Technical Economic and Regulatory Challenges Facing Large Scale Adaption of Carbon Geologic Sequestration

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Carbon Management Technology Conference

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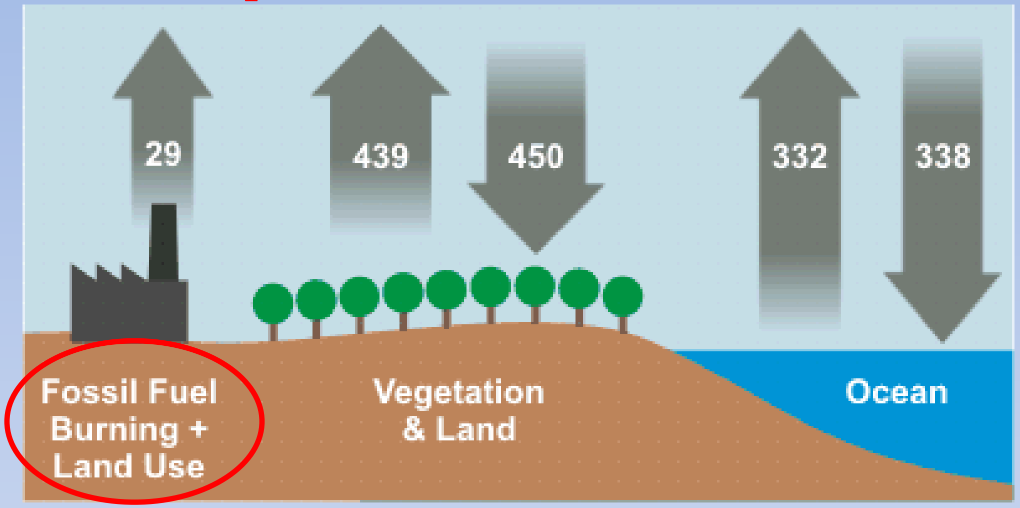
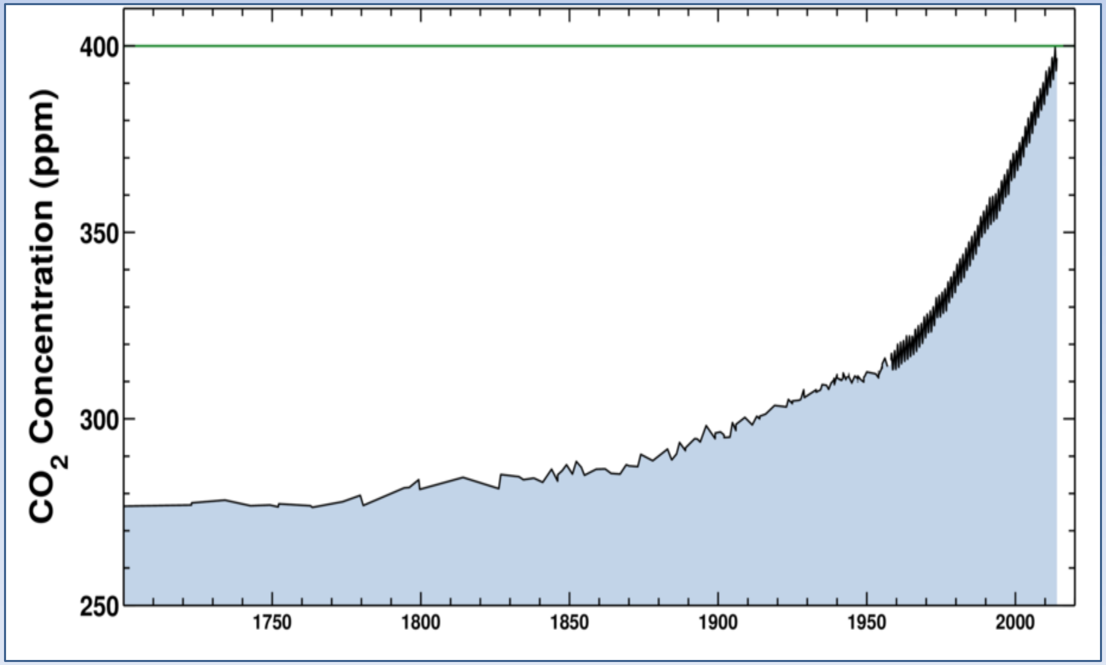
Sugarland, TX

Global CO_2 Cycle

CO_2 Cycle (billion tons per year, GT)

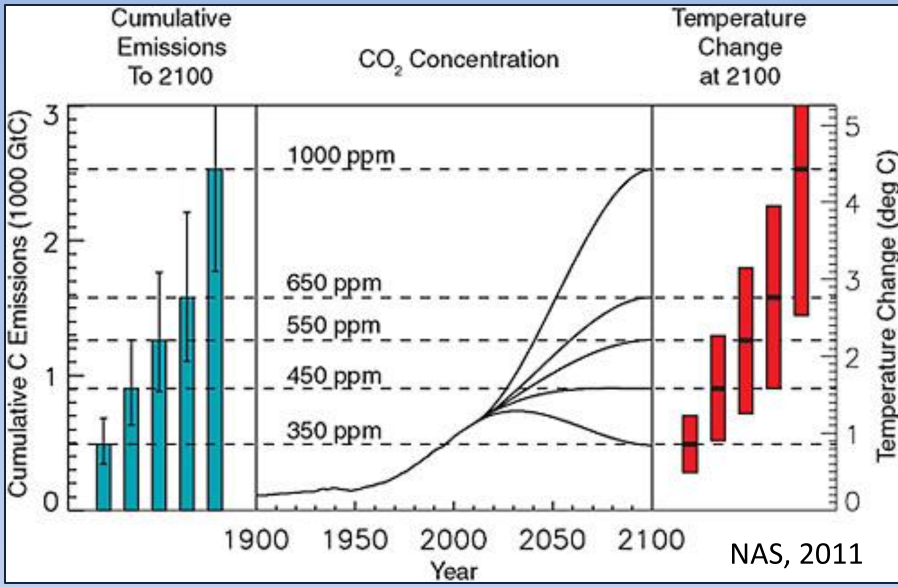


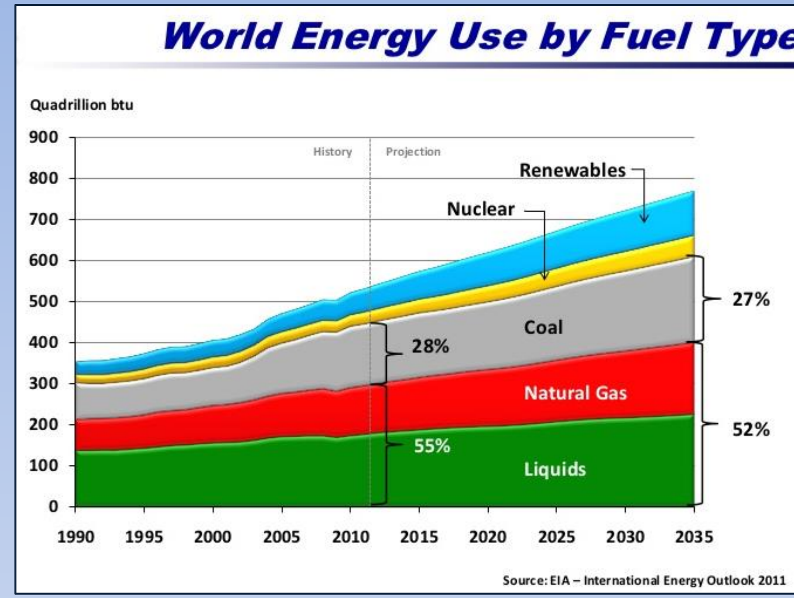
Total Emissions	**800 GT annually**
Natural Sequestration	**788 GT**
Balance	**12 GT**

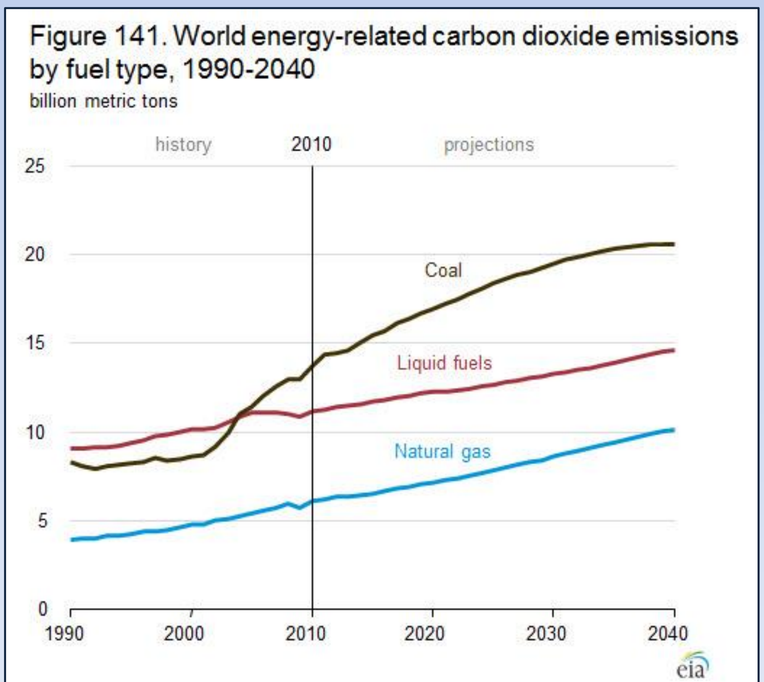


- Atmospheric CO_2 levels rising since start of industrial era.
- Present concentrations of 400 ppm CO_2 close to 2050 target of 450 ppm.

C02 Abatement Targets

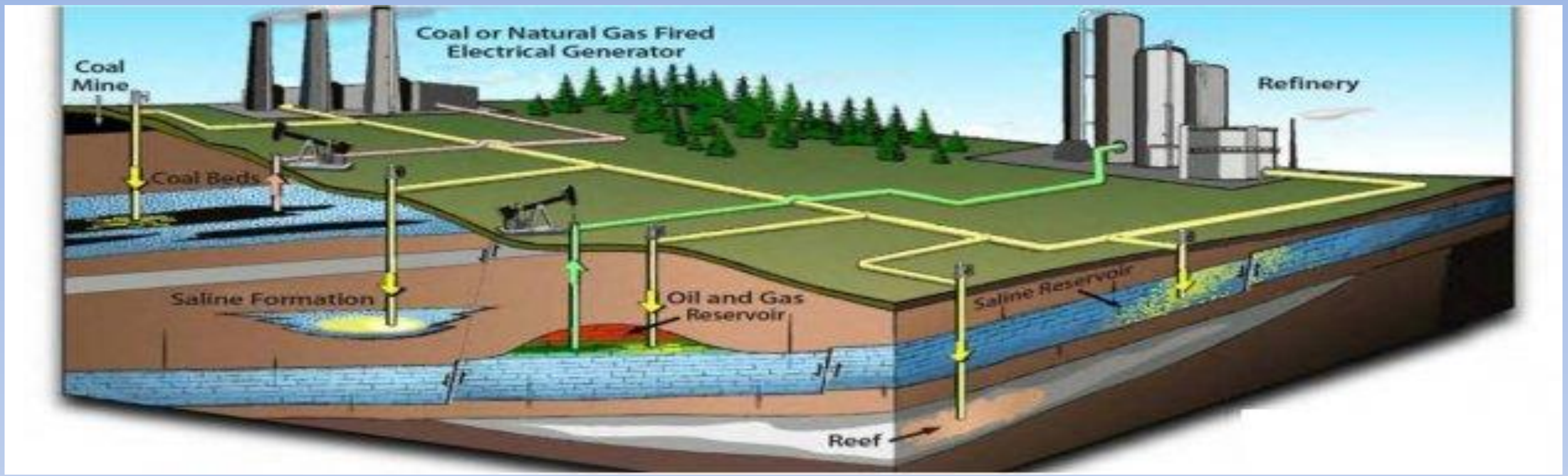


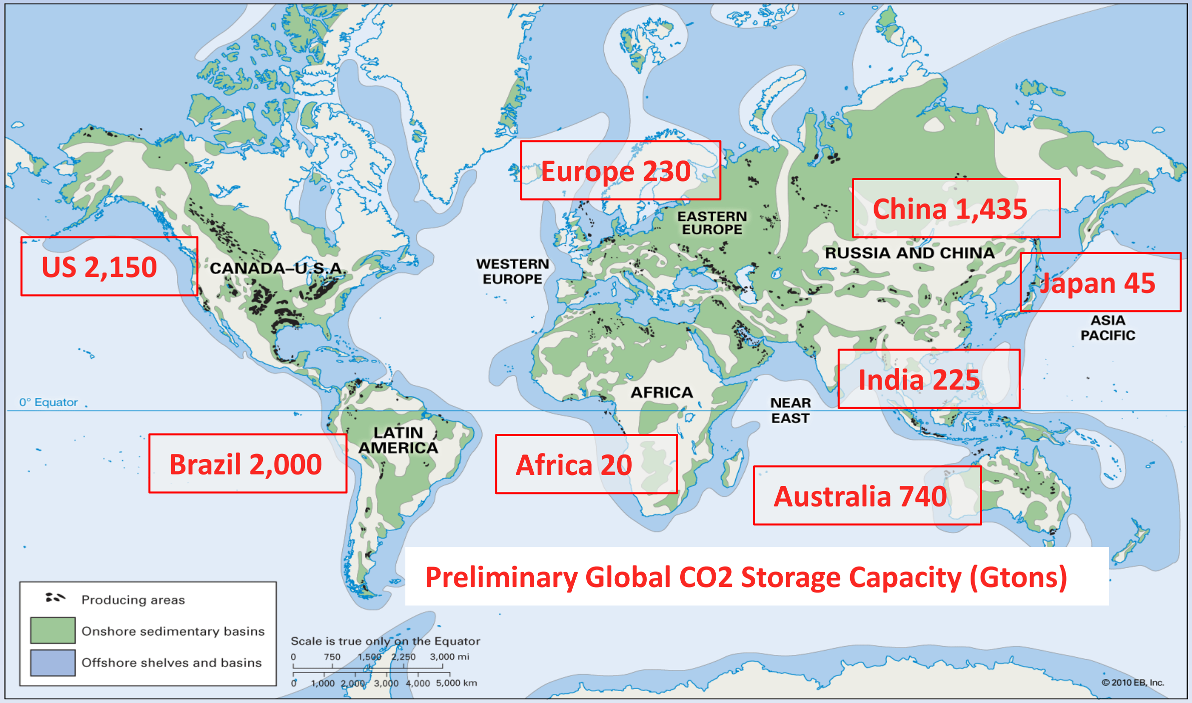




- With business as usual, CO_2 emissions by 2035 will have reached the threshold for limiting temperature rise to 2^{o}C this century
- Need to reduce emissions in the 100s-1000 GT range in this century to meet atmospheric CO_2 and temperature targets

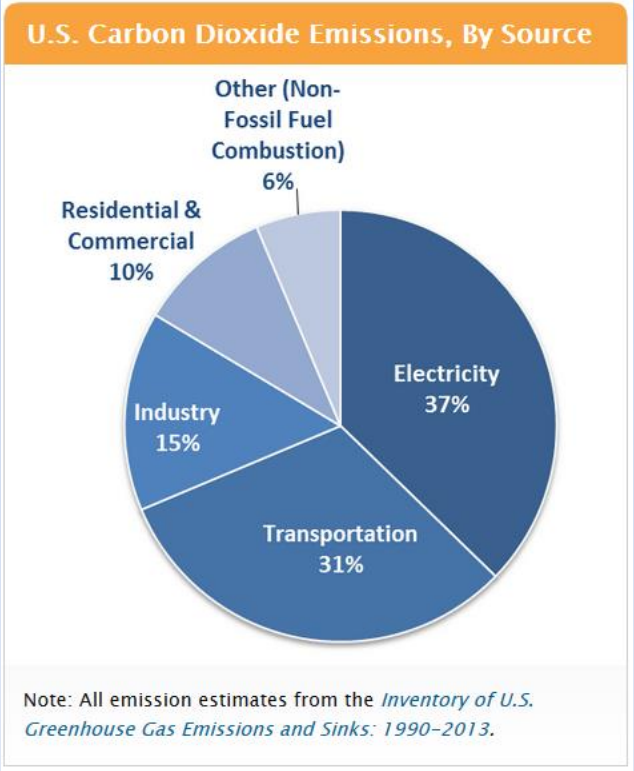
Geologic Sequestration Necessary to Meet Emission Targets



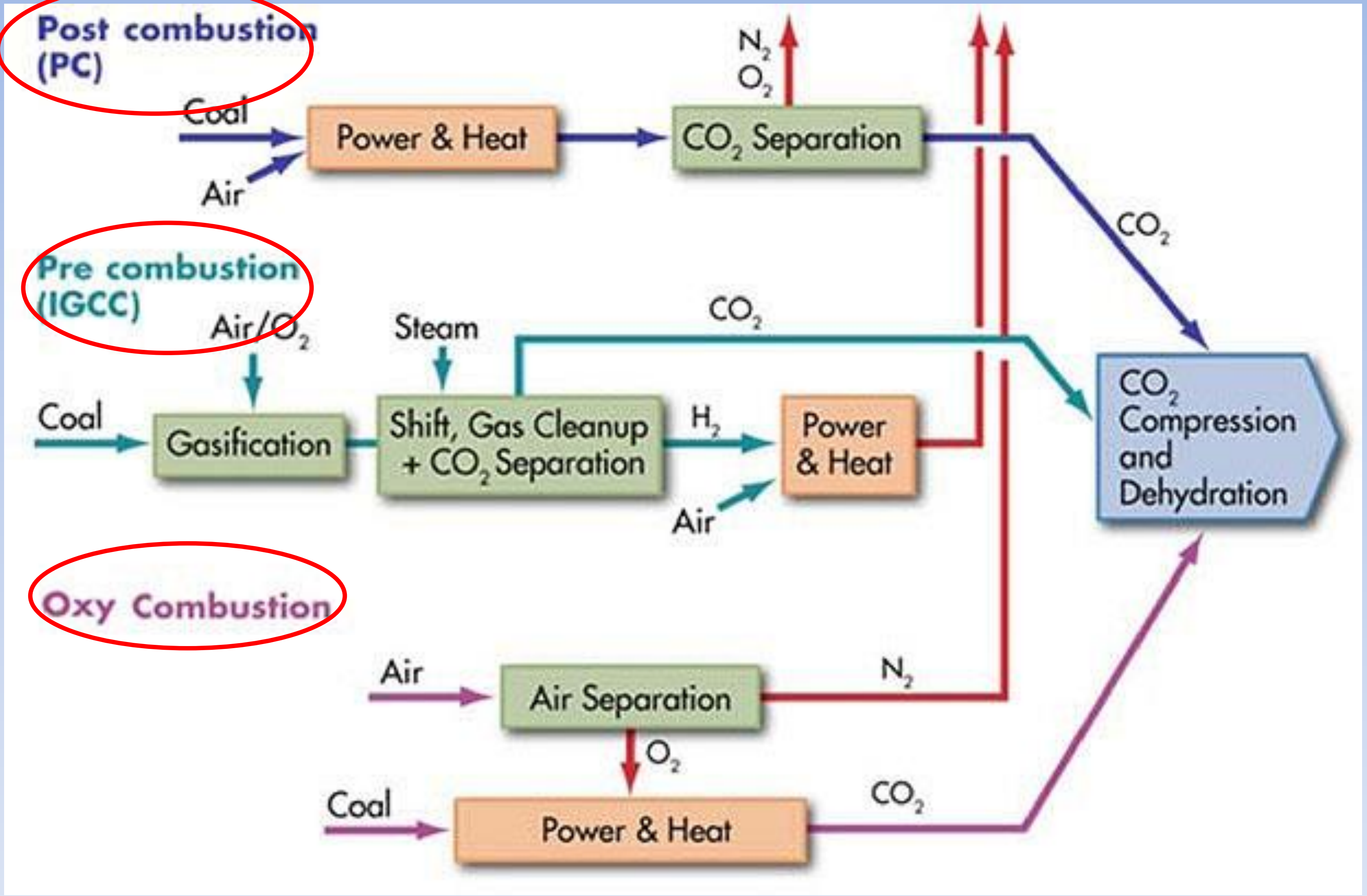


Challenges for Scaling Up CCS

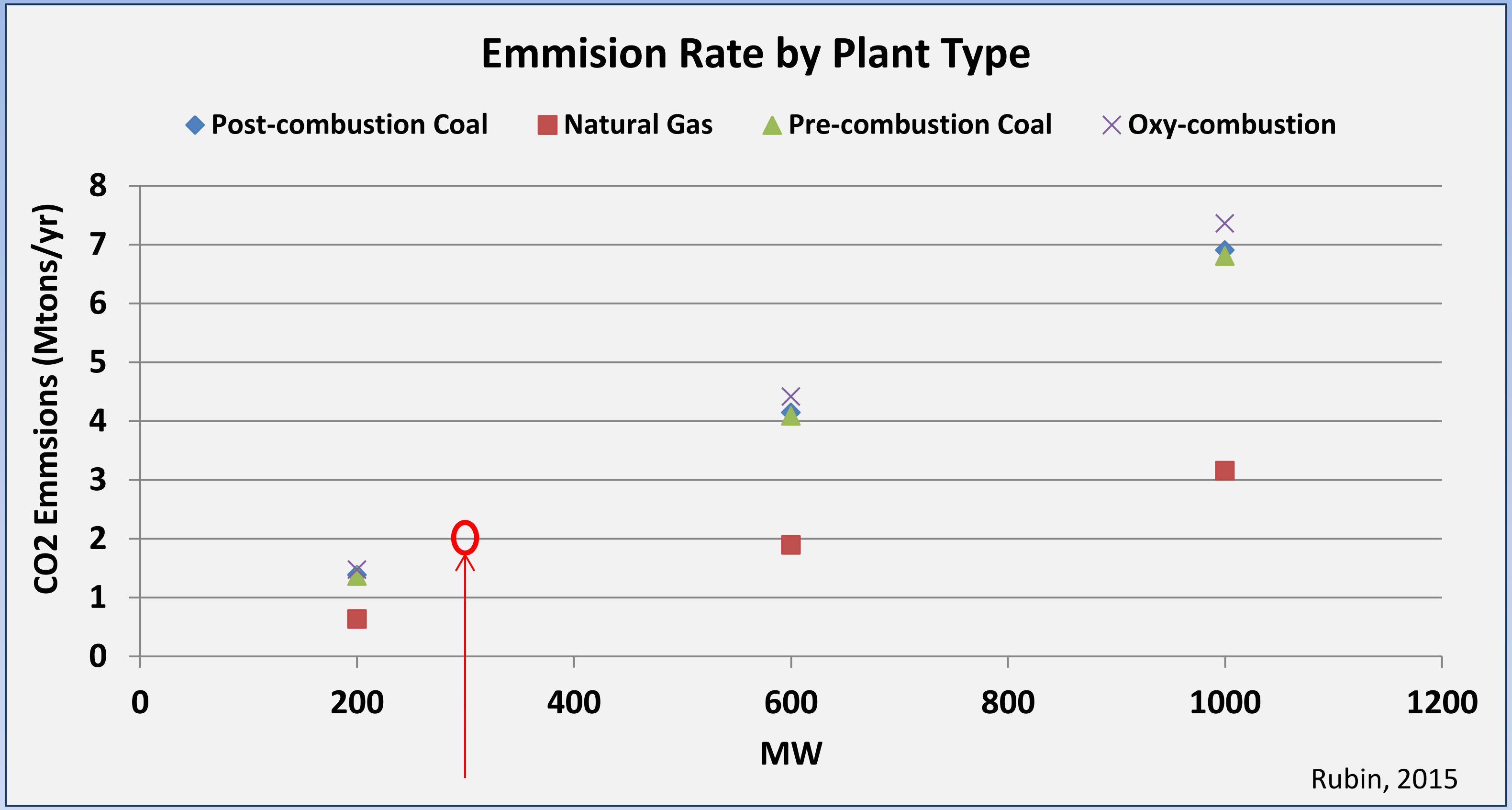
- **Carbon Capture and Storage Costs**
- **Inadequate Transportation Network**
- **Storage Uncertainties including Seismic Risk and Injectivity**
- **Regulatory and Legal Issues**



Carbon Capture Technologies



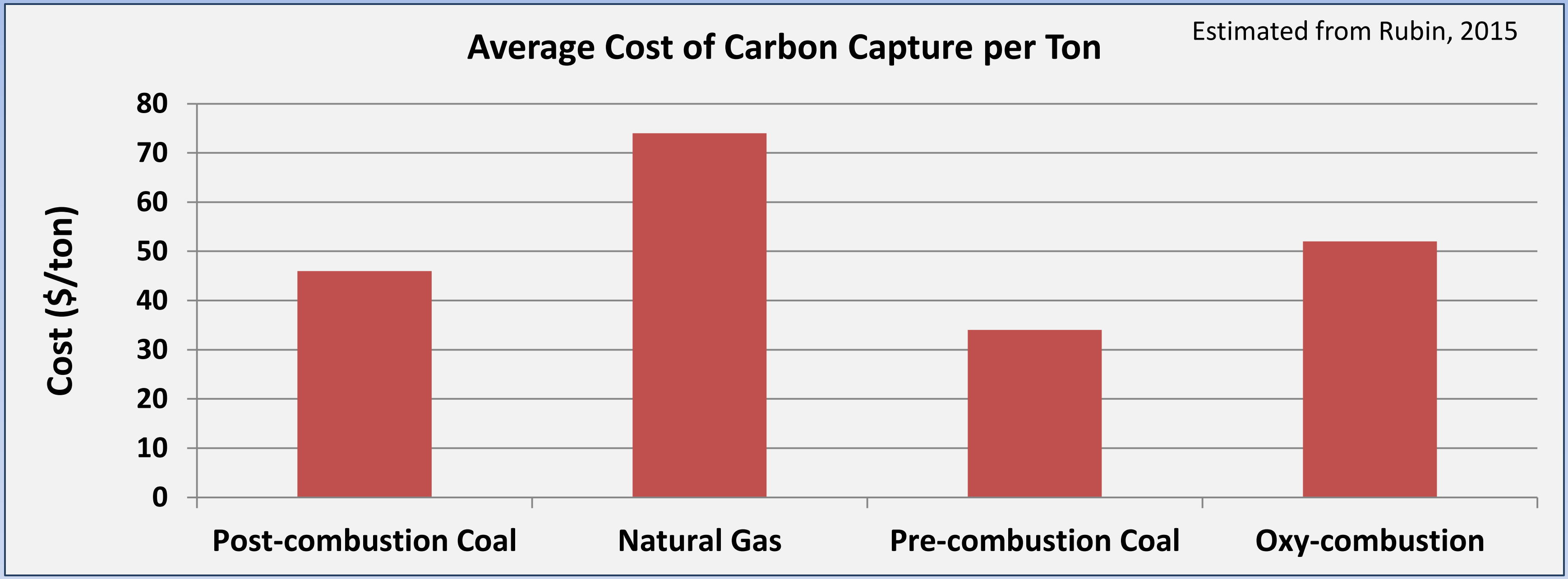
Emissions Rate by Plant Type and Capacity



Typical Power Plant

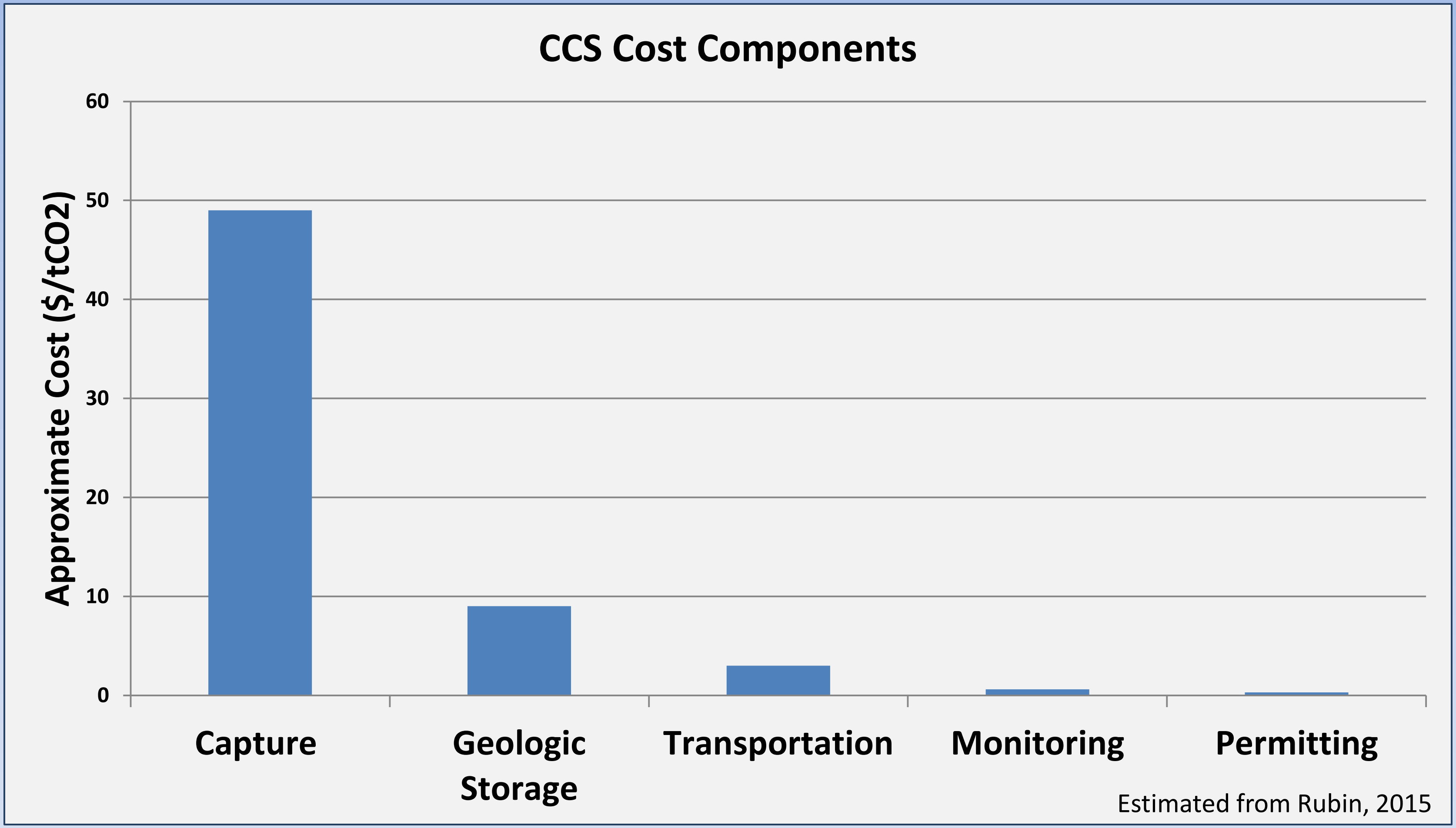
- Most coal-based plants have similar emission rates
- A typical 300 MW coal-based power plant emits ~ 2 $Mtco_2$/year
- Natural gas-based plants emit approximately half the CO_2 of coal-based plant

Cost of Carbon Capture by Plant Type



- For a typical 300 MW plant that emits emits 2 $Mtco_2$/year – annual abatement cost ~ $80M/yr

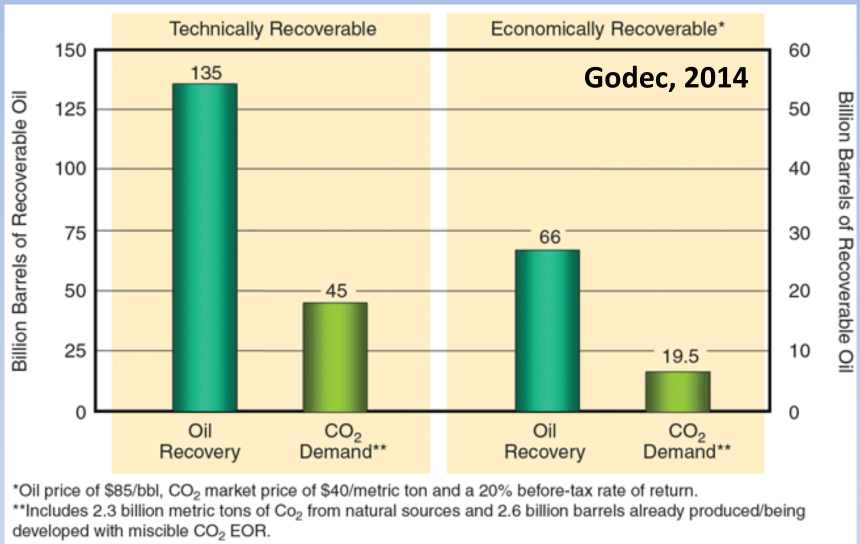
Carbon Capture and Storage Cost Components



- **EOR credits ~ $15 - $40 per ton depending on oil price (Rubin, 2015)**

Cost Mitigation by Enhanced Oil Recovery (EOR)

Affordable cost for EOR ~ 2% of oil price in $/bbl. At $100,= $36/tCO2, at $50=$18.



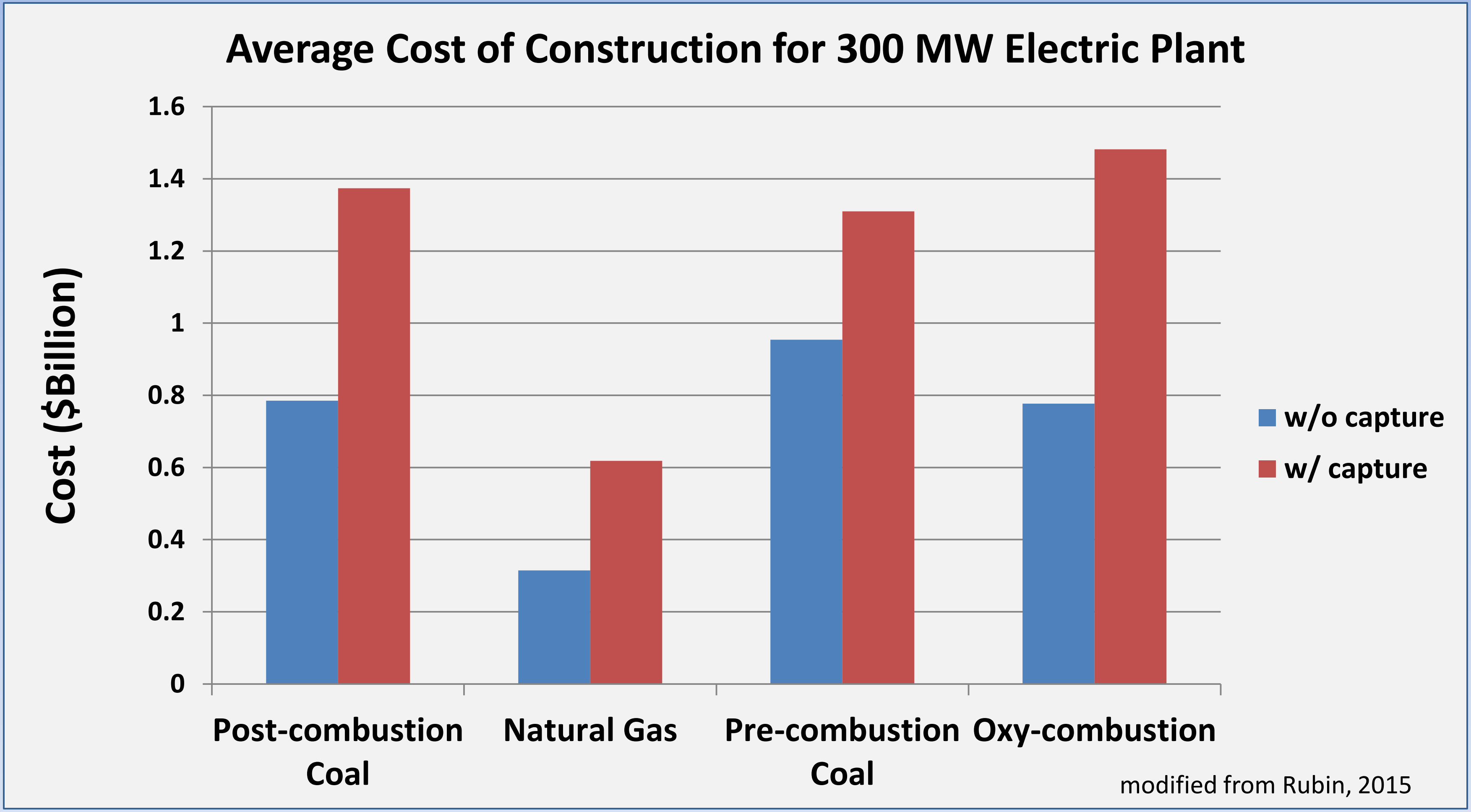
- Large quantities of CO_2 can be used in US for EOR operations

Region	CO_2 EOR Oil Recovery (Billions of barrels)	CO_2 Storage Capacity (Billions of metric tons)
1. Asia Pacific	47	13
2. Central & South America	93	27
3. Europe	41	12
4. FSU	232	66
5. Middle East/North Africa	595	170
6. NA/Other	38	11
7. North America/U.S.	177	51
8. South Africa/Antarctica	74	21
Total	**1,297**	**370**

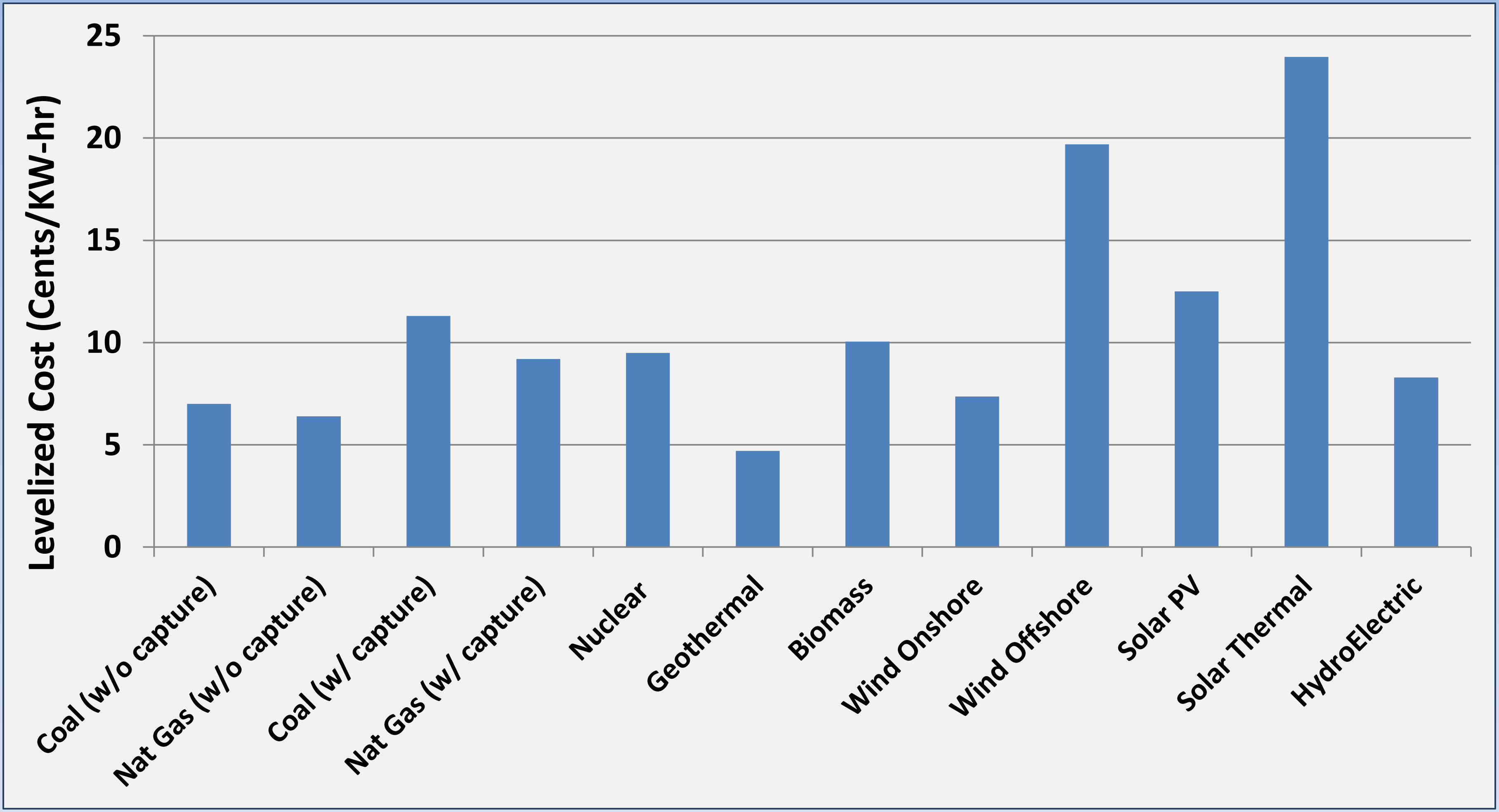
- ~ 370 GT can be stored globally in association with EOR

Godec, 2014

Plan Construction Cost

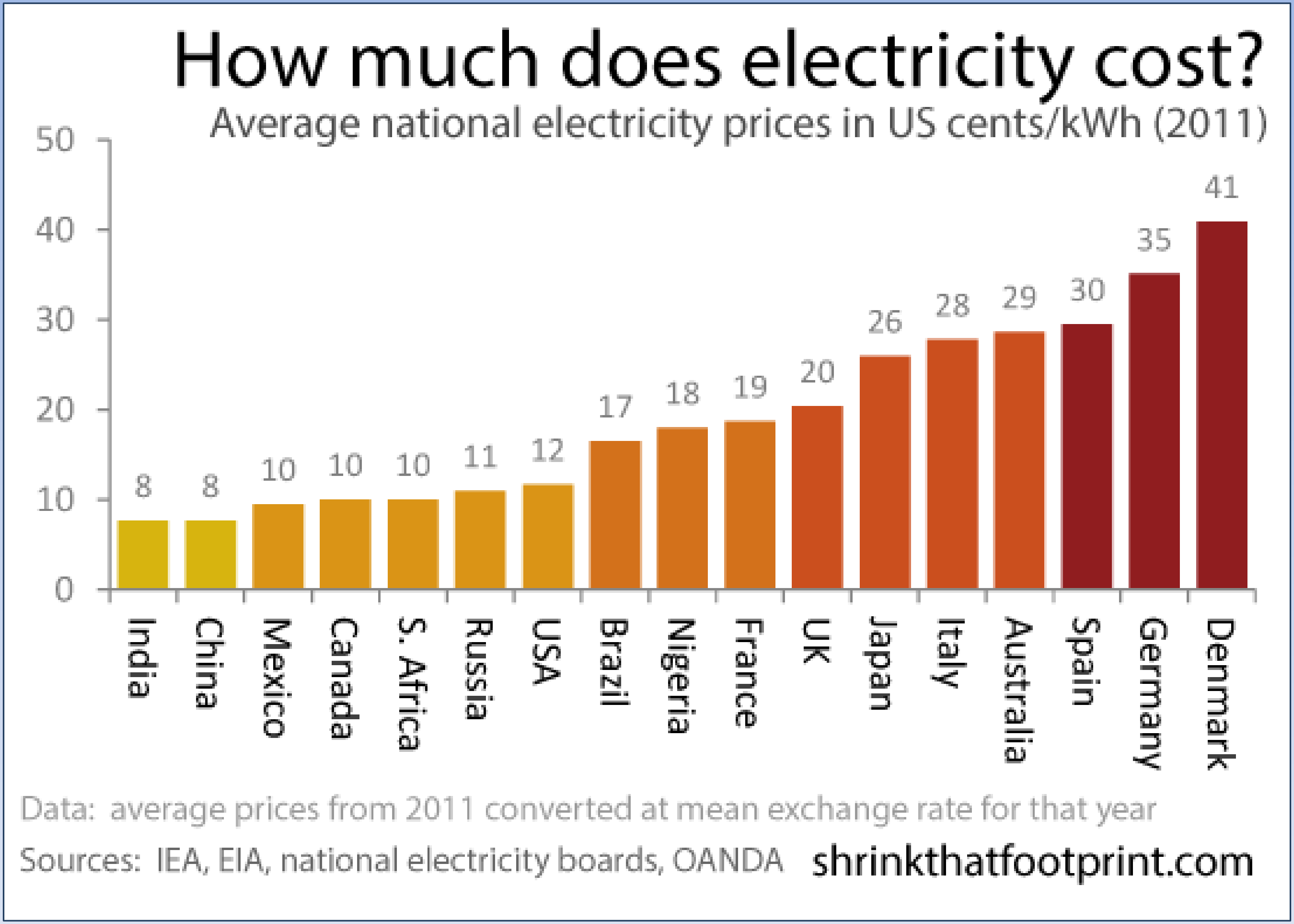


Levelized Cost of Electricity

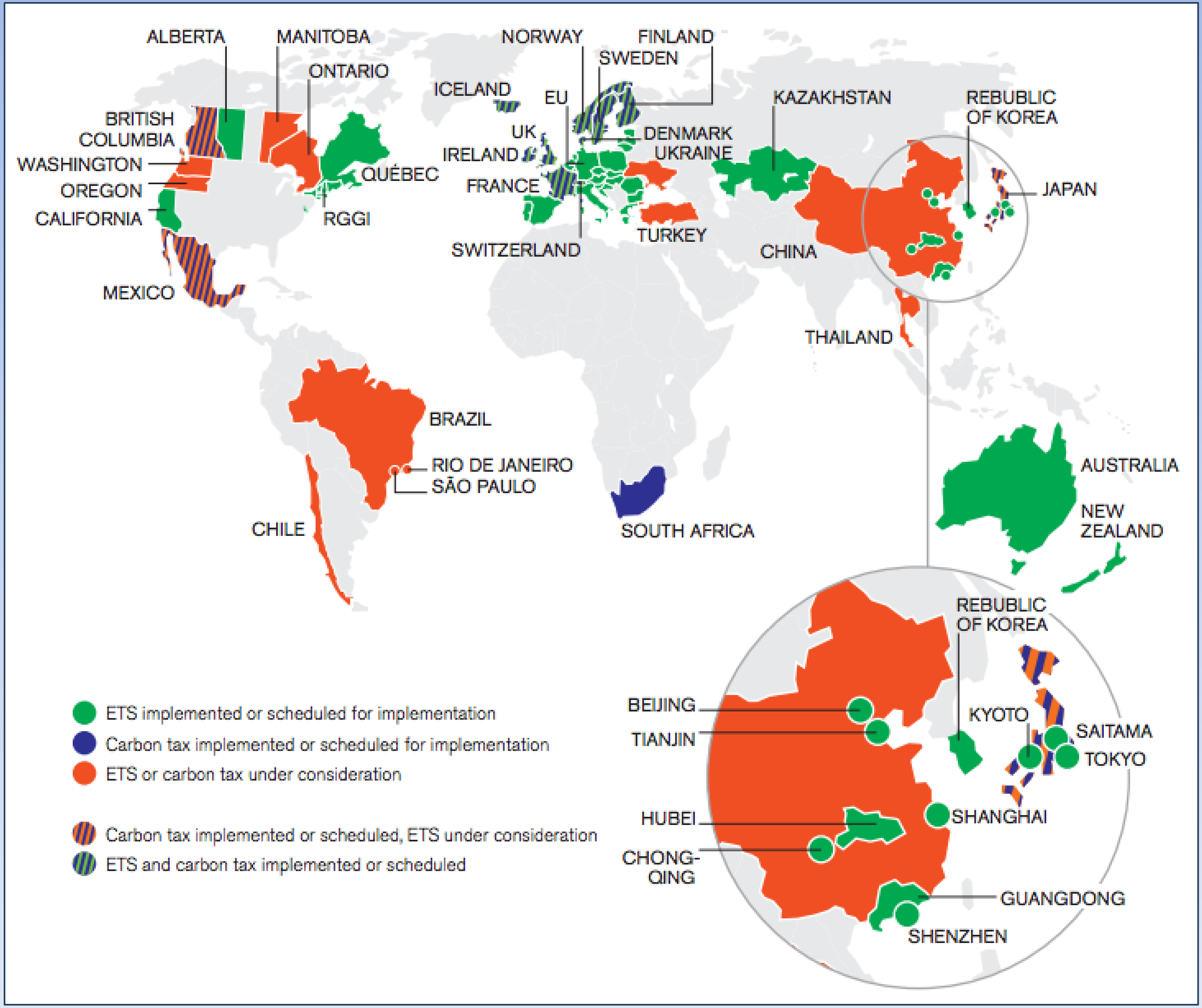


- **Coal plants competitive even with capture and storage costs**

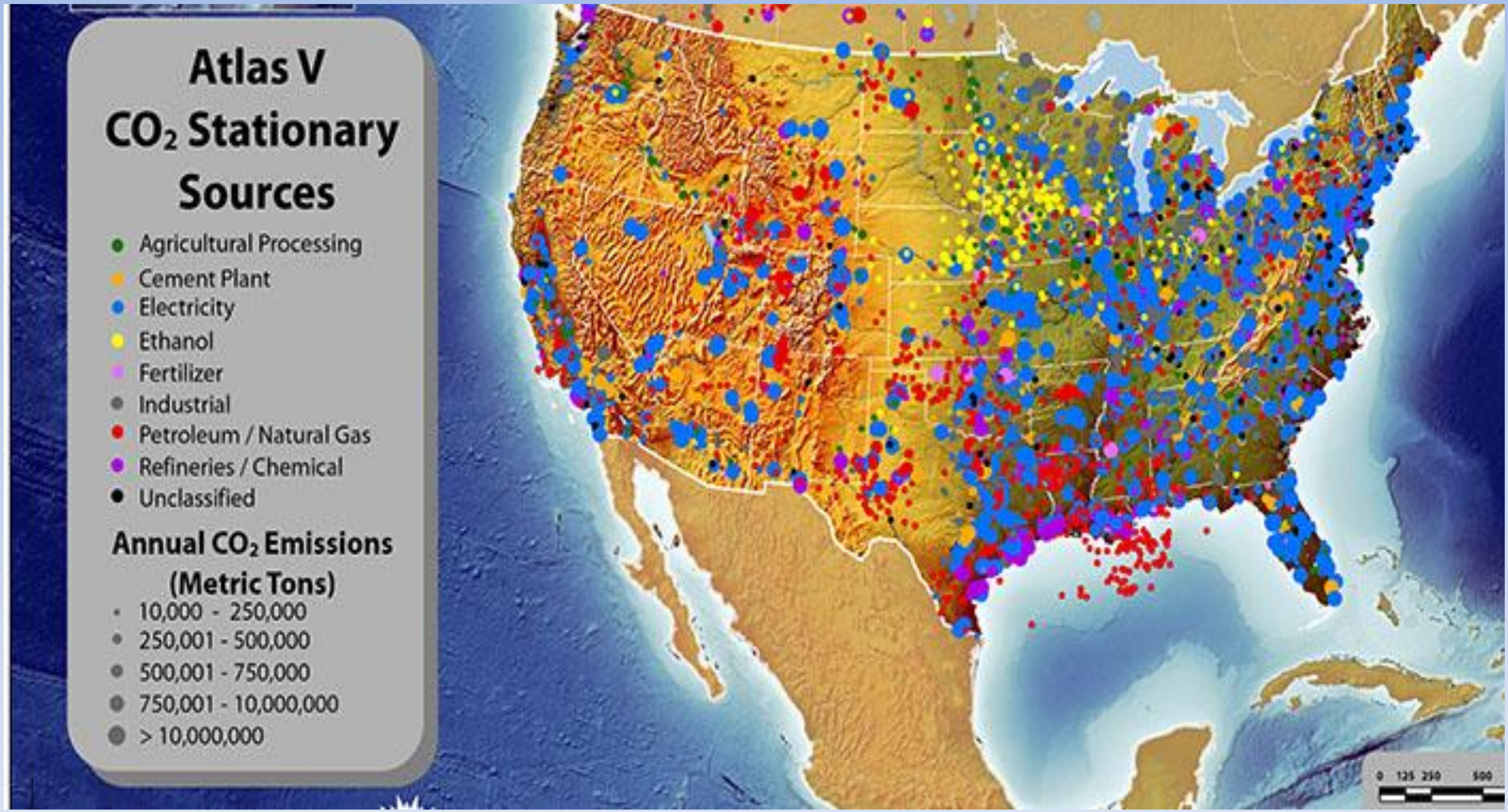
CCS More Competitive Overseas



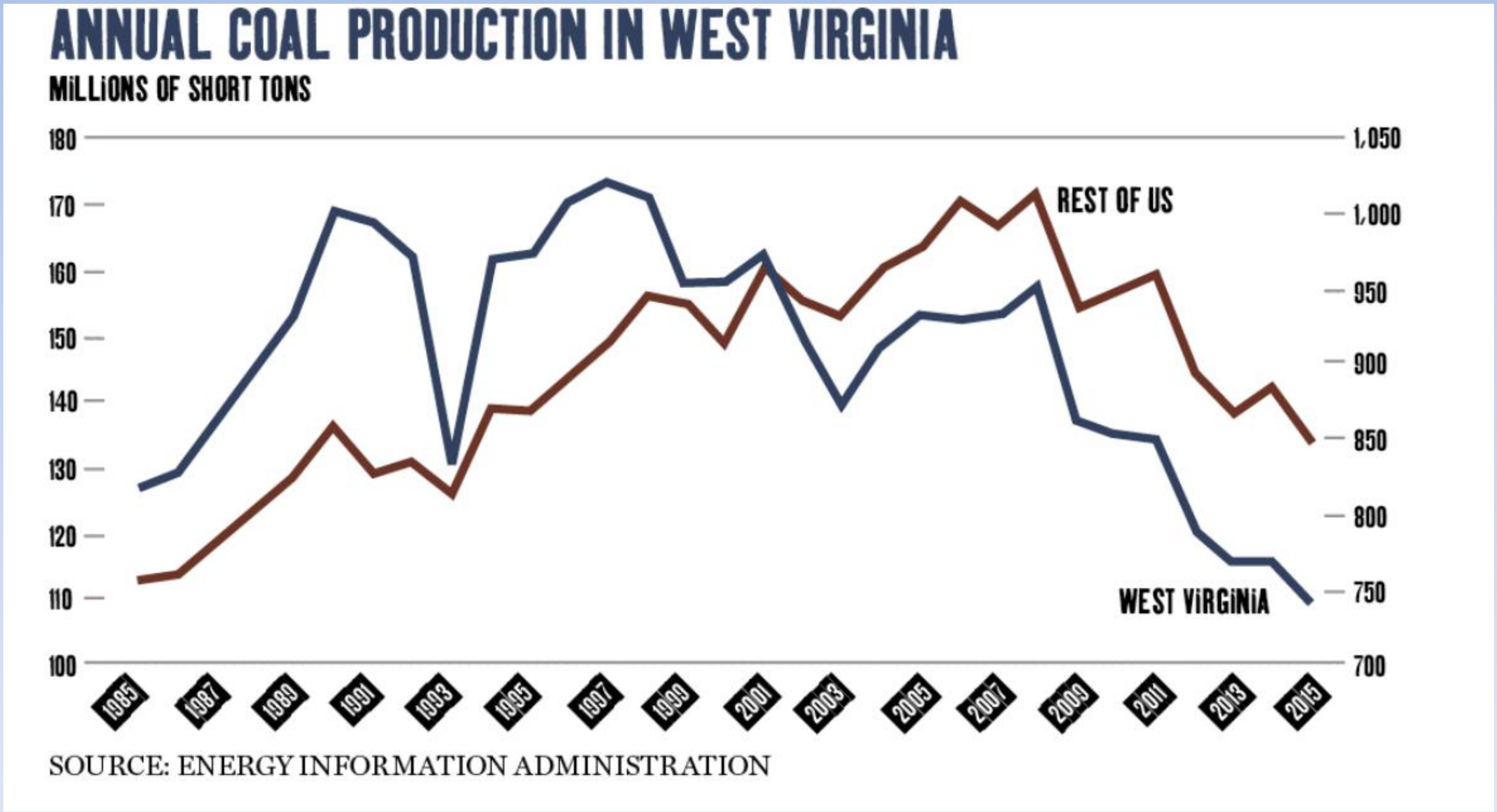
Further Incentive for CSS Adoption and Lowering of Cost with Carbon Credits



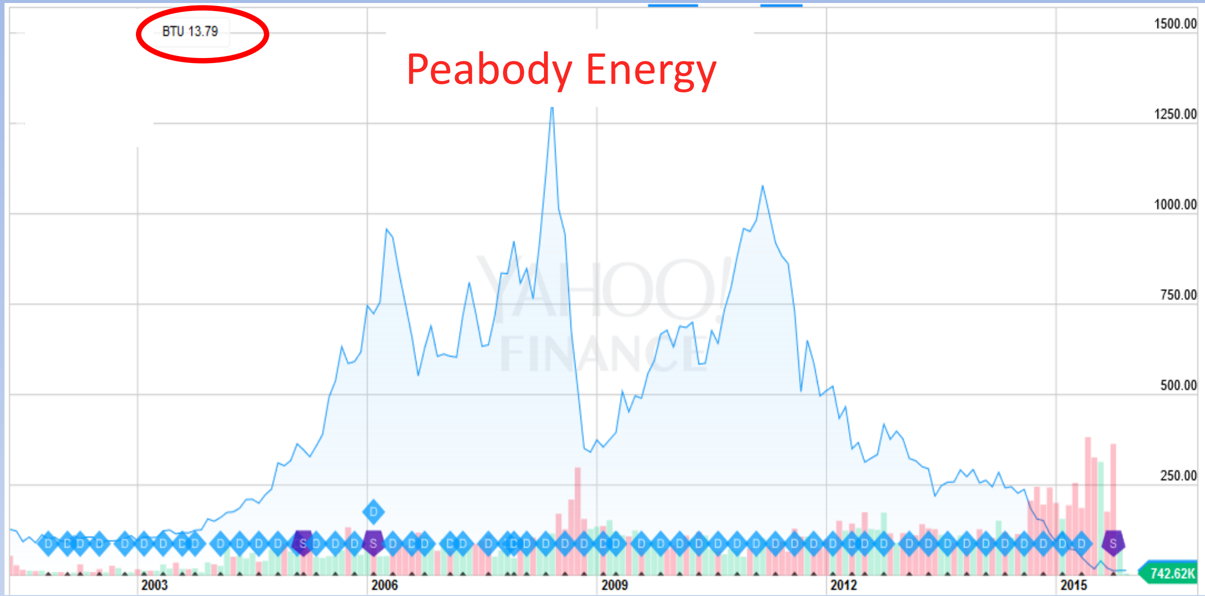
Inadequate CO_2 Pipeline Network



Uncertainty in National Carbon Policy Affecting Coal Production



Uncertainty in Carbon Policy Causing Fiscal Distress for Coal Miners



- 26 coal mining companies have filed for bankruptcy protection in the past 5 years

Arch Coal expects to file for bankruptcy protection within months

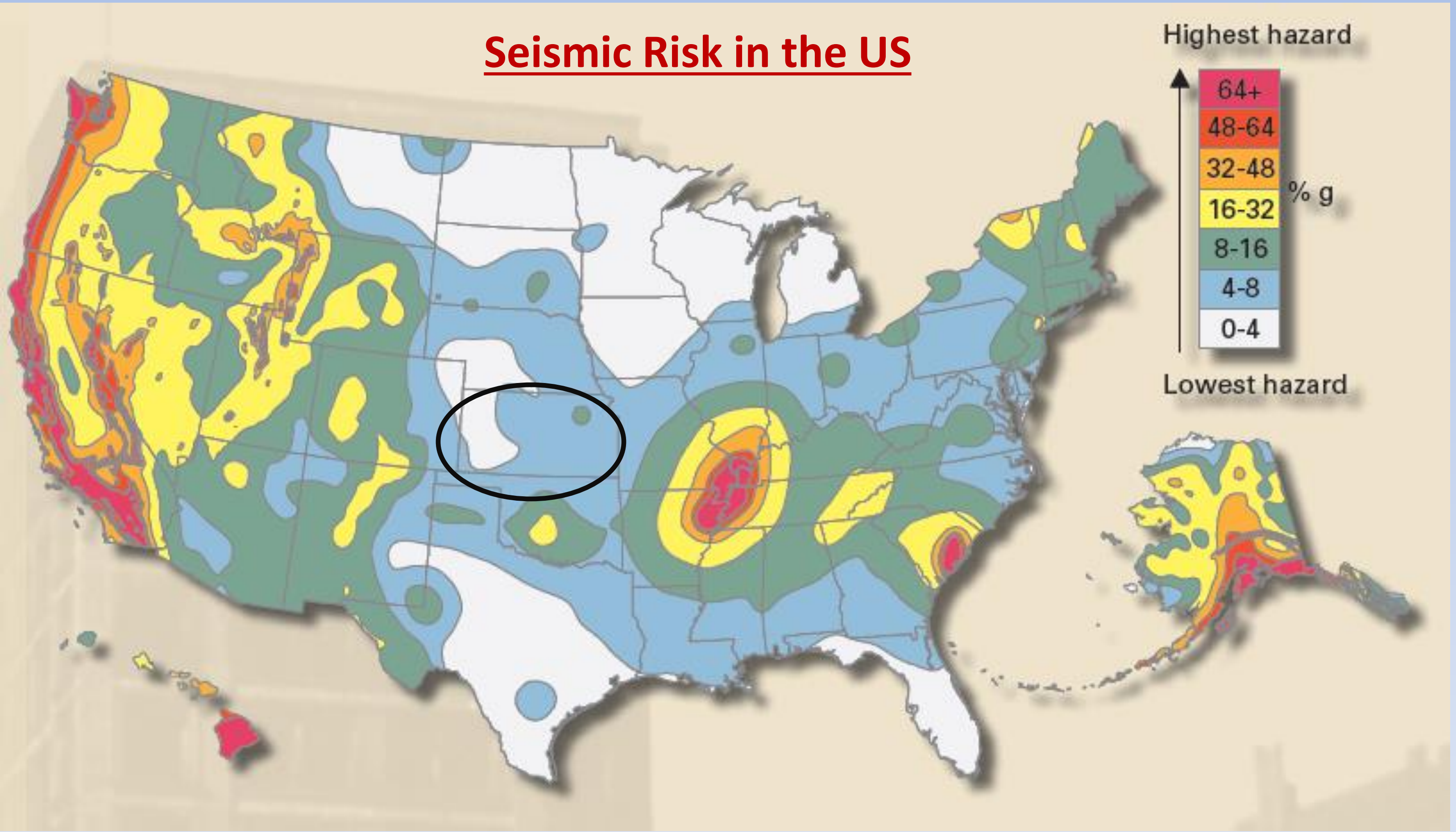
REUTERS November 9, 2015 6:14 PM

* Out-of-court restructuring deal unlikely - sources

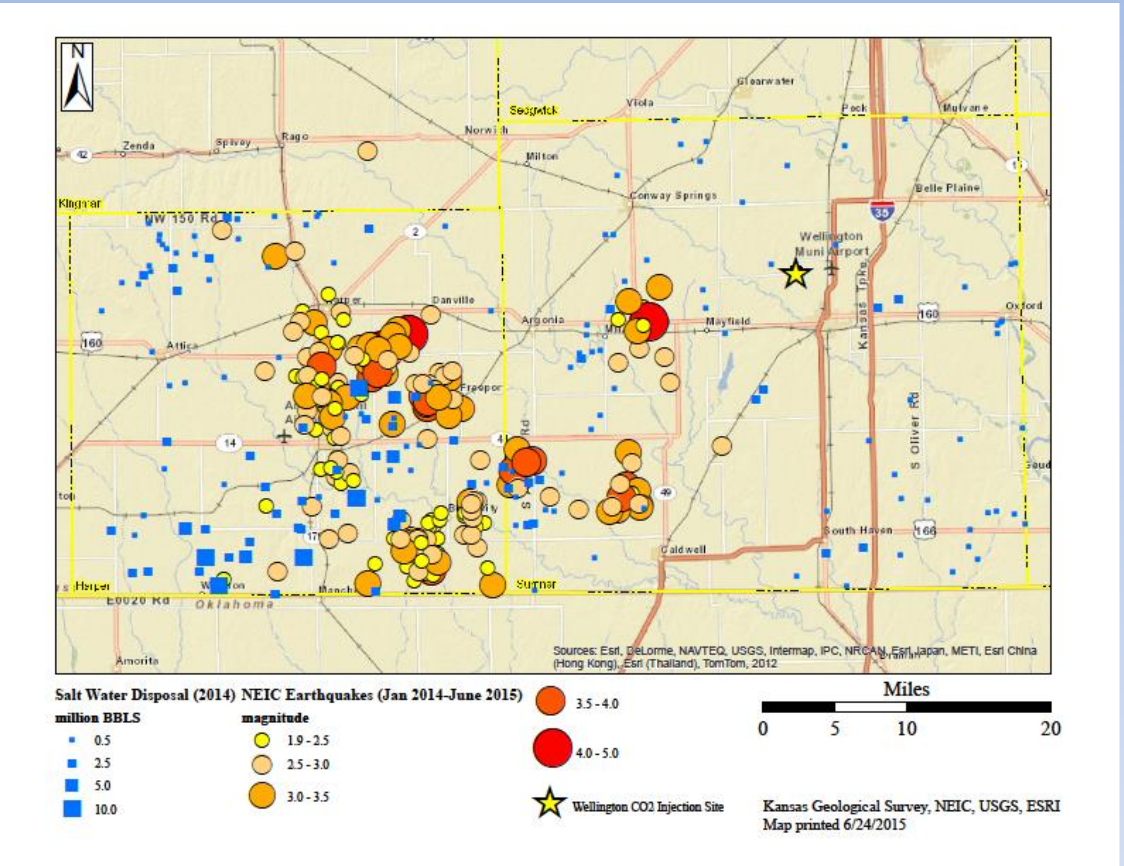
* Filing could take place before Dec. 15 bond payment

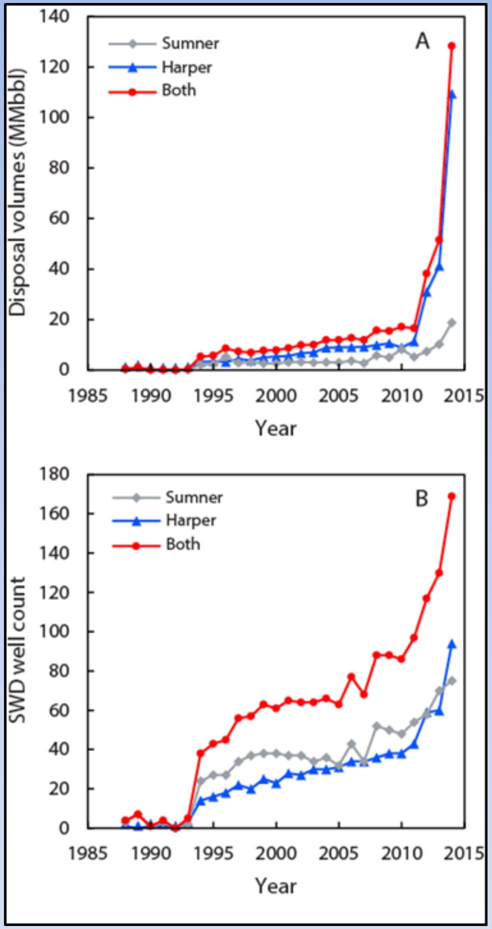
Storage Risk – The Case of Kansas

- **Kansas was assumed to lie in a seismically benign area**



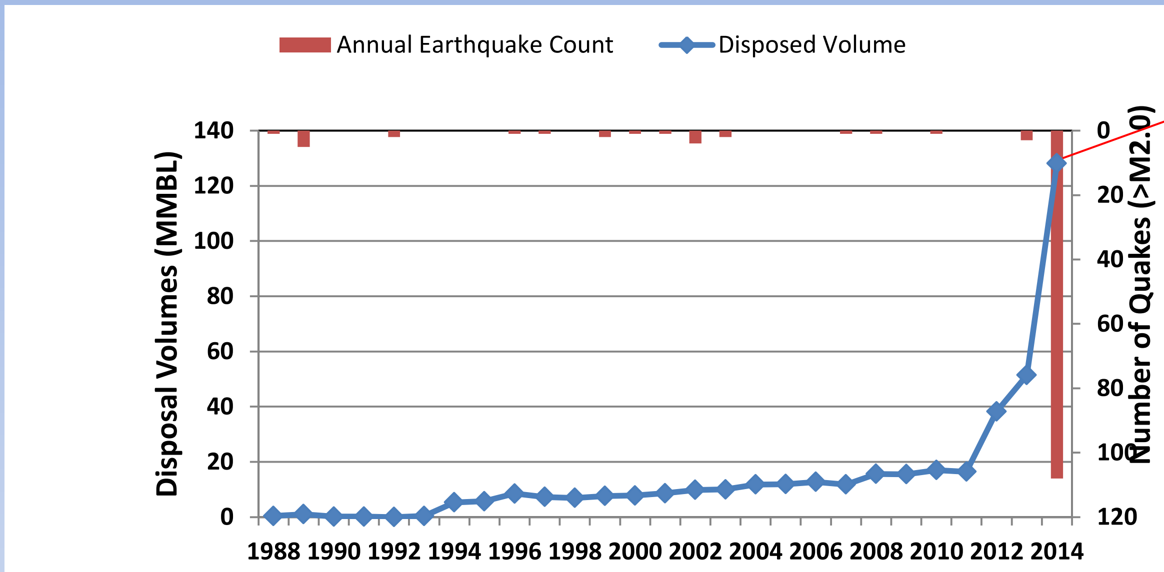
Earthquake Trends in Southern Kansas



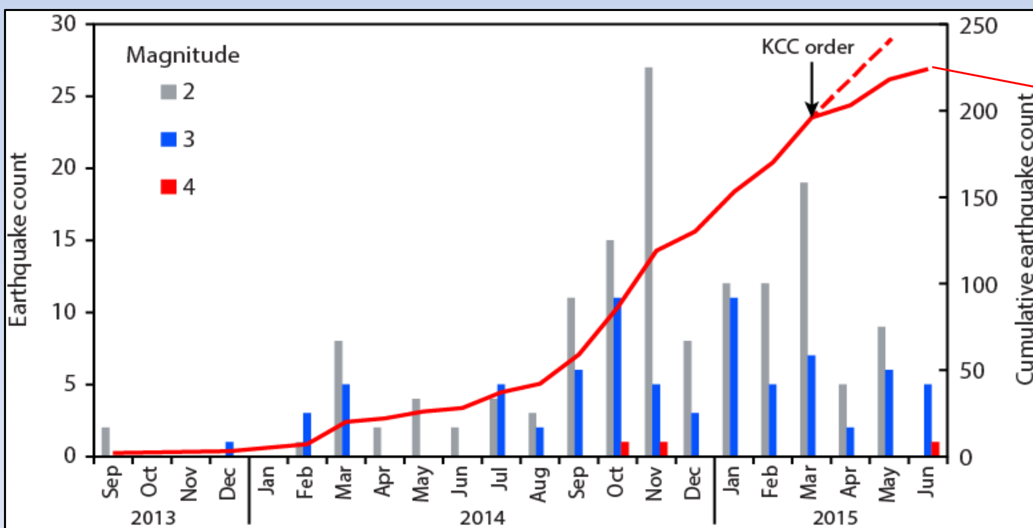


- Large earthquakes (> M3.8) in past year associated with waste water injection in saline aquifer being considered for CO_2 injection
- EPA now requires seismic risk assessment at Class VI injection well sites

Seismic Trends and Implications for CSS

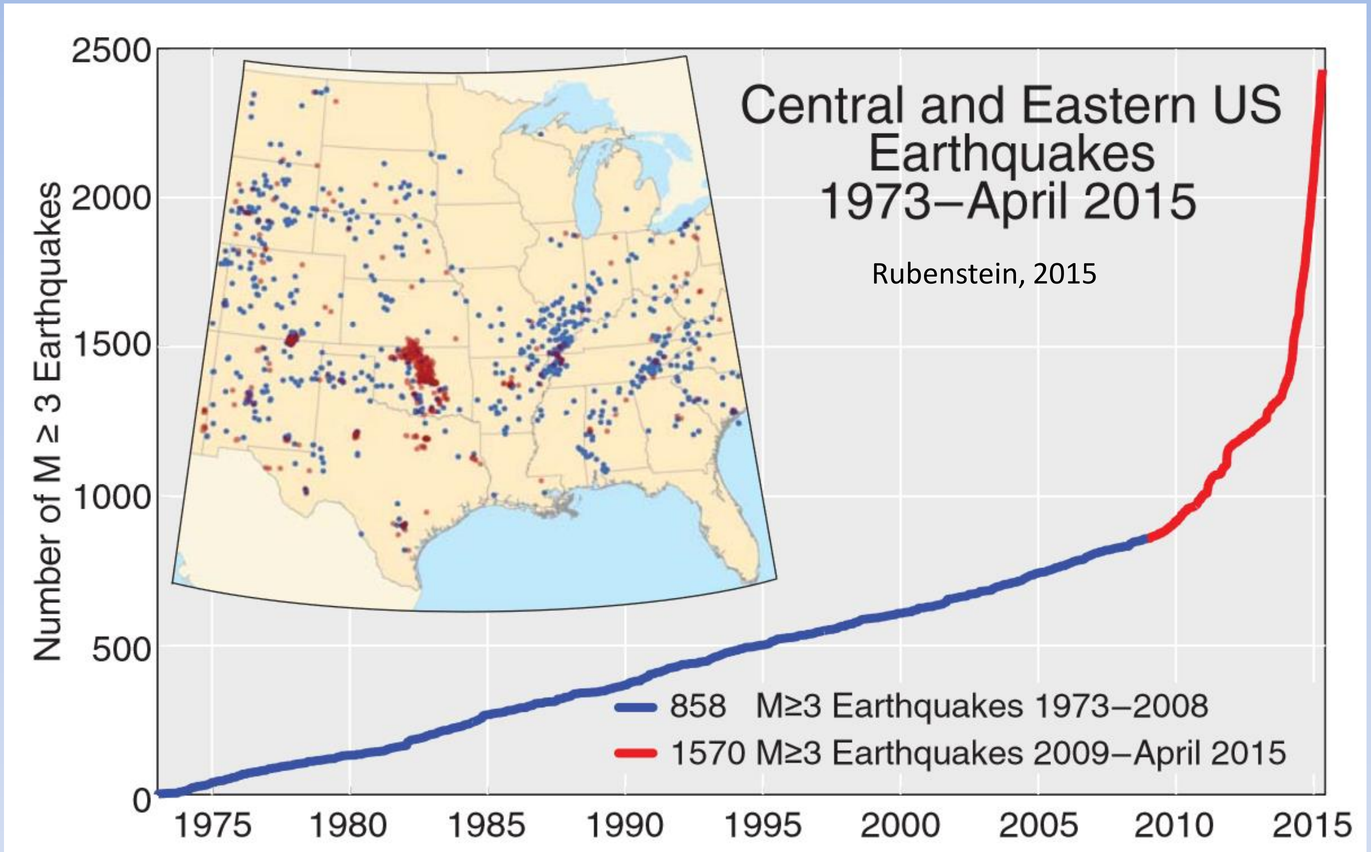


Equivalent to 16 Mtons of CO_2 (~ 8 years of CO2 emissions from a 300 MW electric power plant



- Some abatement in seismicity following restrictions on injection rates and volumes in Kansas

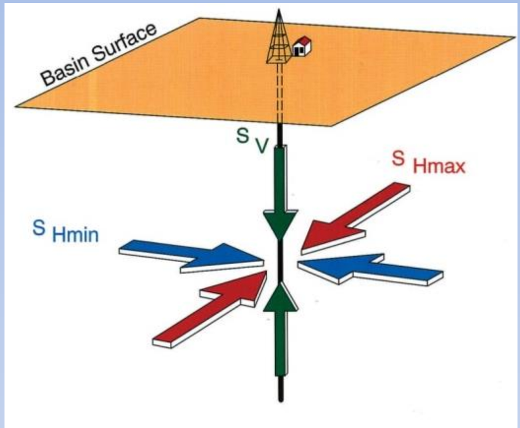
Earthquake Trends in Central and Eastern US



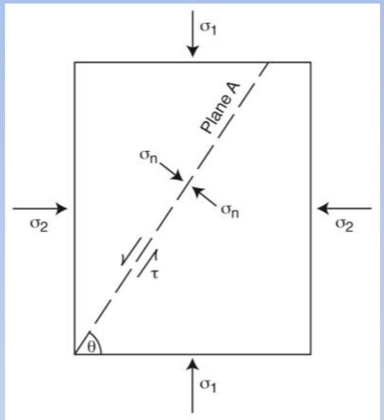
- **Induced seismicity linked to waste disposal in saline aquifers being considered for CO_2 storage**

Induced Seismicity - Physical Mechanisms

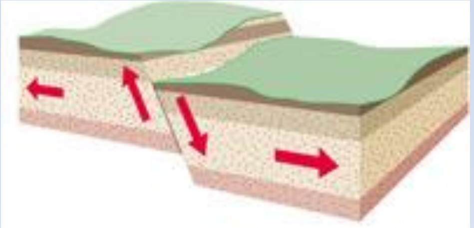
Subsurface Stress Field

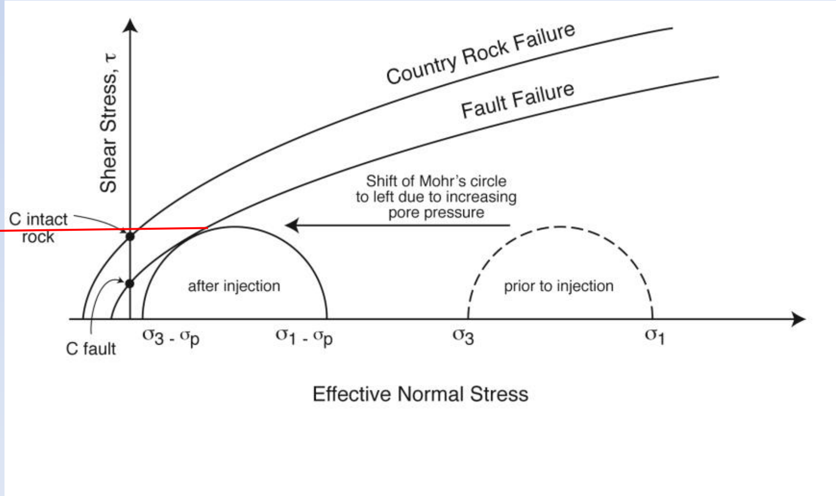


Stresses on Fault Plane



Effect of Injection on Fault Stability

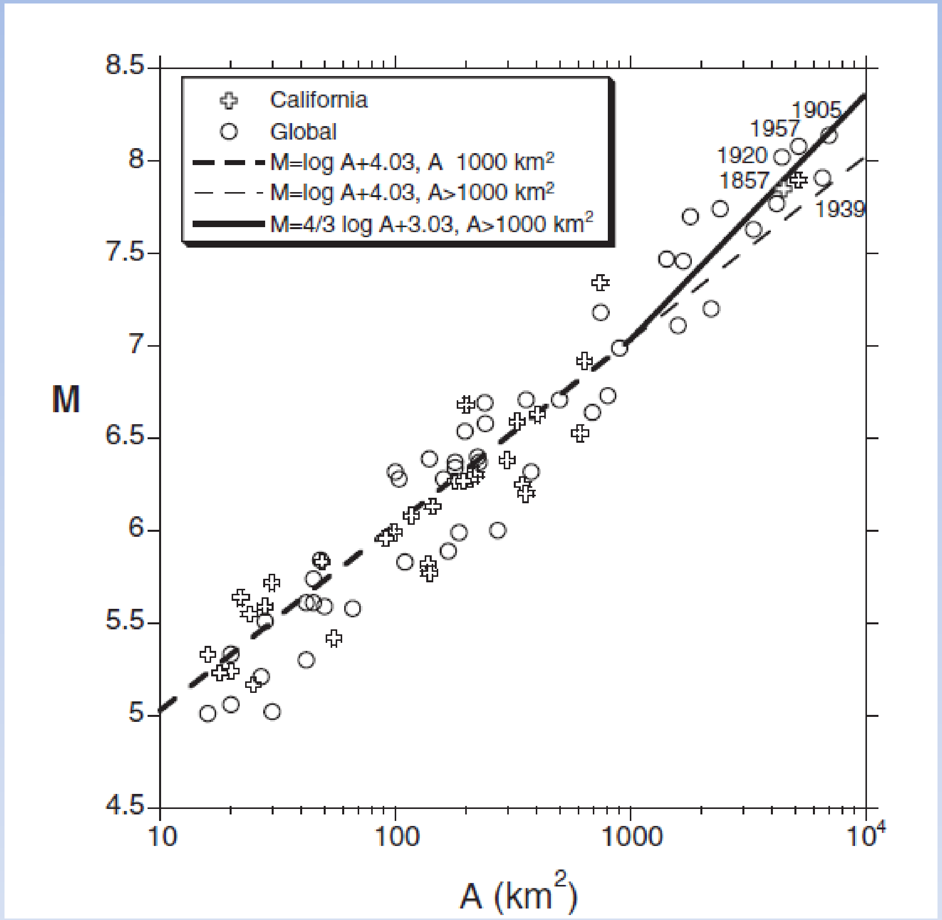


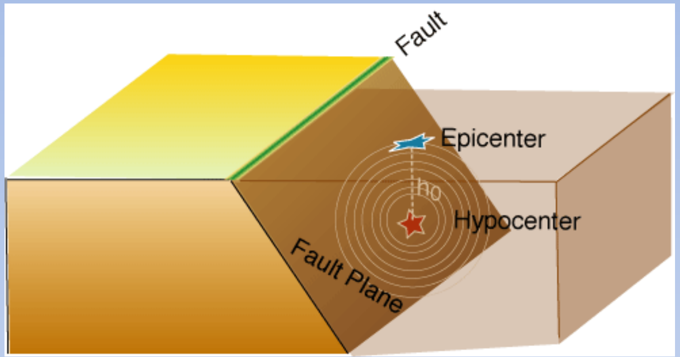


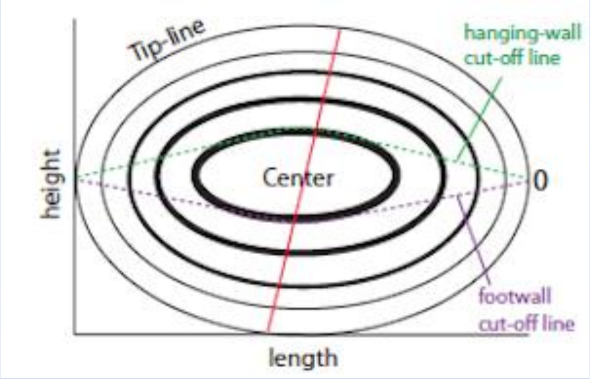
Relationship Between Earthquake Magnitude and Infrastructure Damage

Richter Magnitudes	Description	Earthquake Effects	Frequency of Occurrence
Less than 2.0	Micro	Micro-earthquakes, not felt.	About 8,000 per day
2.0-2.9	Minor	Generally not felt, but recorded.	About 1,000 per day
3.0-3.9	Minor	Often felt, but rarely causes damage.	49,000 per year (est.)
4.0-4.9	Light	Noticeable shaking of indoor items, rattling noises. Significant damage unlikely.	6,200 per year (est.)
5.0-5.9	Moderate	Can cause major damage to poorly constructed buildings over small regions. At most slight damage to well-designed buildings.	800 per year
6.0-6.9	Strong	Can be destructive in areas up to about 160 kilometres (100 mi) across in populated areas.	120 per year
7.0-7.9	Major	Can cause serious damage over larger areas.	18 per year
8.0-8.9	Great	Can cause serious damage in areas several hundred miles across.	1 per year
9.0-9.9	Great	Devastating in areas several thousand miles across.	1 per 20 years
10.0+	Epic	Never recorded; see below for equivalent seismic energy yield.	Extremely rare (Unknown)

Relationship Between Fault Plane Area and Earthquake Magnitude



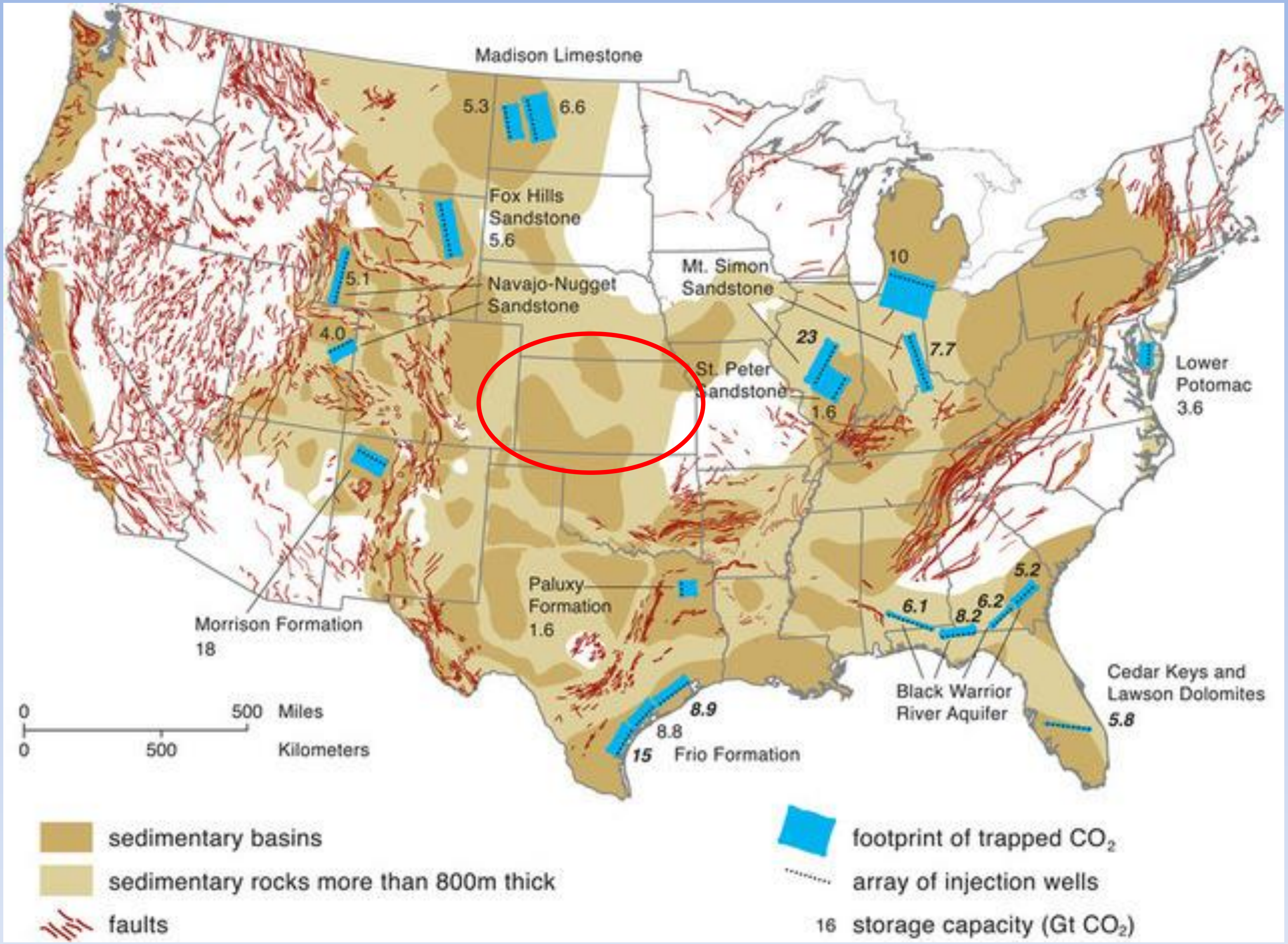




Faults are approximately as long as deep

- **Faults less than 3.5 km (2.3 mi) long are not likely to cause severe damage even if they slip. Need to map large faults.**

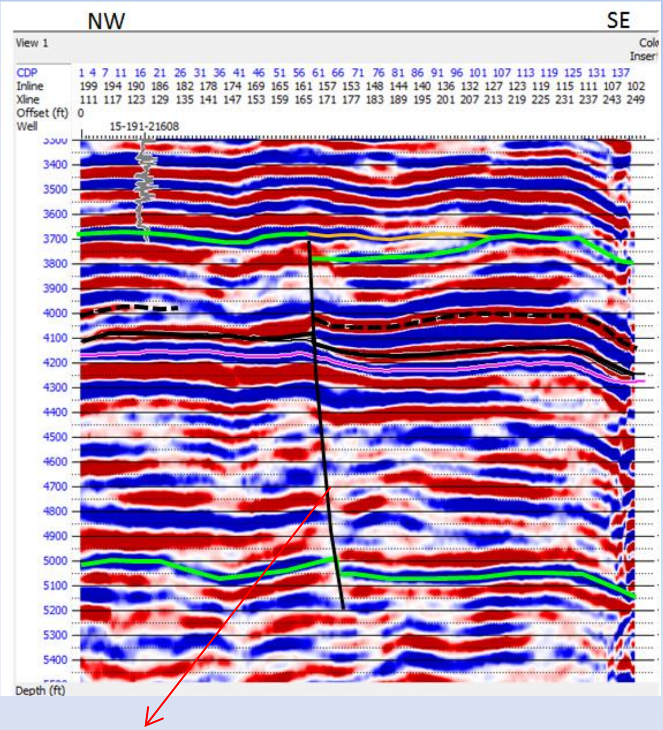
Inadequate Fault Mapping

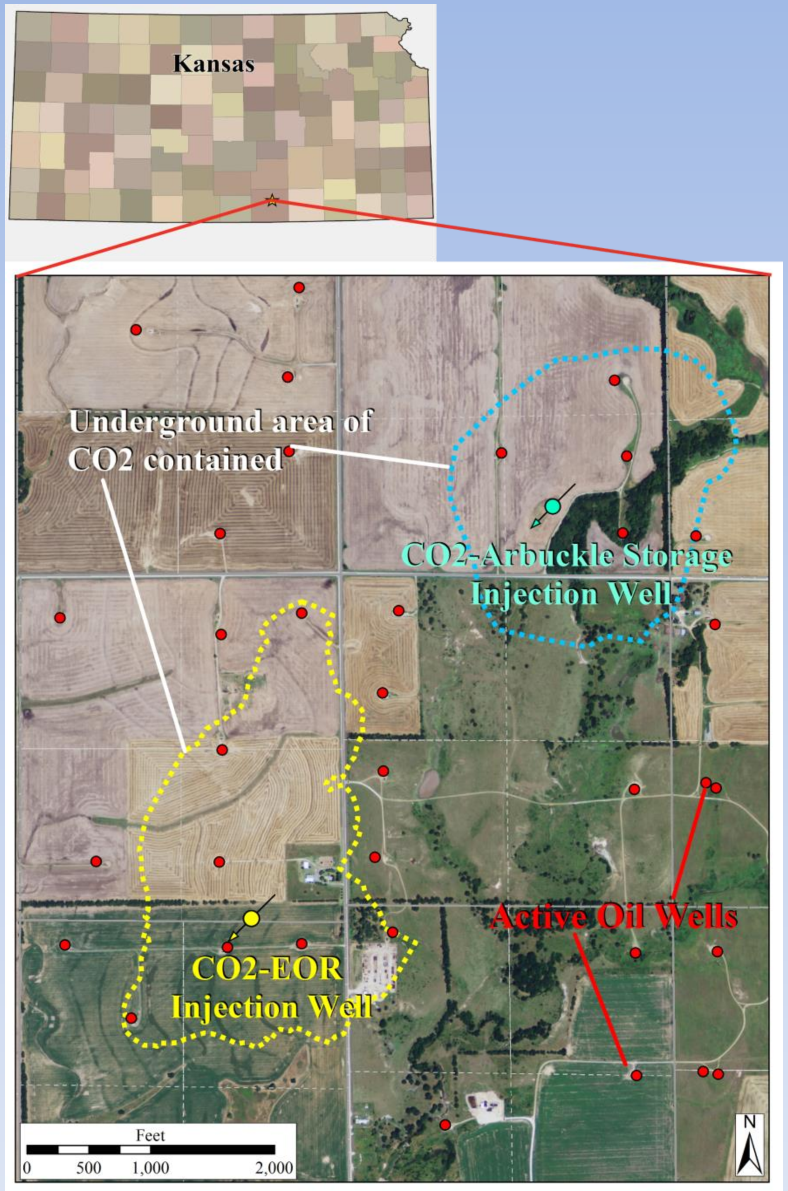


- **Faults in naturally dormant areas not adequately mapped.**

Wellington CO_2 Sequestration and EOR Site

- Approximately 26,000 tons to be injected in the Arbuckle aquifer for CO_2 sequestration and 26,000 tons in the overlying Mississippian reservoir for EOR.





- Extensive data acquisition required to identify faults and assess seismic risk

Regulatory Issues

- **US EPA Class VI permit required to inject:**
  - **Goals**

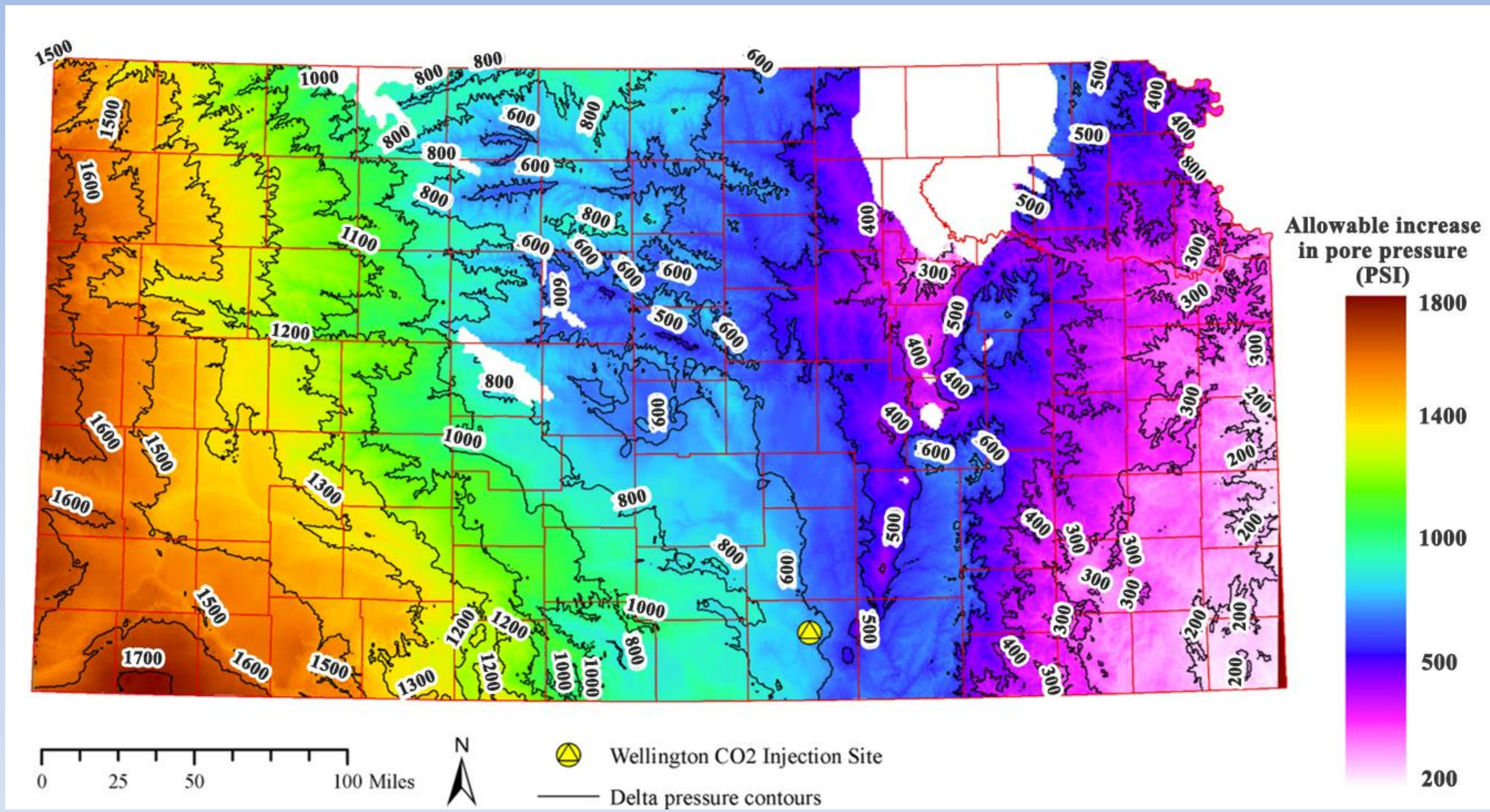
    a) prevent CO_2 migration into Underground Sources of Drinking Water (USDW) – TDS > 10,000 ppm (substantially higher than drinking water limit of 500 ppm)

    b) protect caprock Integrity

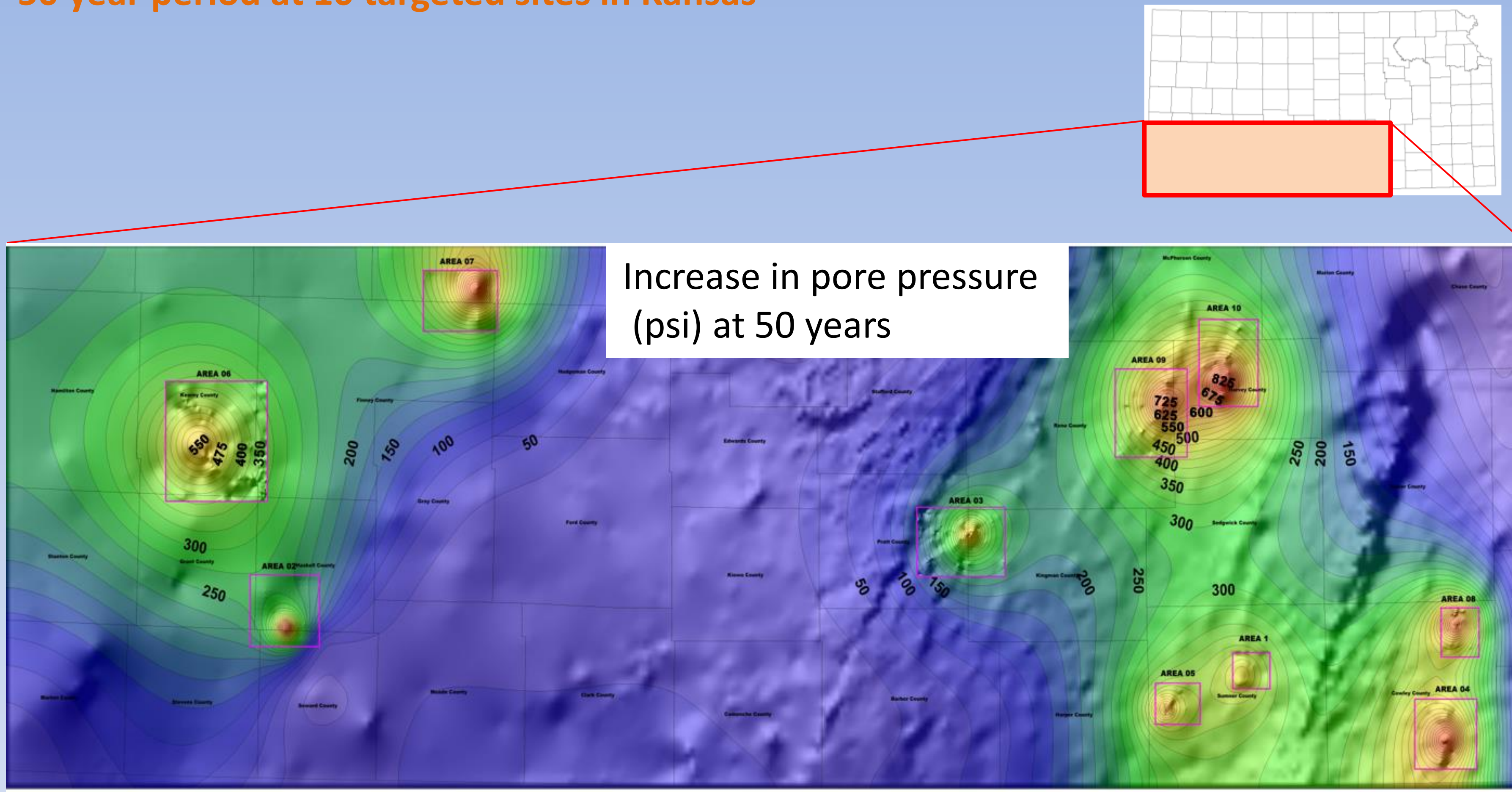
    c) prevent earthquakes

  - **Expensive multi-year process requiring deep drilling, testing, and analysis to characterize the formation and perform corrective action on wells within the EPA Area of Review (AoR)**
  - **50 years post-injection monitoring period**
  - **Between $8 -$70 million financial assurance (bond/insurance, @ 5% cost could be as high as $3.5 million annually)**
  - **Guidelines required for defining aquifer – 2 GPD/day yield threshold for well quite restrictive**
  - **Fracture gradient restriction fairly stringent**

Maximum Allowable (Fracture-Based) Increase in Pore Pressure (psi)



Simulated increase in pore pressures due to injection of 12 million tons/year of CO_2 over a 50 year period at 10 targeted sites in Kansas

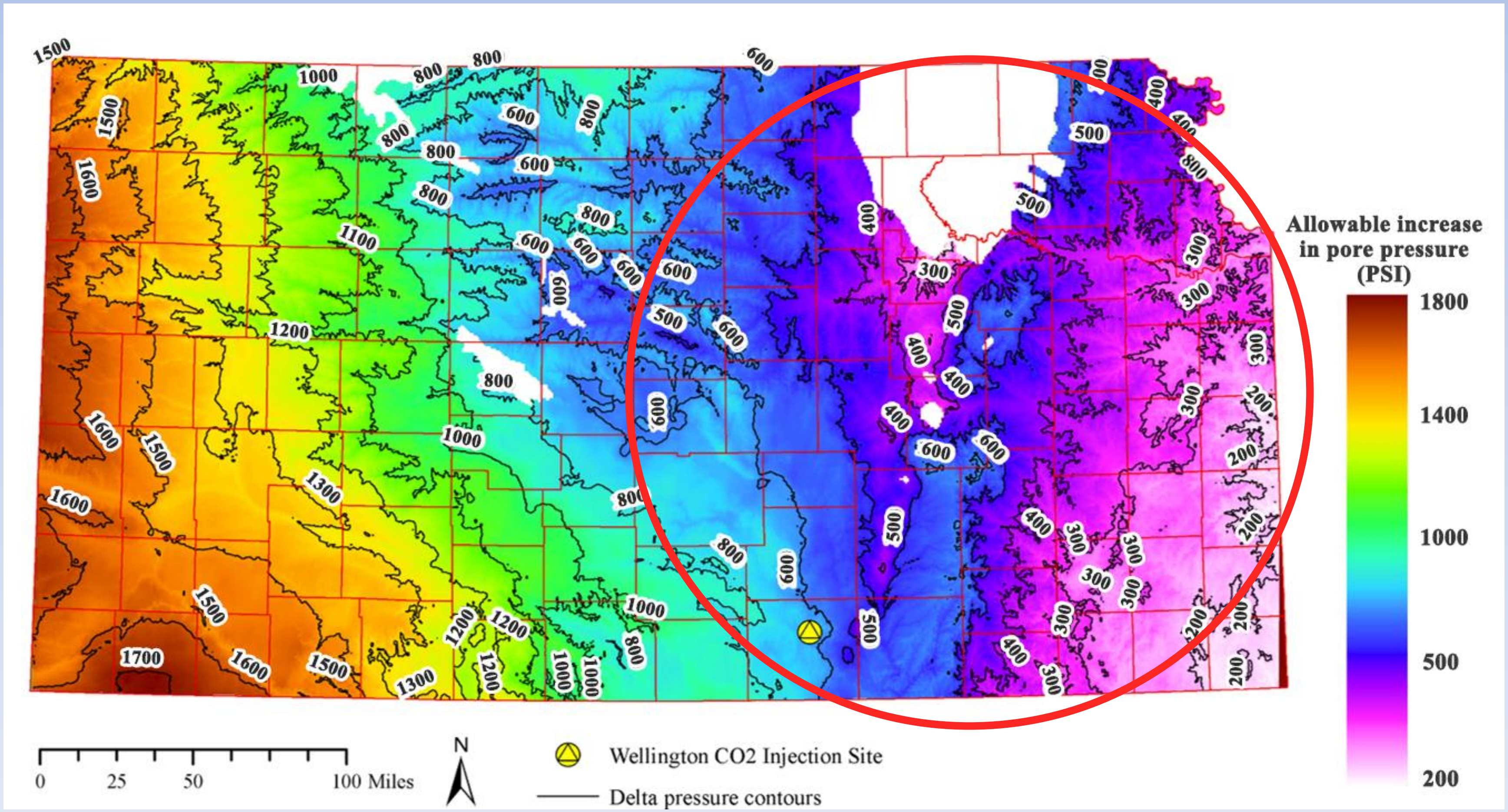


Williams, Gerlach, Fazelalavi, Doveton, et al., 2014

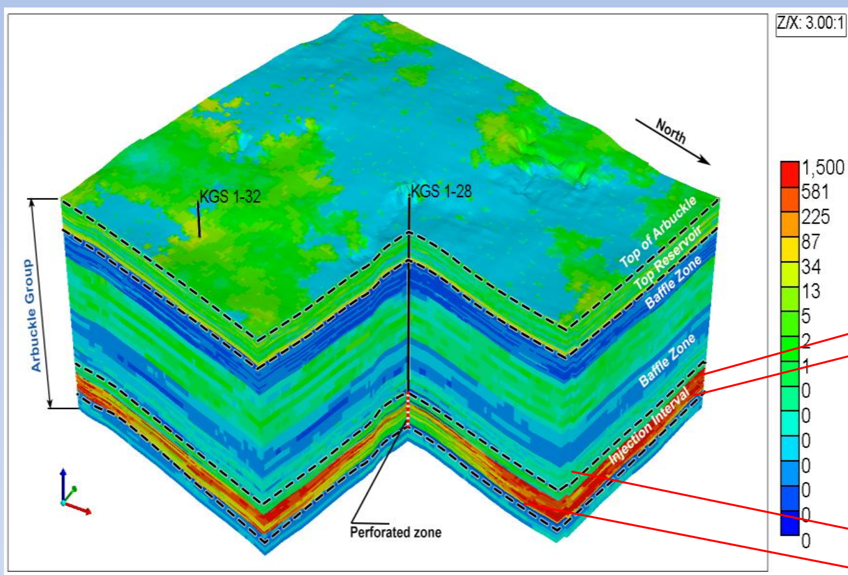
- **Pressures greater than 700 psi can occur in the injection zone**

Maximum Allowable Fracture-Based Increase in Pore Pressure

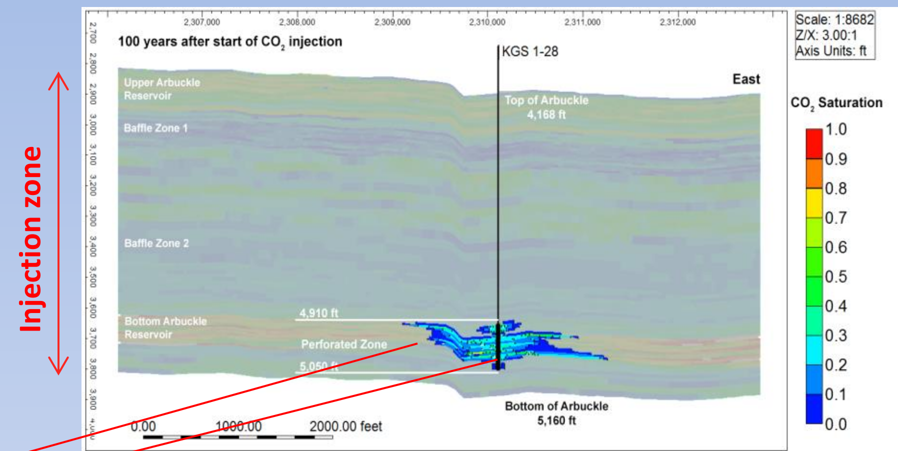
- May not be feasible to inject in large areas due to fracture gradient requirement even in the presence of tight caprock and confining layers within the injection zone



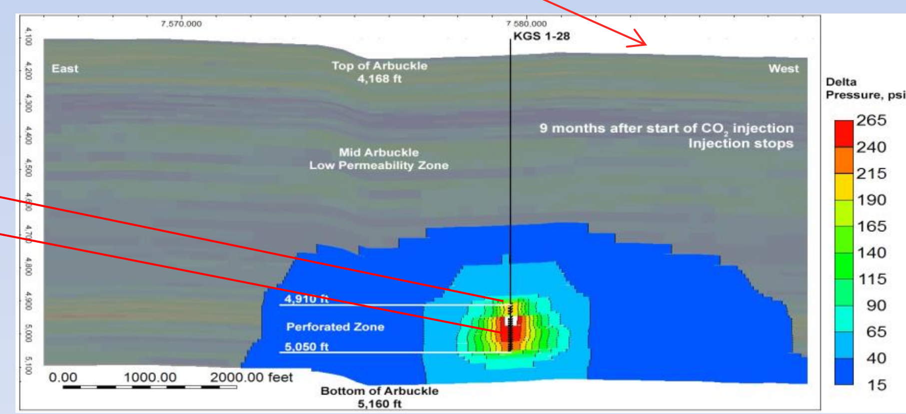
Effect of Stratification on Plume Migration and Pressure Distribution At Wellington CO2 Storage Site



Holubnyack, Rush, Fazelalavi (KGS)

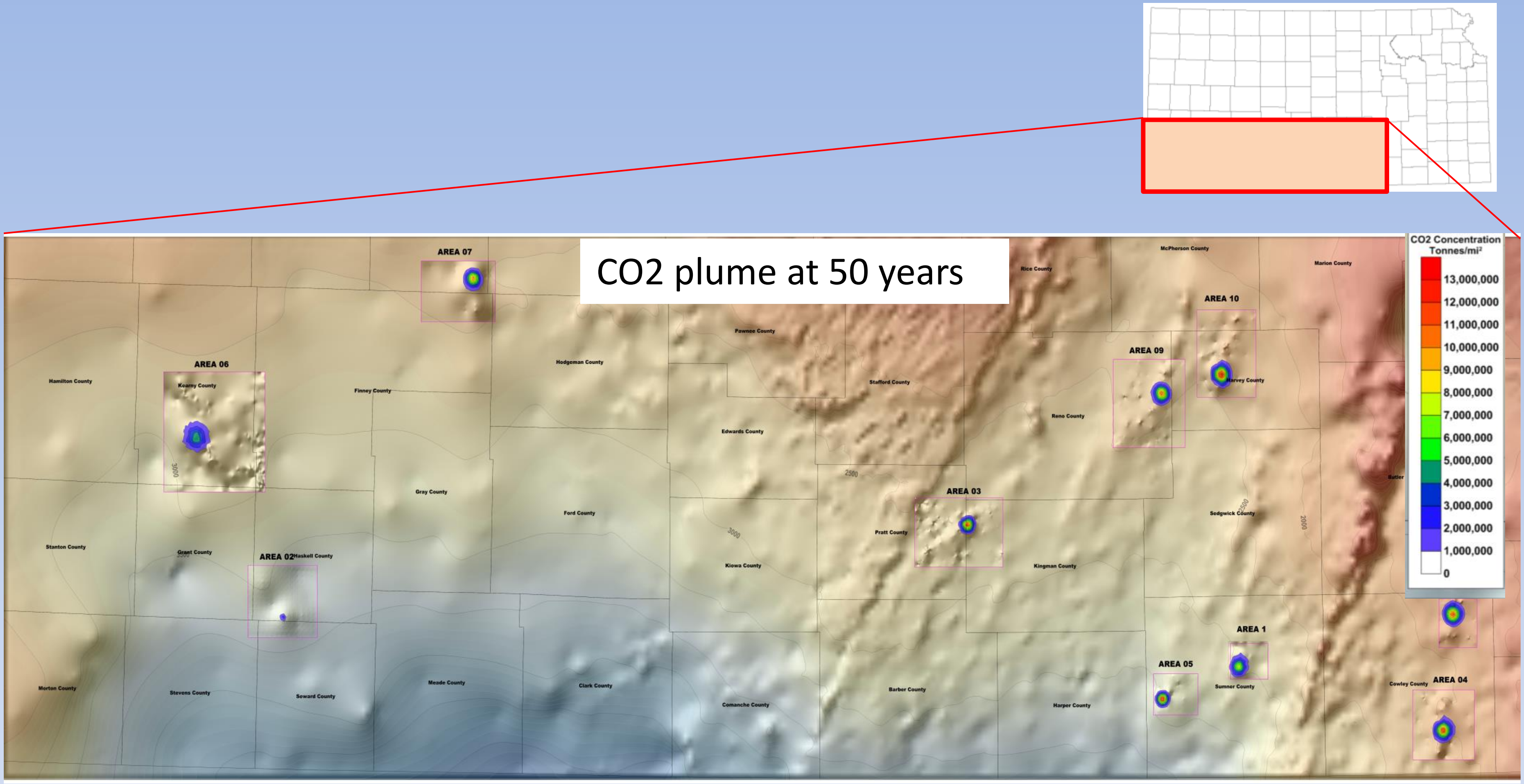


Entry pressure in caprock is 955 psi



- CO_2 to remain deep in the injection zone. Negligible pressure increase at base of caprock

Simulated Sequestered Volumes of CO_2 in Kansas



- Total sequestered volume over 50 year period ~ 0.65 GT (almost a decade of CO2 emissions in Kansas).

Other Outstanding Issues Hindering CSS Adoption

- Lack of formal national/global carbon emissions policy
- Creation of an industry-financed trust fund
- Adoption of substantive or procedural limitations on claims
- Laws and regulations regarding ownership of pore space and long-term stewardship
- Standards to account for cross-border movement of stored CO_2
- Negative public perception