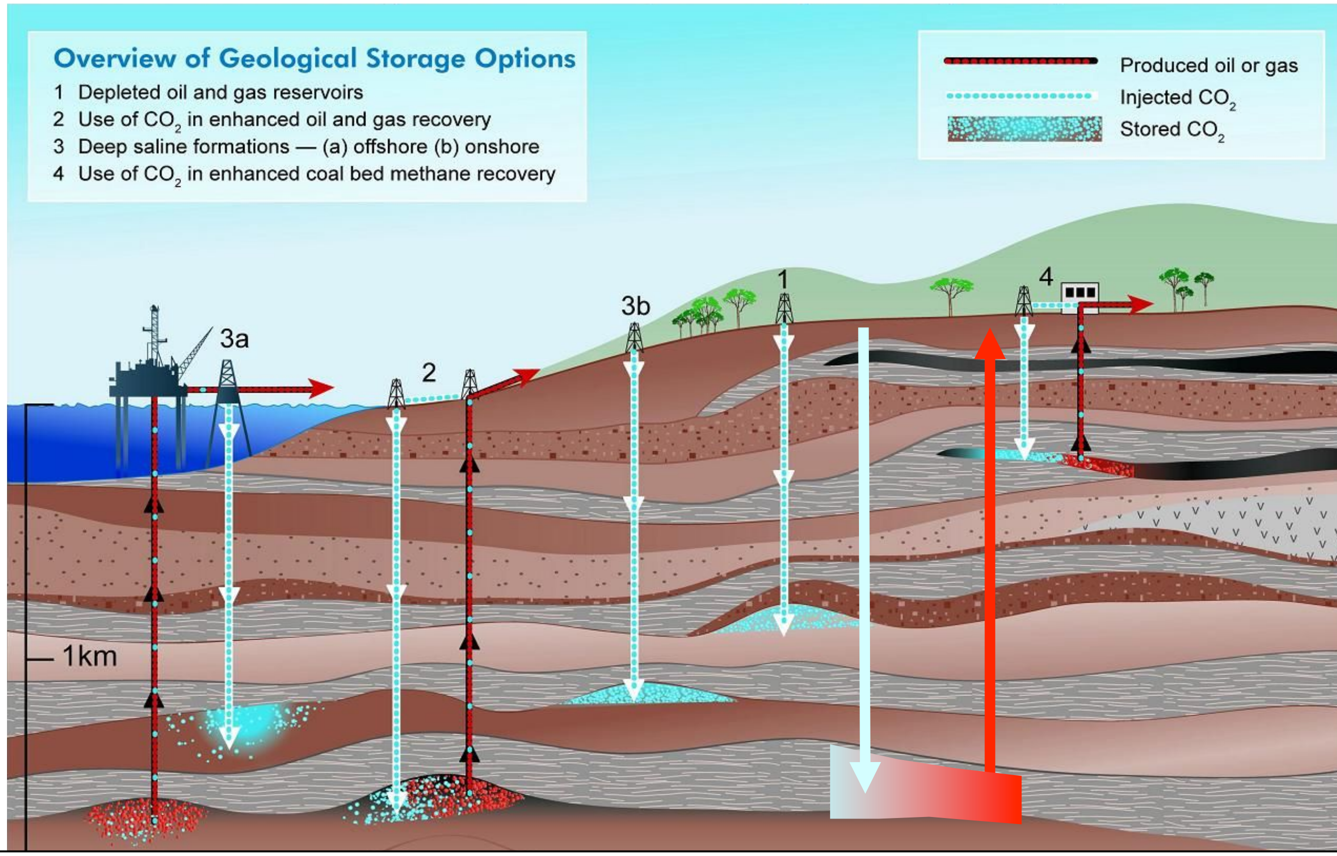

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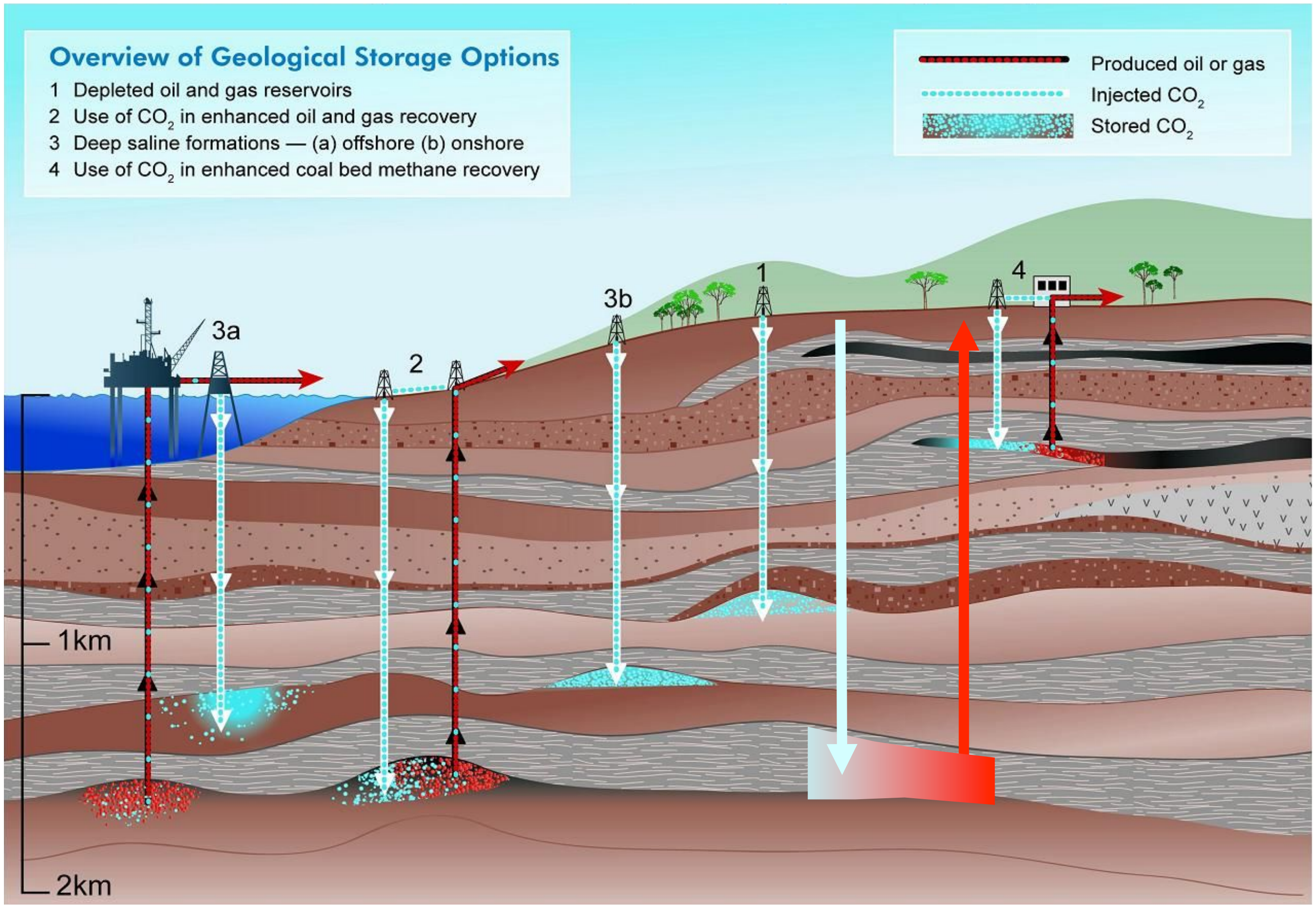
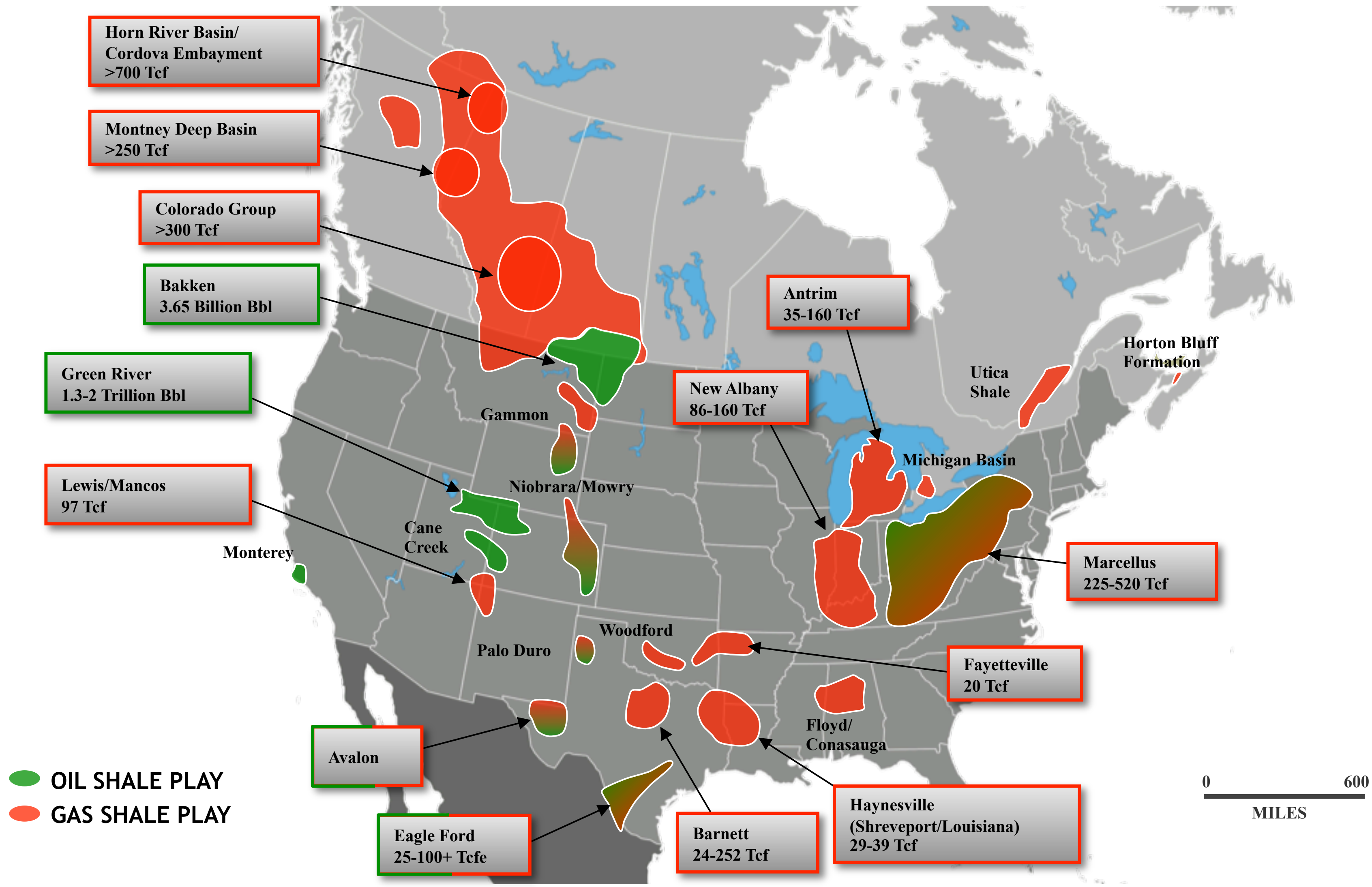
Saline Aquifers in Well-Cemented Sedimentary Formations



LIMITED INJECTIVITY – Many saline aquifers will not have sufficient permeability to permit injection at high rates for long periods of time without significant pressure build up

NORTH AMERICAN SHALE PLAYS



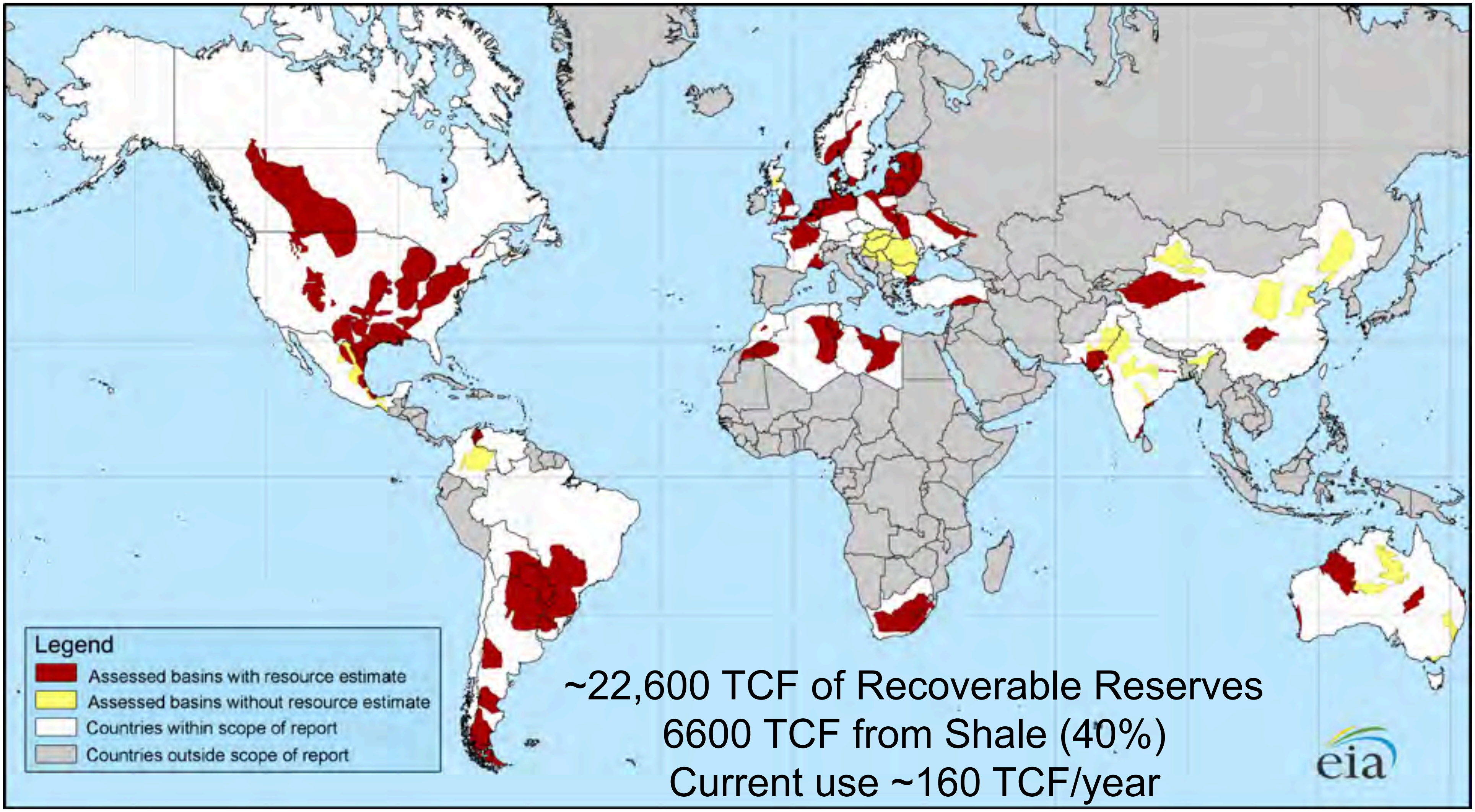
North American Gas Supplies

	2009 Natural Gas Market[1] (trillion cubic feet, dry basis)			Proved Natural Gas Reserves[2] (trillion cubic feet)	Technically Recoverable Shale Gas Resources (trillion cubic feet)
	Production	Consump-tion	Imports (Exports)		
North America					
United States[4]	20.6	22.8	10%	272.5	862
Canada	5.63	3.01	(87%)	62.0	388
Mexico	1.77	2.15	18%	12.0	681

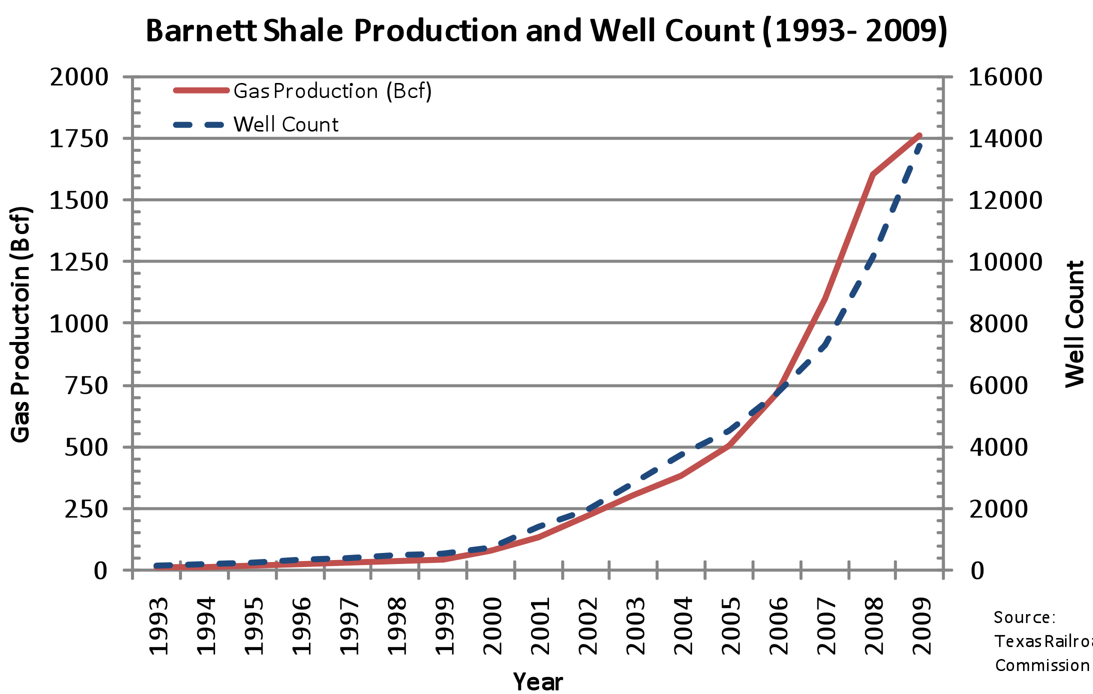
North American Total Resource
~2300 TCF (85% Shale Gas)
"100 years of Natural Gas"
U.S. Consumption 23 TCF/y

EIA, April 2011

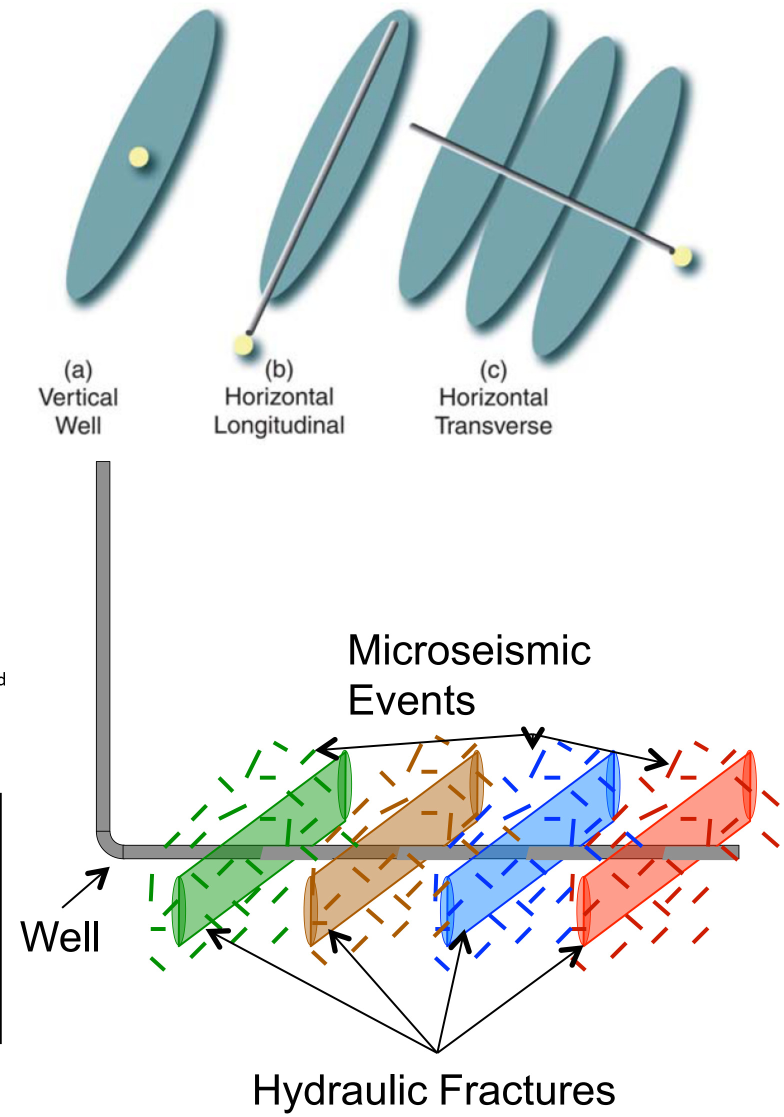
Global Shale Gas Resources



Drilling/Completion Technology Key To Barnett Success

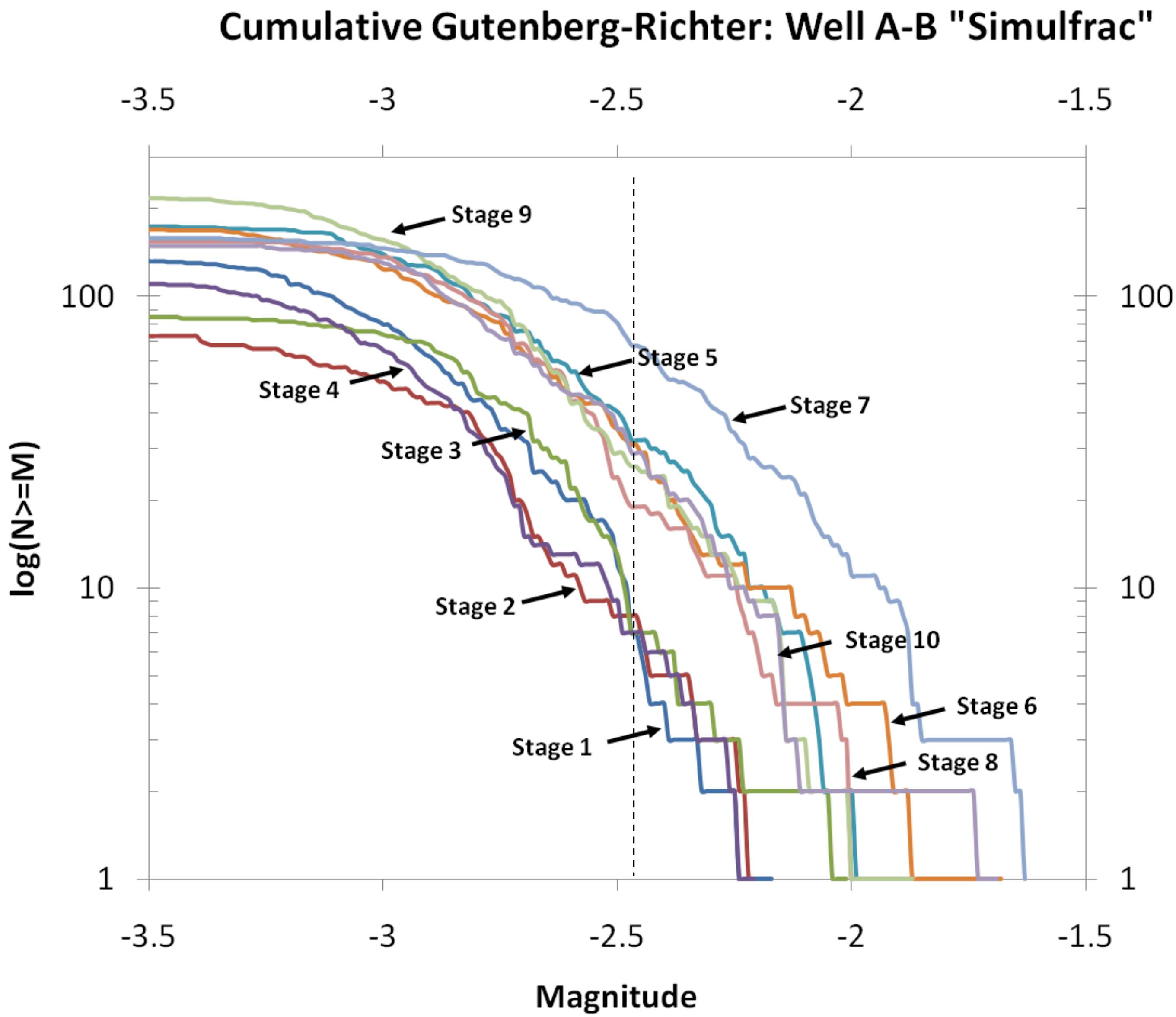


Source: Texas Railroad Commission

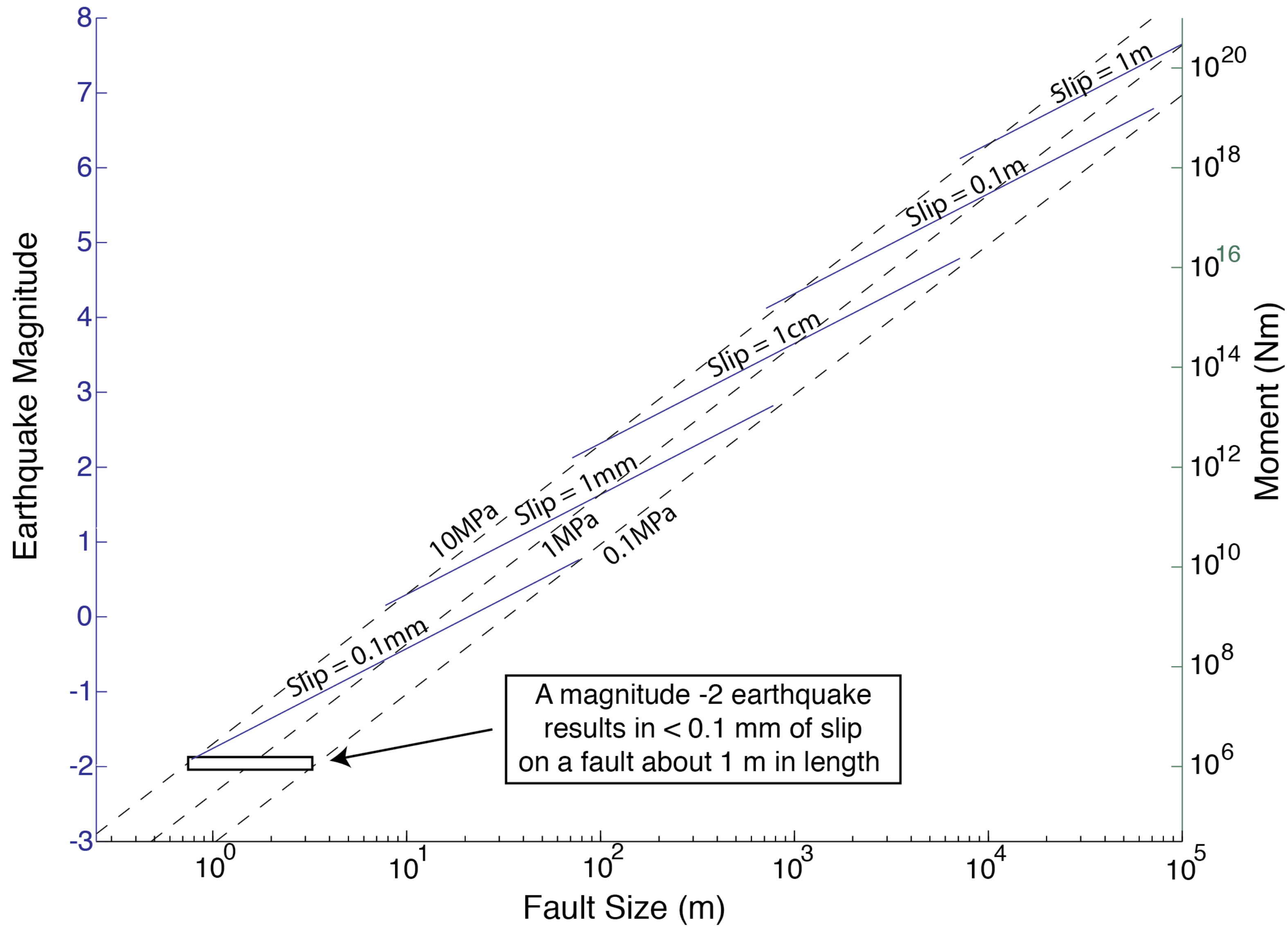


Horizontal Drilling and Multi-Stage
Slick-Water Hydraulic Fracturing
Induces Microearthquakes (M ~ -1 to M~ -3)
To Create a Permeable Fracture Network

Microearthquakes in Barnett Shale



What is a Magnitude -2 Earthquake?



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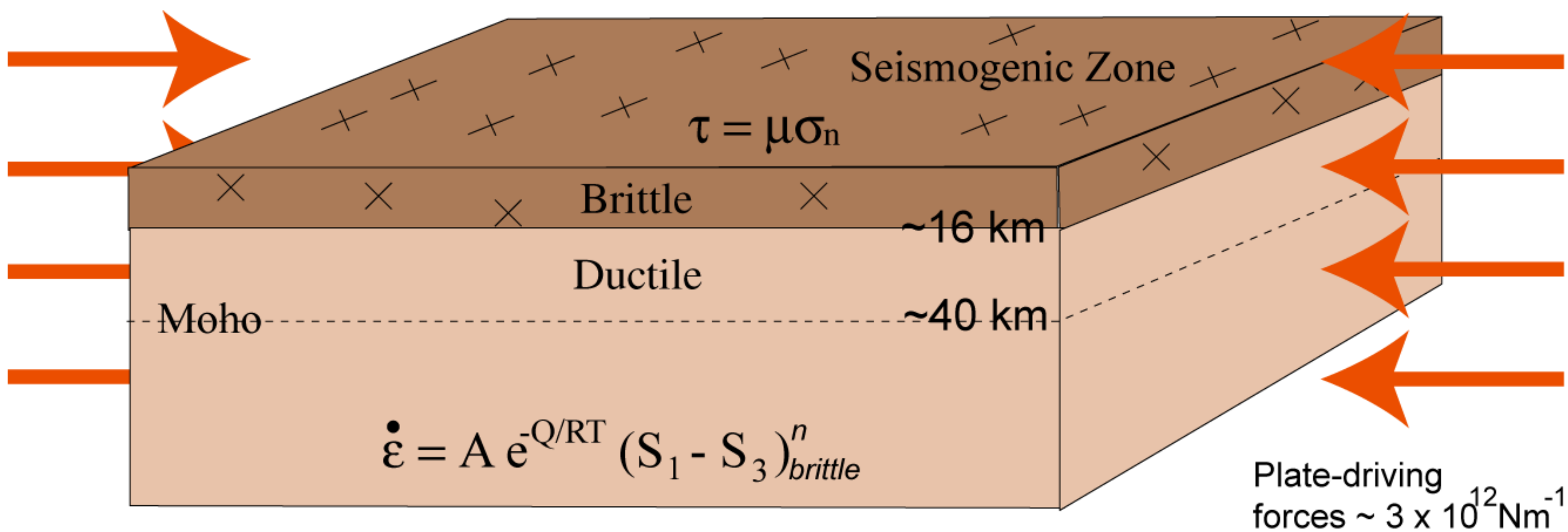
The Context of Concern: In Most Places, The Brittle Crust is in Frictional Failure Equilibrium

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



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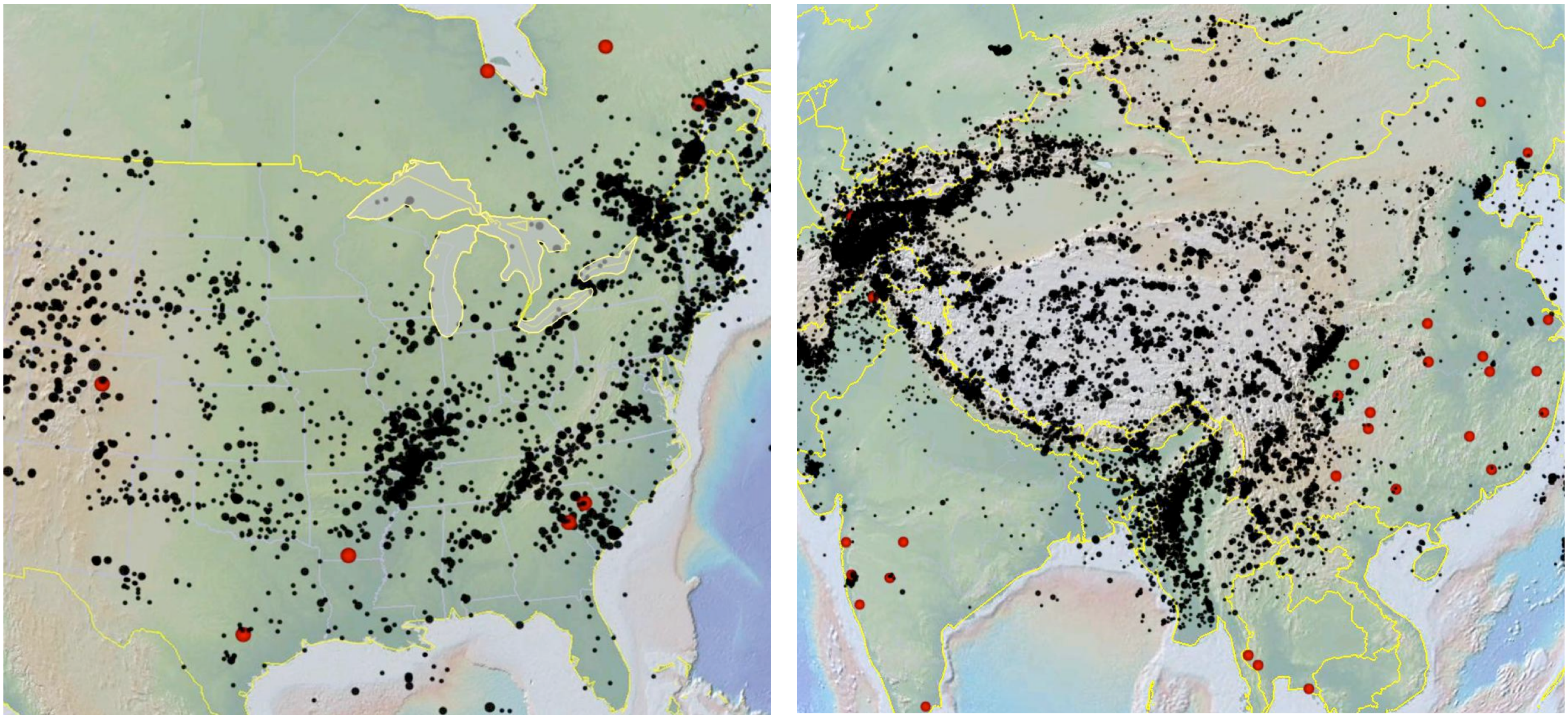
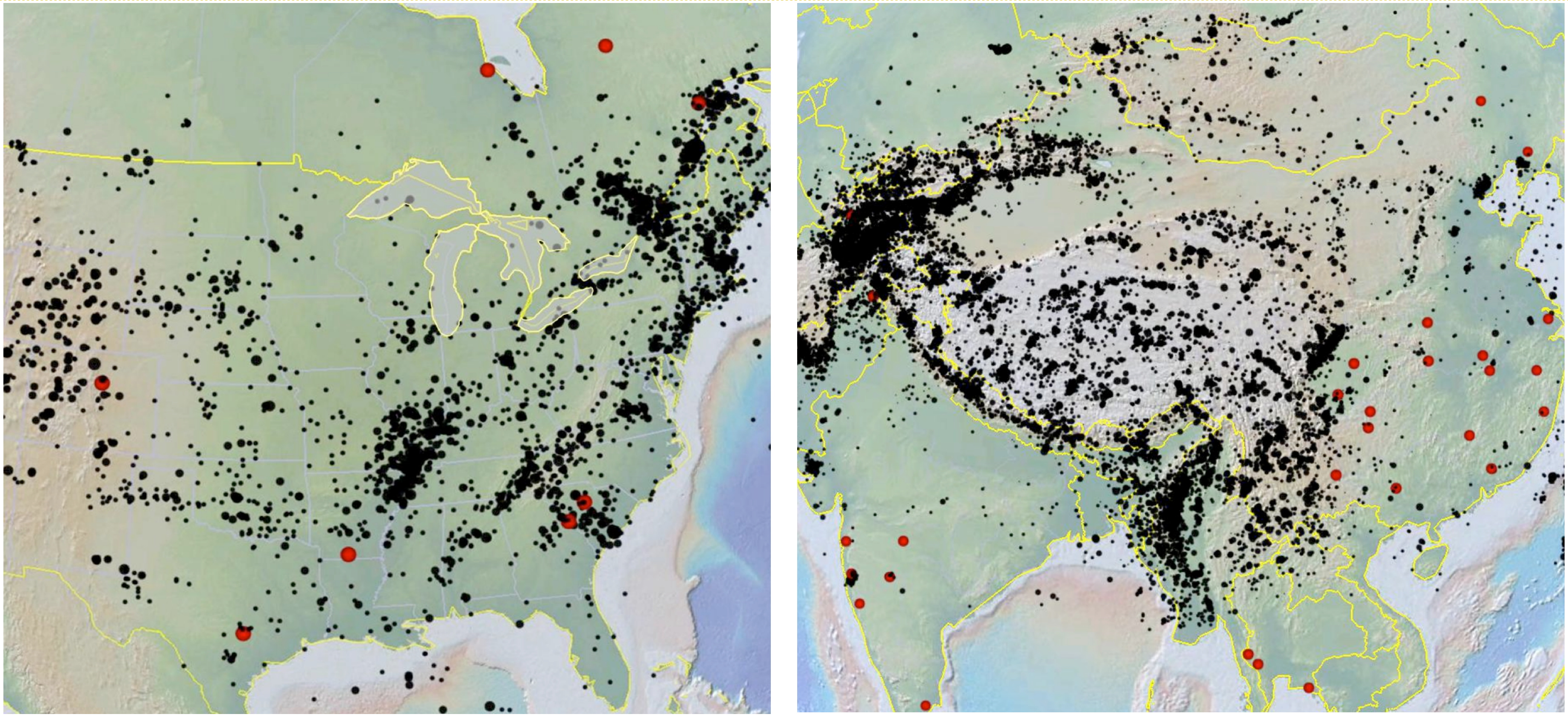


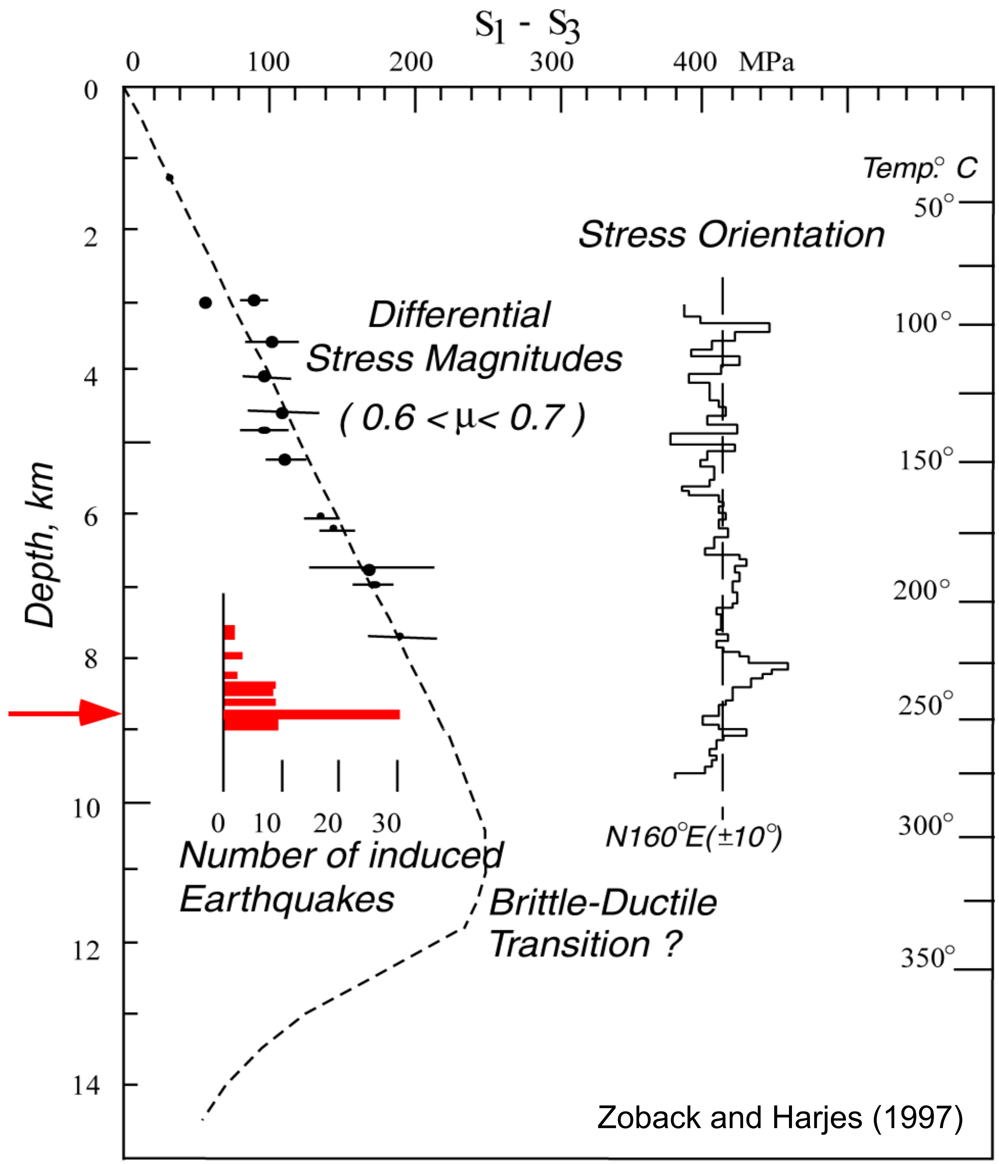
1. Intraplate Earthquakes Occur Nearly Everywhere

Reservoir “Induced” Seismicity

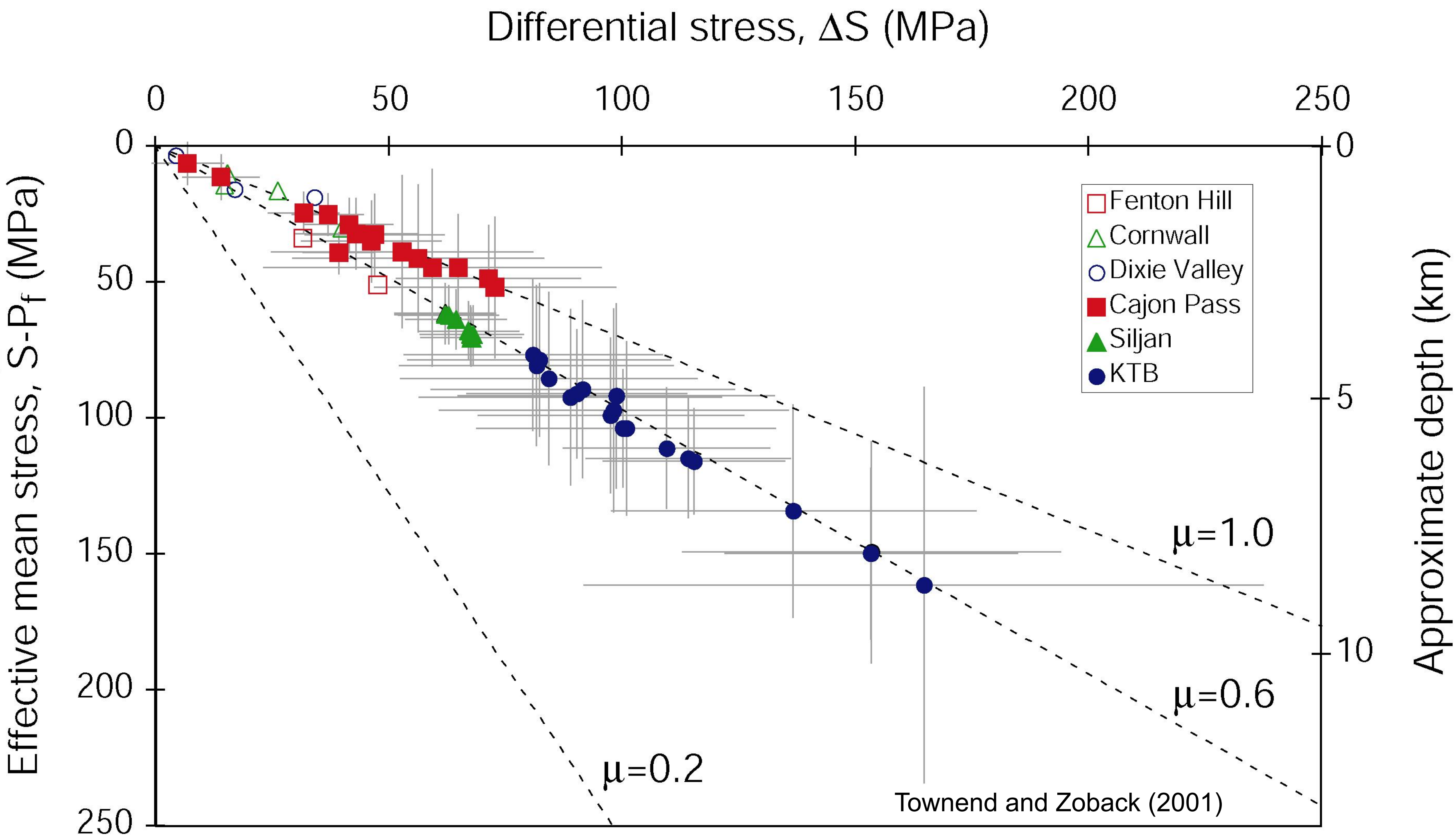


2. Seismicity is Often Triggered by the Extremely Small Pressure Perturbation Associated with Reservoir Impoundment

3. Deep Borehole Stress Measurements

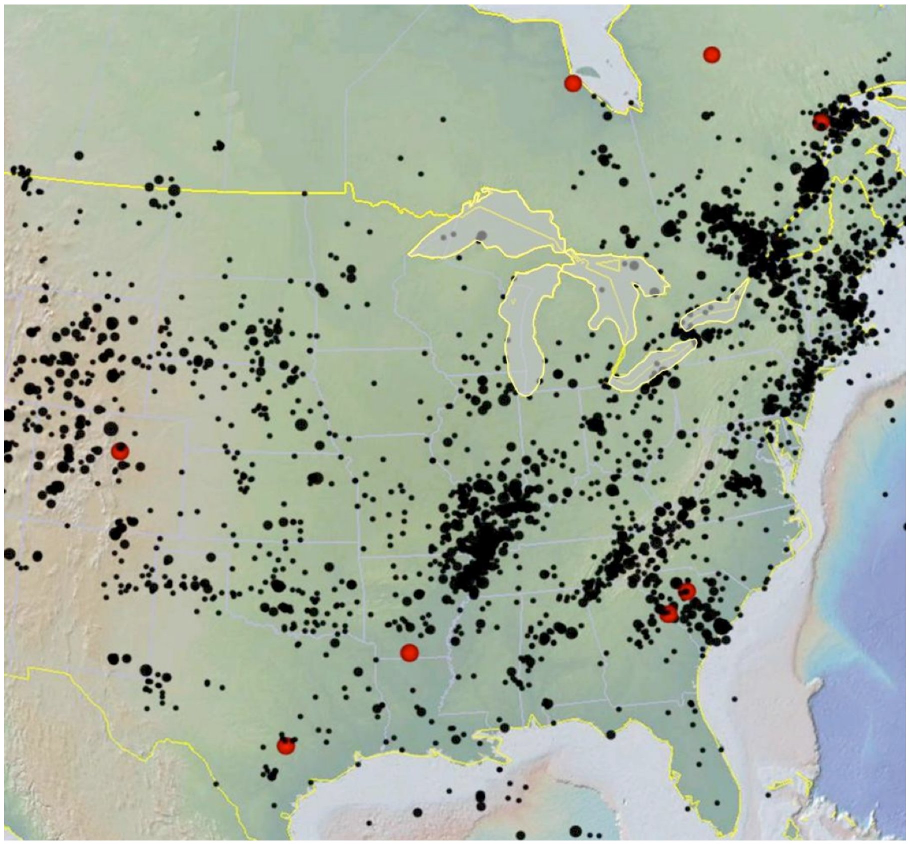


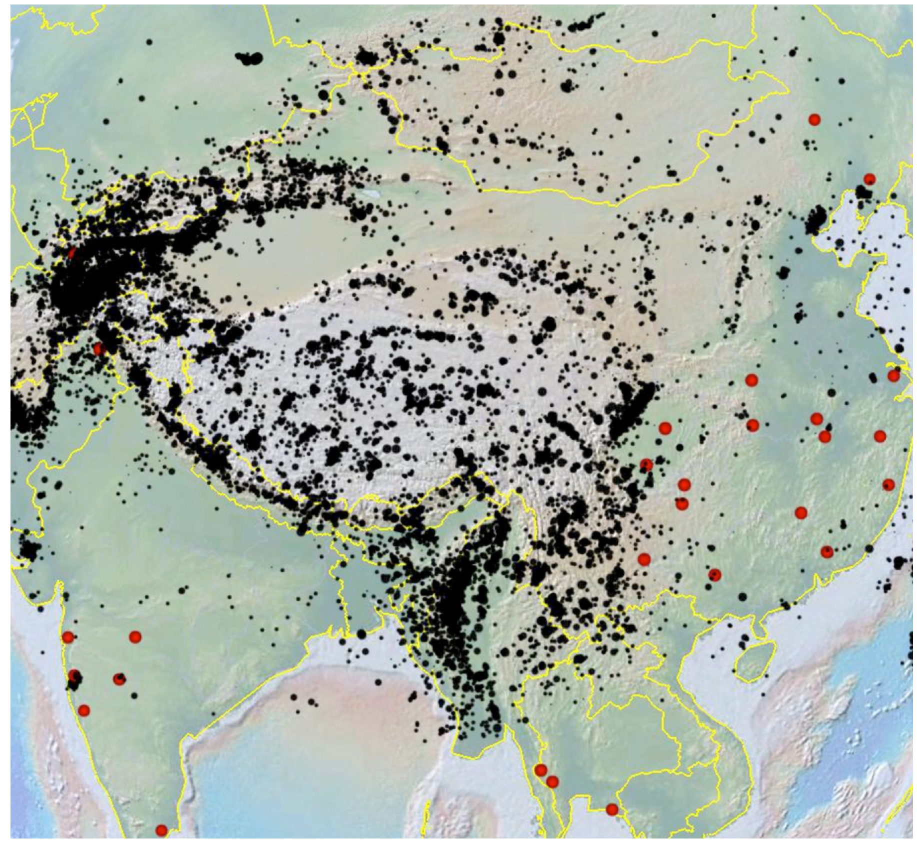
Highly Stress in Intraplate Areas
Hydrostatic Pore Pressure



How Faulting Keeps the Crust Strong

Are Stress Magnitudes Lower in Stable Areas?

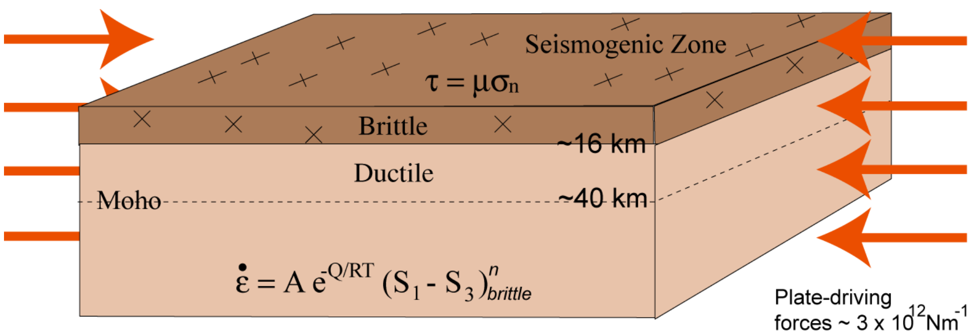




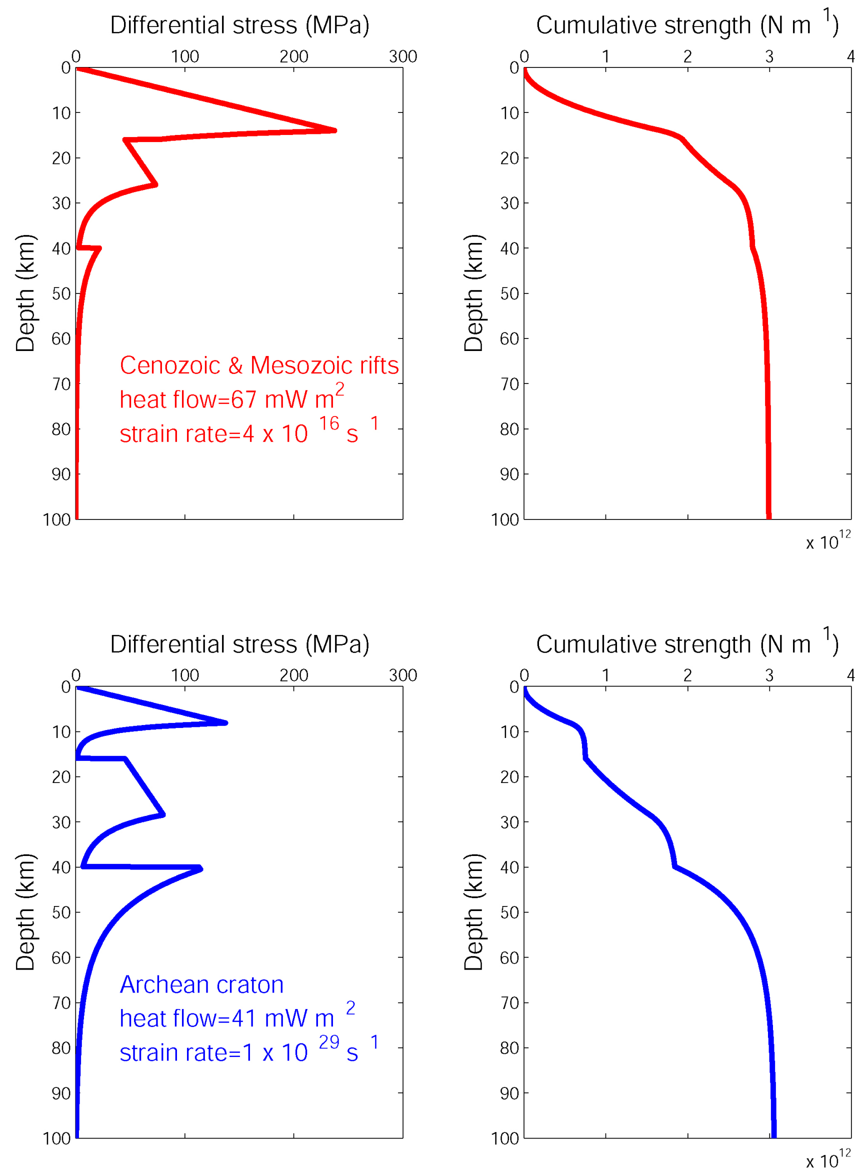
Reservoir Triggered Seismicity – No!

“Stable” Intraplate Regions are Critically-Stressed, But Deform Slowly

Brittle Failure in Critically-Stressed Crust Caused By Creep in Lower Crust and Upper Mantle



Zoback, Townend and Grollimund (2002)



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CO_2 Sequestration Research Projects

Powder River Basin

- •CBM Production
- •ECBM/Environment/Sequestration
- •Collab. with Western Res. Foundation

Mountaineer, West Virginia

- •Deep aquifer injection
- •Point source - Coal Burning power plant
- •Collaboration with DOE, NETL, Battelle, AEP, BP, Schlumberger, Ohio Coal Development Office

Michigan Basin

- •Deep aquifer injection
- •Permeabilitiy enhancement

Teapot Dome

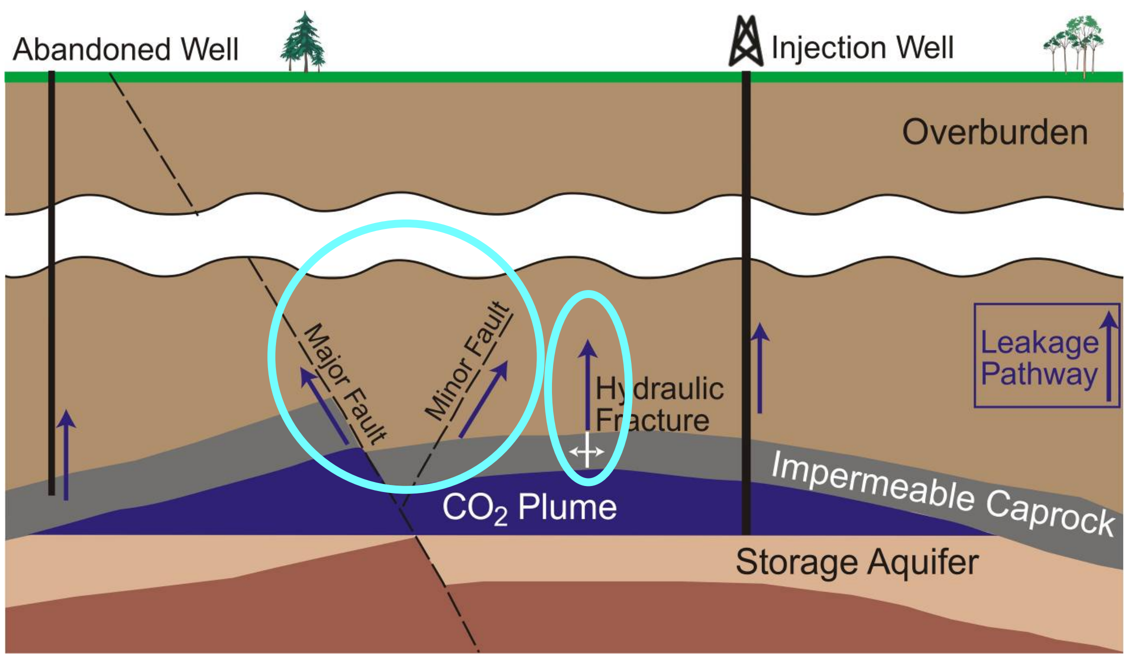
- •Depleted Oil and Gas Reservoir
- •Sequestration seal capacity
- •Collaboration with LLNL, DOE. RMOTSI

GCEP Stanford University

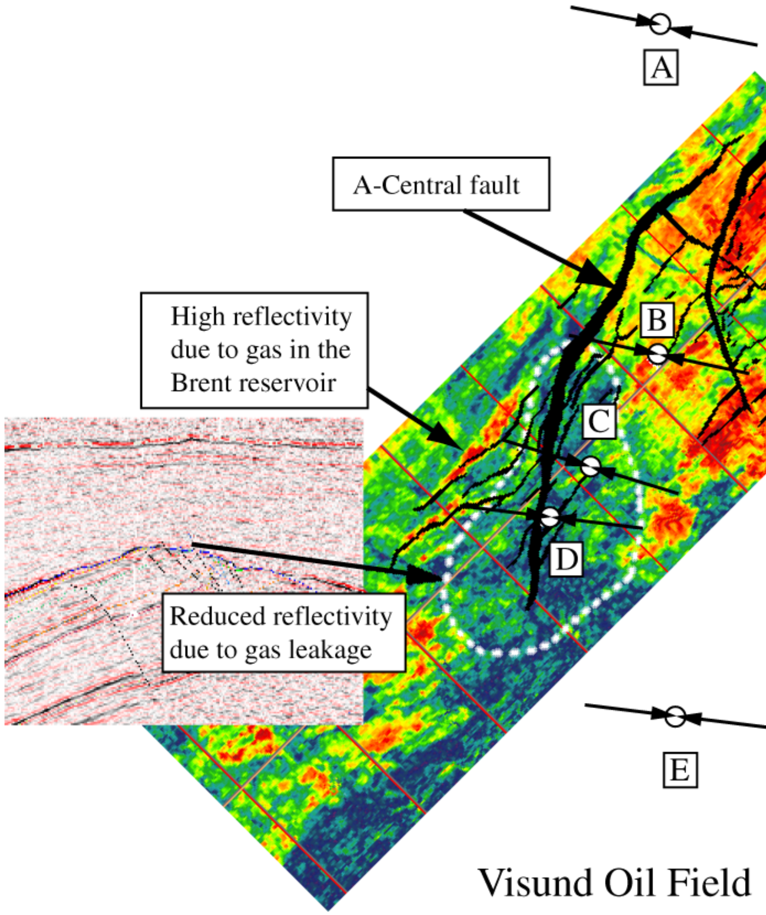
Global Climate & Energy Project

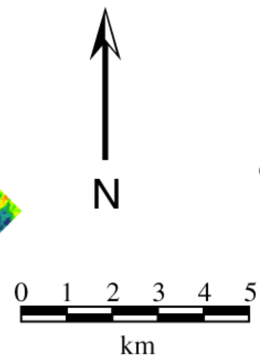
Geomechanics and CO_2

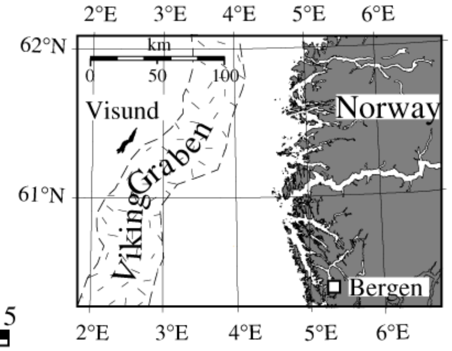
- How Likely is the Change in Pressure Resulting from CO_2 Injection to:
  - Induce Slip on Reservoir Bounding Faults?
  - Induce Slip on Faults Within the Reservoir and Cap Rock?
  - Hydrofrac the Cap Rock?

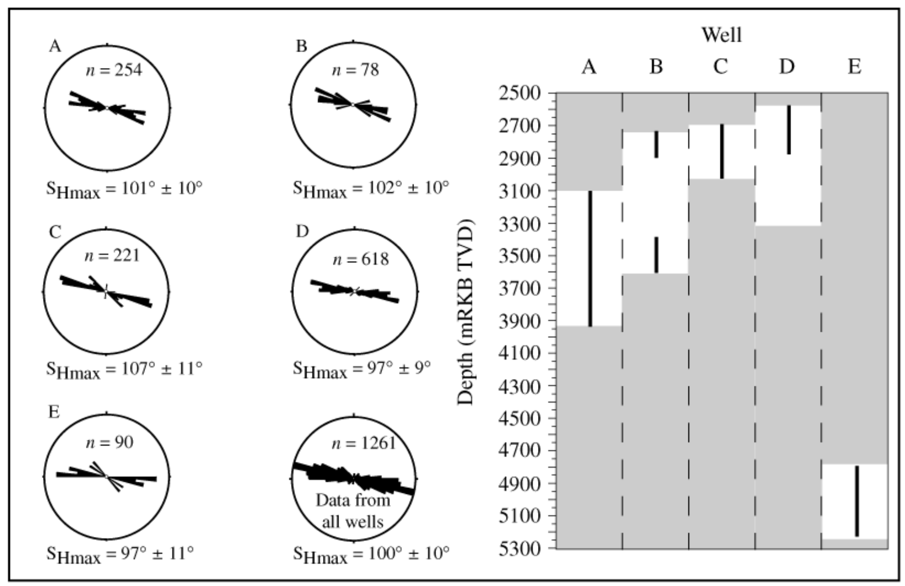


Methodologies Used Widely in the Oil and Gas Industry







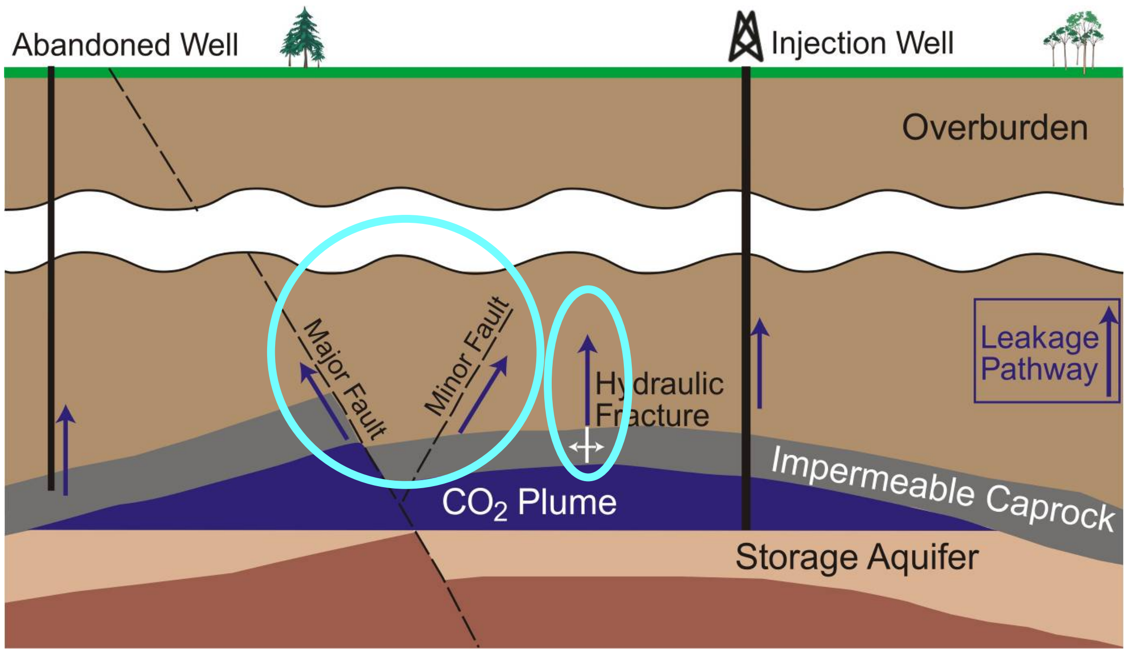


Strike-Slip/Reverse

Wiprut and Zoback (2002)

Geomechanics and CO_2

- Case Studies
  - AEP Mountaineer Site, W. Virginia
  - Mt. Simon Sandstone, Illinois Basin
  - Teapot Dome, Wyoming

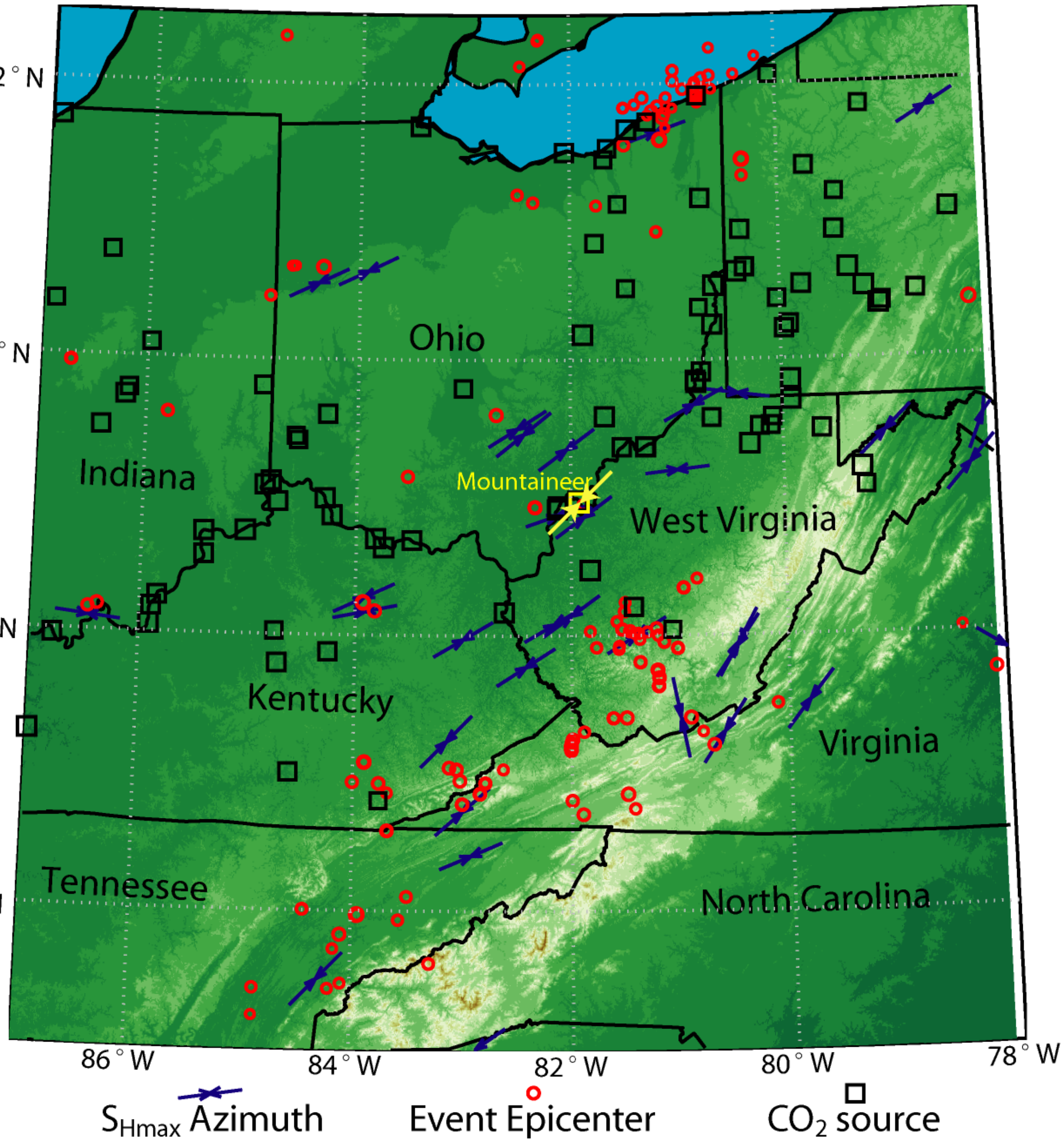


AEP Mountaineer Project: New Haven, WV

NY Times Sept. 21, 2009

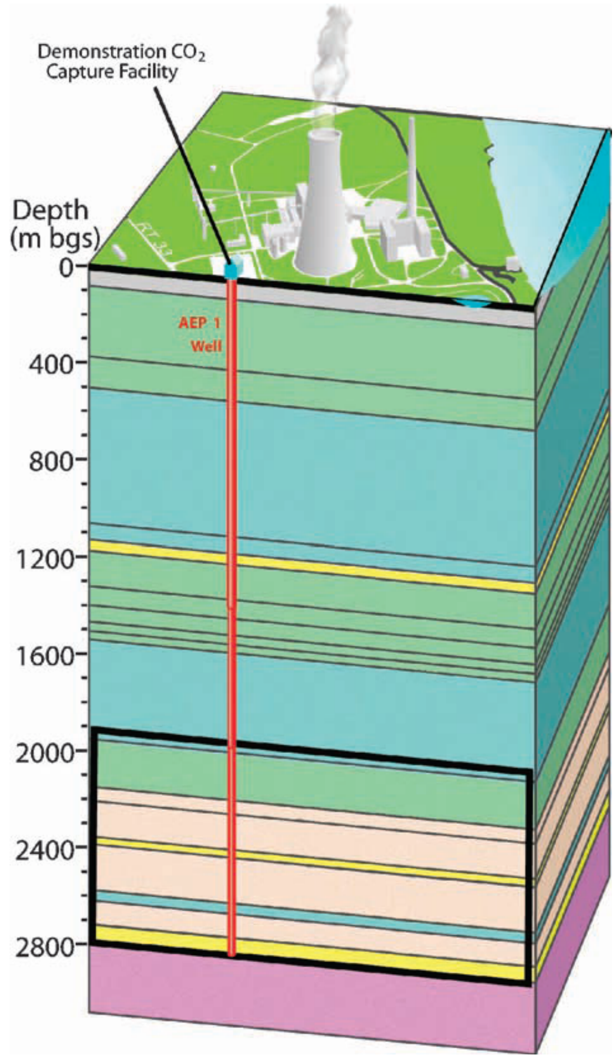
Current Plans to Inject 100 ktons/y for 2-5 years

Regional Seismicity and CO_2 Point Sources



AEP Mountaineer Project

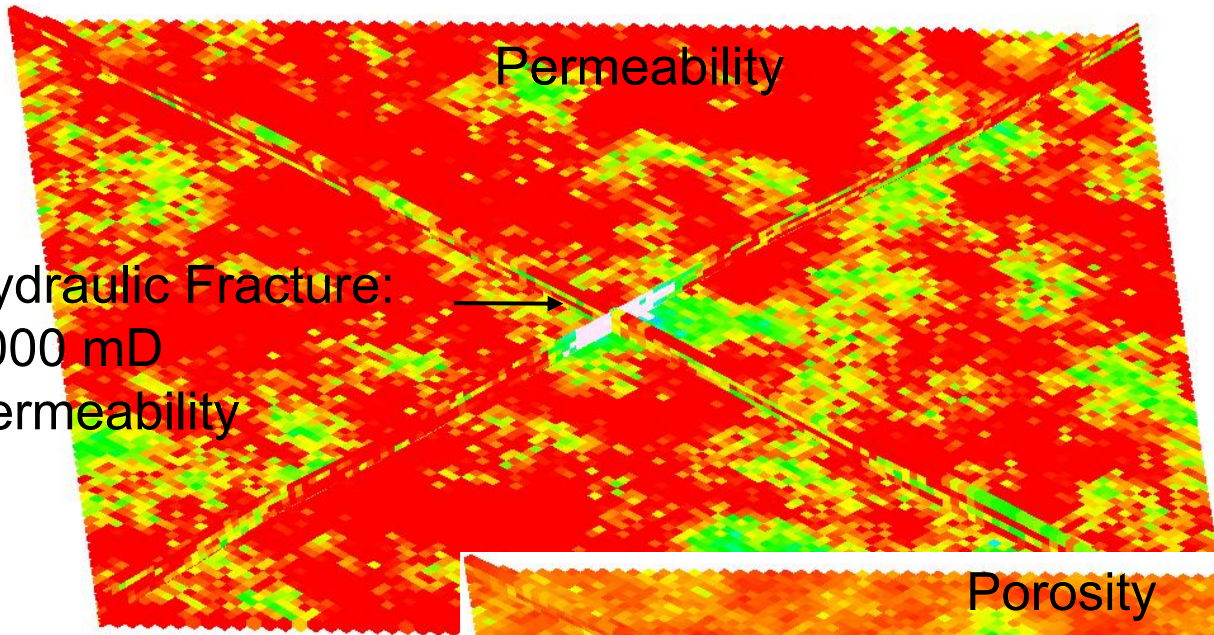
AEP Mountaineer
CO_2 Emissions
~7 Mton/year



183 Coal burning plants in Ohio River Valley (emitting 700 Megatons of CO_2/year)

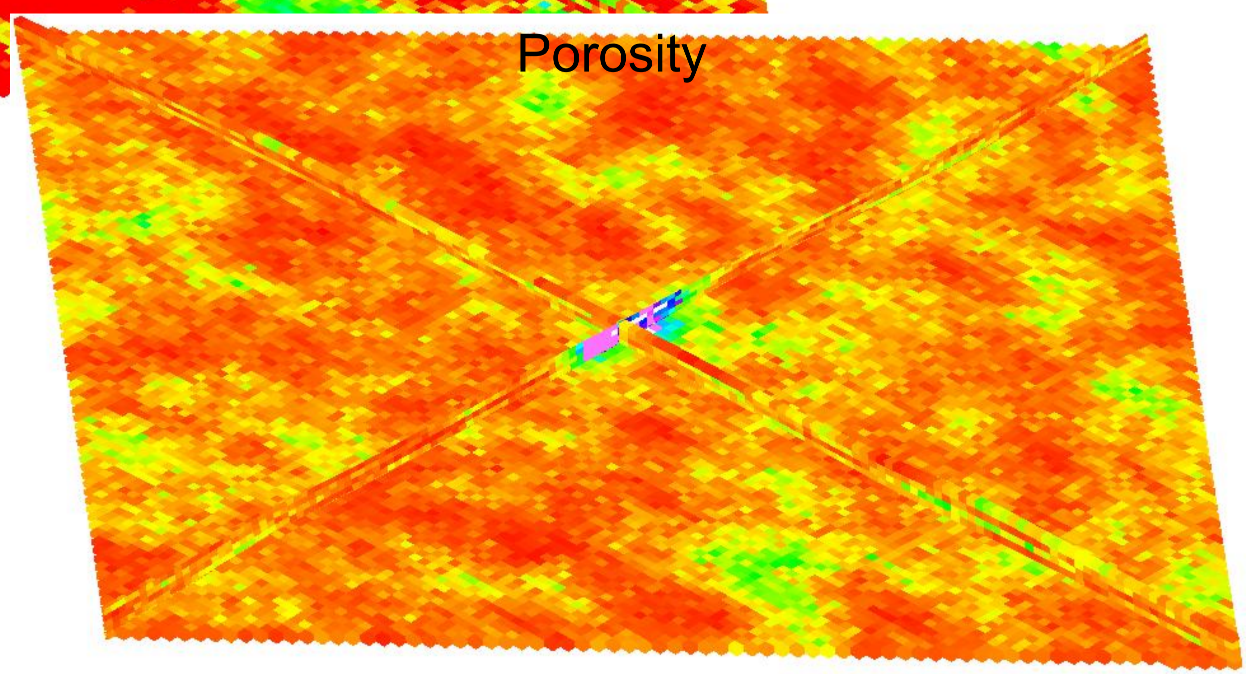
Lucier, Zoback et al. (2006)

Reservoir Simulations with Hydraulic Fractures to Stimulate Injection



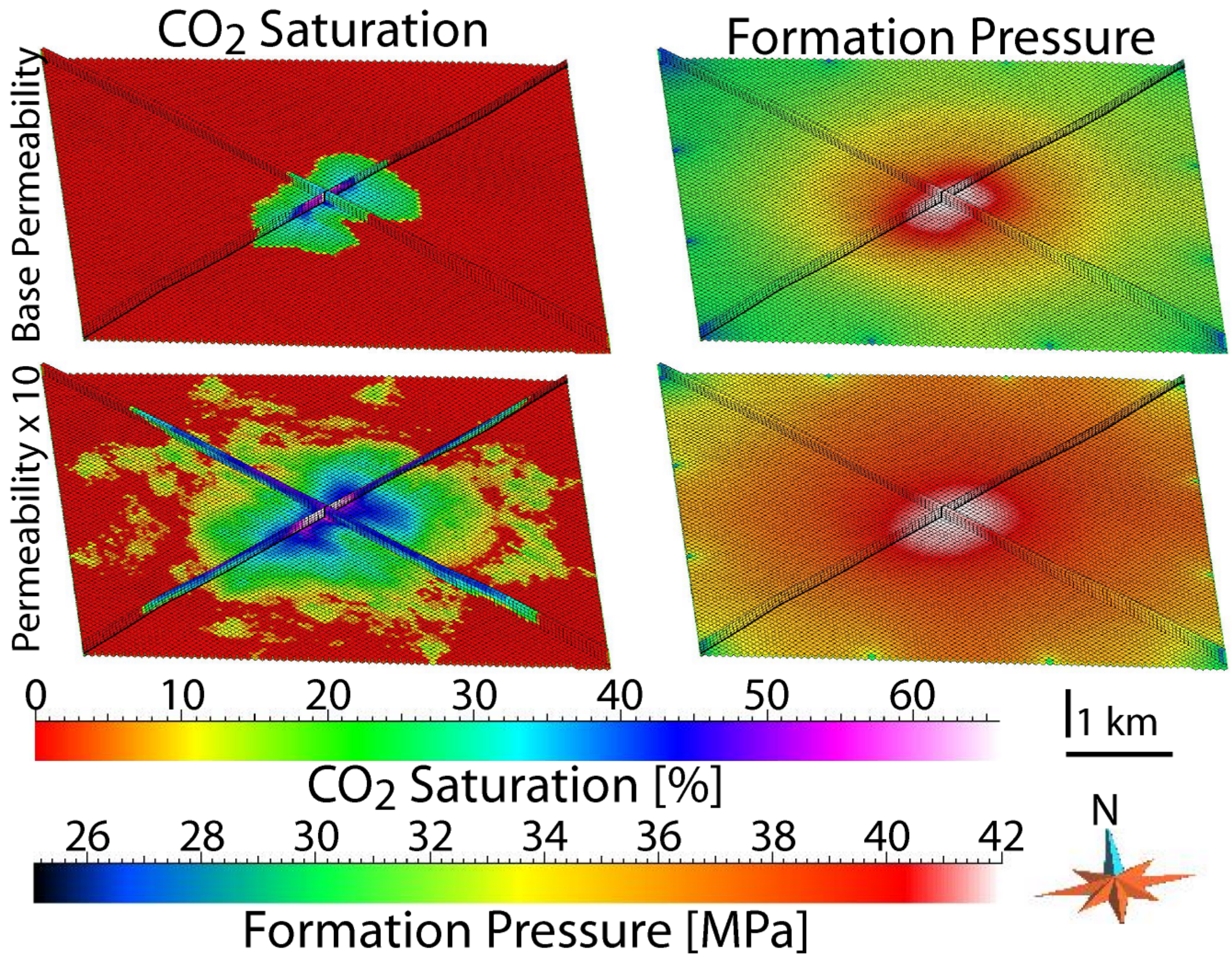
Hydraulic Fracture:
1000 mD
Permeability

6 km x 6 km



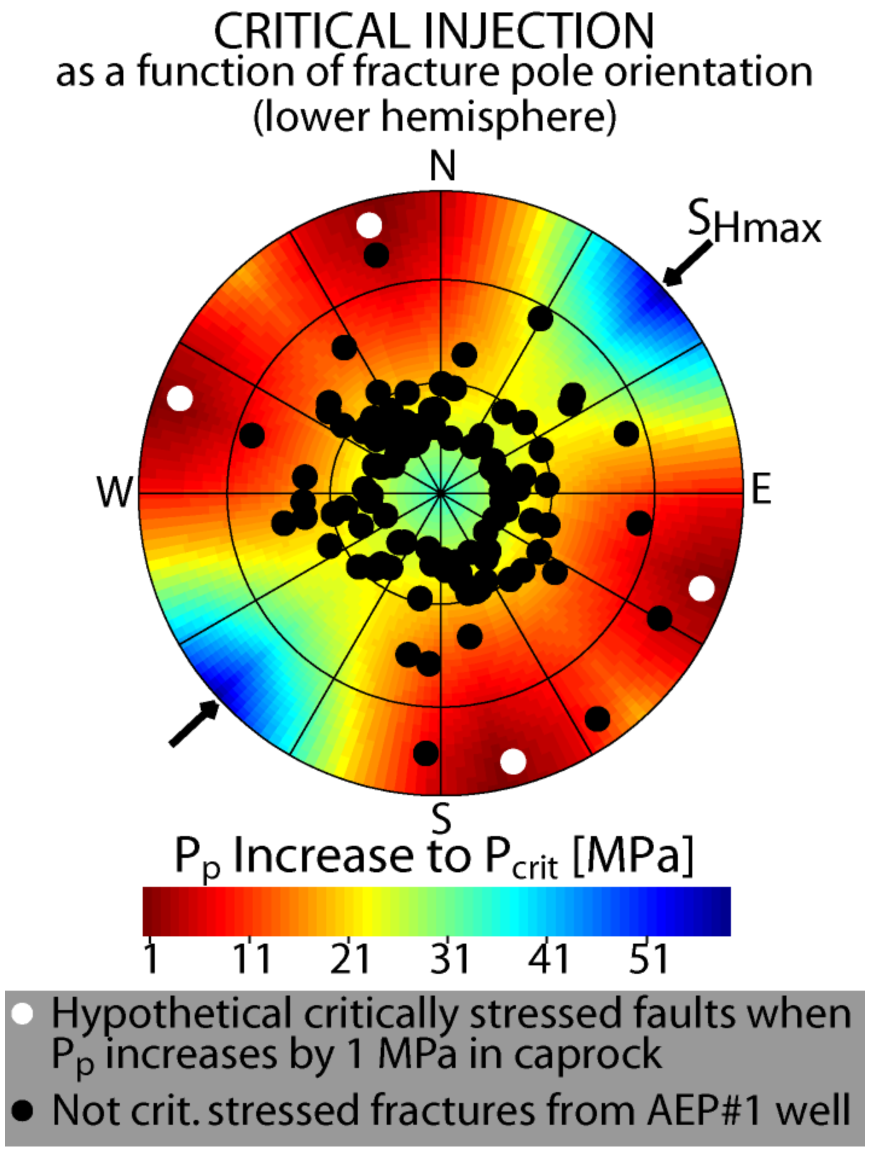
Geostatistics based on data from a Single well

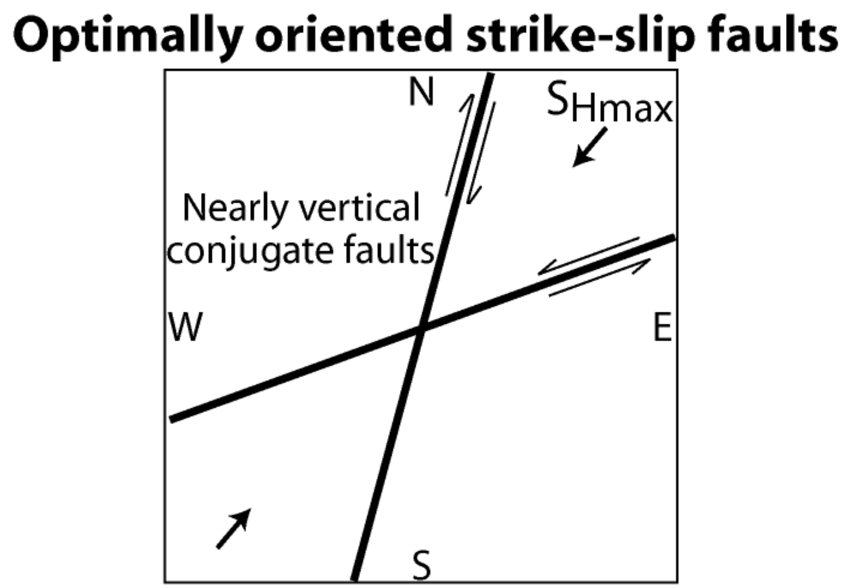
After CO_2 Injection for 30 Years



Note that the pressure front moves ahead of CO_2 front

Slip on Optimally-Oriented Fault Planes





Injection rate limited to 35,000 tons/year to avoid triggering slip on faults (3.5 Mpa)