Potential for Enhanced Methane Production from Coal, with Concomitant CO_2 Sequestration – Examples from a High-Rank Coal (Pottsville Formation, Black Warrior Basin) and a Low-Rank Coal (Wilcox Group, Texas Gulf Coast Basin)*

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Abstract

Point sources emissions from industrial and power plants are primary sources of CO_2, a major greenhouse gas. Capture and injection of this CO_2 into unminable coals may be a viable method of reducing CO_2 emissions, while simultaneously enhancing methane recovery from coal. To assess feasibility of CO_2 sequestration and enhanced coalbed methane (ECBM) recovery, we evaluated Pottsville bituminous coal (technically feasibile only) and Wilcox subbituminous coal (both technically and economically viable).

For the Pottsville, we simulated ECBM recovery and CO_2 storage, using a 3-layer reservoir model of Pottsville coal zones in Blue Creek Field. Factors investigated included: volumes of methane recovered and CO_2 sequestered; CO_2 injection rates; injection pressures; well spacing; advance coal dewatering; soak benefits; injected gas composition; and single vs. multiple zone injection.

Injection of pure CO_2 resulted in methane recovery two times greater than injection of flue gas (90% N_2 - 10% CO_2). Dewatering prior to CO_2 injection delayed breakthrough time and allowed higher injection rates but did not significantly affect the CO_2 volume stored. Soak time did not significantly impact CO_2 storage. If 100% CO_2 is injected in an 80-acre, 5-spot well pattern, completed in only the major coal zone, 0.20 Bcf of ECBM would be produced and 0.57 Bcf of CO_2 would be stored.

For the Wilcox, we used a reservoir simulator to assess well spacing, injectant fluid composition, injection rate, and dewatering on ECBM recovery and CO_2 sequestration. Probabilistic simulation of 100% CO_2 injection in an 80-ac, 5-spot pattern indicates that Wilcox coals can produce 0.48-0.85 Bcf ECBM and store 1.27-2.25 Bcf CO_2. Results of flue-gas (87% N_2 - 13% CO_2) injection indicate that Wilcox coals can store 0.34-0.59 Bcf CO_2 with ECBM recovery of 0.68-1.20 Bcf. Economic modeling of CO_2 storage and ECBM recovery for 100% CO_2 injection indicates negative economic results for the conditions investigated, using natural gas prices of \$2 to \$12/Mscf and CO_2 credits of \$0.05 to \$1.58/Mscf CO_2 (\$1.00 to \$30.00/ton CO_2). Injection of flue gas results in better economic performance than injection of 100% CO_2.

These study results suggest that CO_2 storage with concomitant ECBM production may be technically feasible in both high- and low-rank coals. Economic modeling of the Texas low-rank coals indicates that moderate increases in either gas price or carbon credits could generate attractive economic conditions.

References

Ayers, W.B. Jr., and A.H. Lewis, 1985, The Wilcox Group and Carrizo Sand (Paleogene) in east-central Texas; depositional systems and deep-basin lignite: The University of Texas at Austin, Bureau of Economic Geology, 19 p., plus 30 plates.

Ayers, W.B., Jr., and W.R. Kaiser, 1986, Regional depositional setting, resources, and quality of lignite in the Wilcox Group of East Texas and the Jackson Group of East and South Texas: Environmental and Coal Associates, Houston, Texas, p. 69-114.

Pashin, J.C., R.E. Carroll, R.H. Groshong, Jr., D.E. Raymond, et al., 2004, Geologic screening criteria for sequestration of CO2 in coal – Quantifying potential of the Black Warrior coal-bed methane fairway, Alabama: Final Technical Report, US Department of Energy, National Energy Technology Laboratory, Contract DE-FC26-00NT40927, 254 p.

Potential for Enhanced Methane Production from Coal, with Concomitant CO_2 Sequestration –

Examples from a High-Rank Coal (Pottsville Fm, Black Warrior Basin) and a Low-Rank Coal (Wilcox Gp, Texas Gulf Coast Basin)

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G. Hernandez[2], R. O. Bello[3], and Ting He[4]

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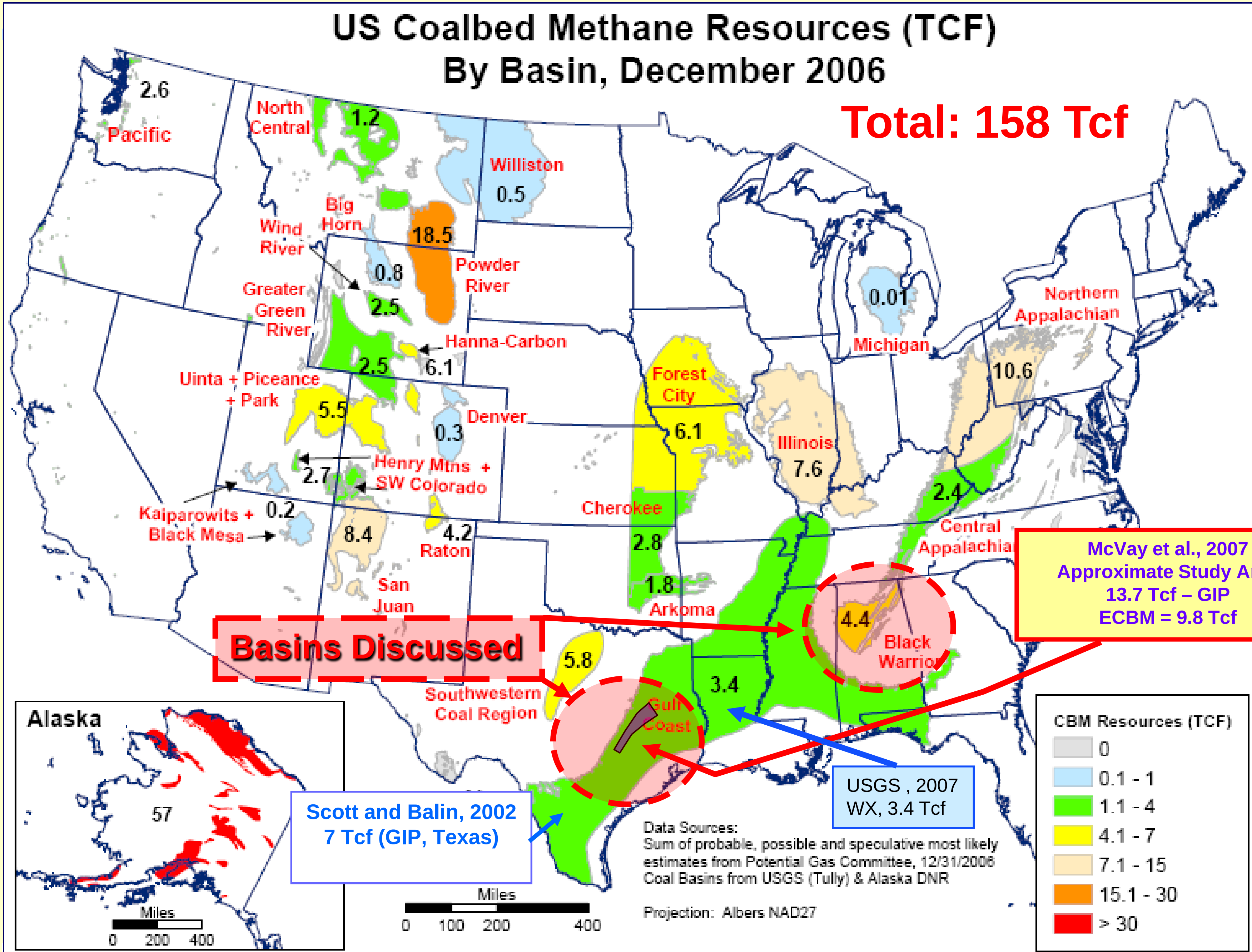
AAPG ANNUAL MEETING

April 12, 2011

<u>OBJECTIVES</u>: Review and contrast potential for CO_2 sequestration in, and enhanced recovery of CH_4 from, coal beds in selected areas of the Black Warrior and Texas Gulf Coast basins.

Outline

- **Pottsville coal, Blue Creek Field, Black Warrior Basin (technical assessment, only)**
- **Wilcox Coal, East-Central Texas (technical and economic assessments)**
- **Contrasts between the Coalbed Gas Systems**
- **Coal beds as Geologic Media for CO_2 Sequestration**



www.eia.doe.gov; November 2007

Potential for CO_2 Sequestration and Enhanced Coalbed Methane Production, Blue Creek Field, Black Warrior Basin

- **Statement of Problem:**

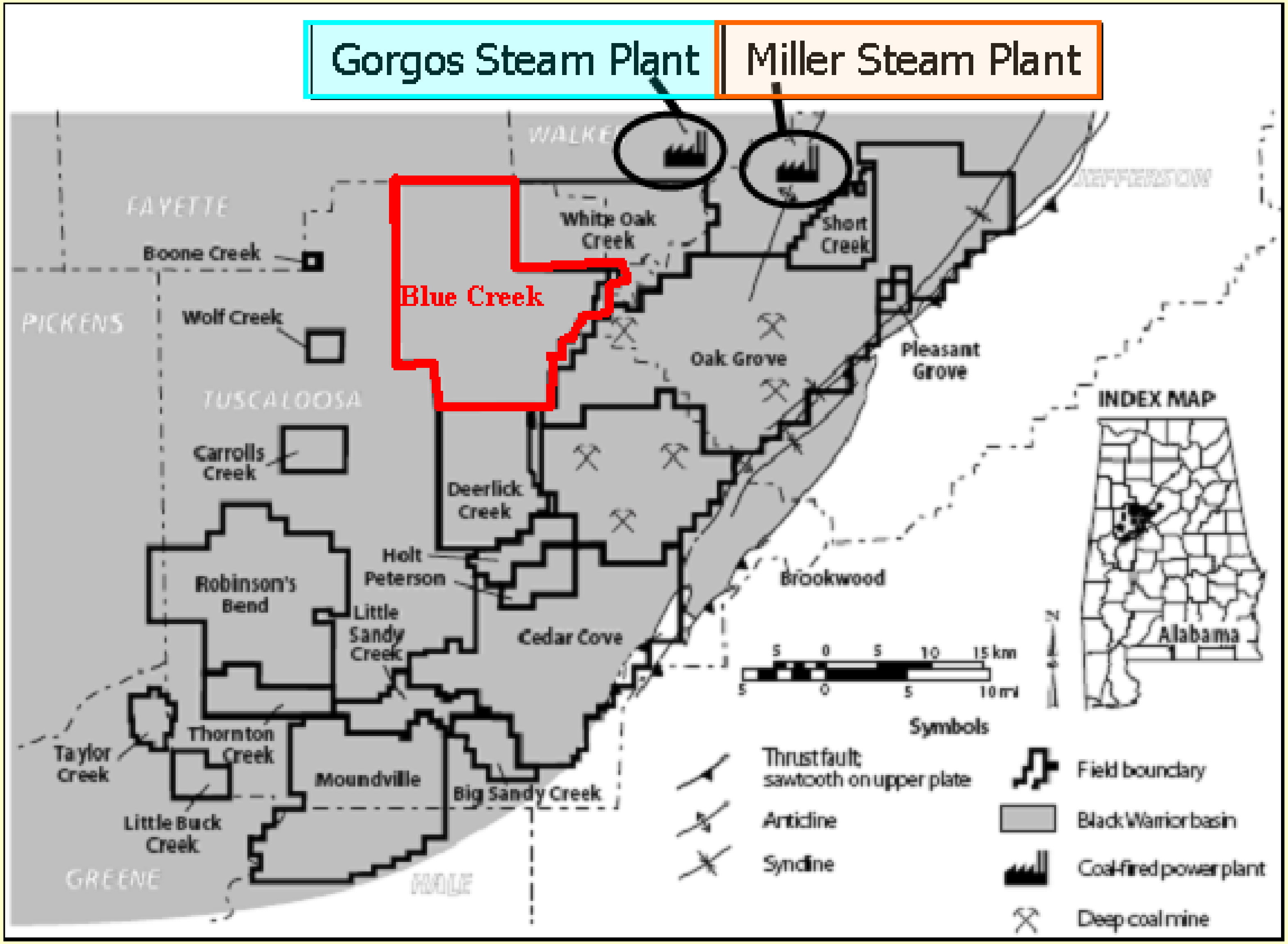
Alabama CO_2 emissions are 31 MMton/yr (9th in Nation)

Electricity generating plants, point-source emitters of CO_2, are located close deep coal deposits

These coals could be used to sequester CO_2; a benefit could be enhanced Coalbed methane production

Objective:
Determine the potential for CO_2 sequestration and ECBM Production in Blue Creek field

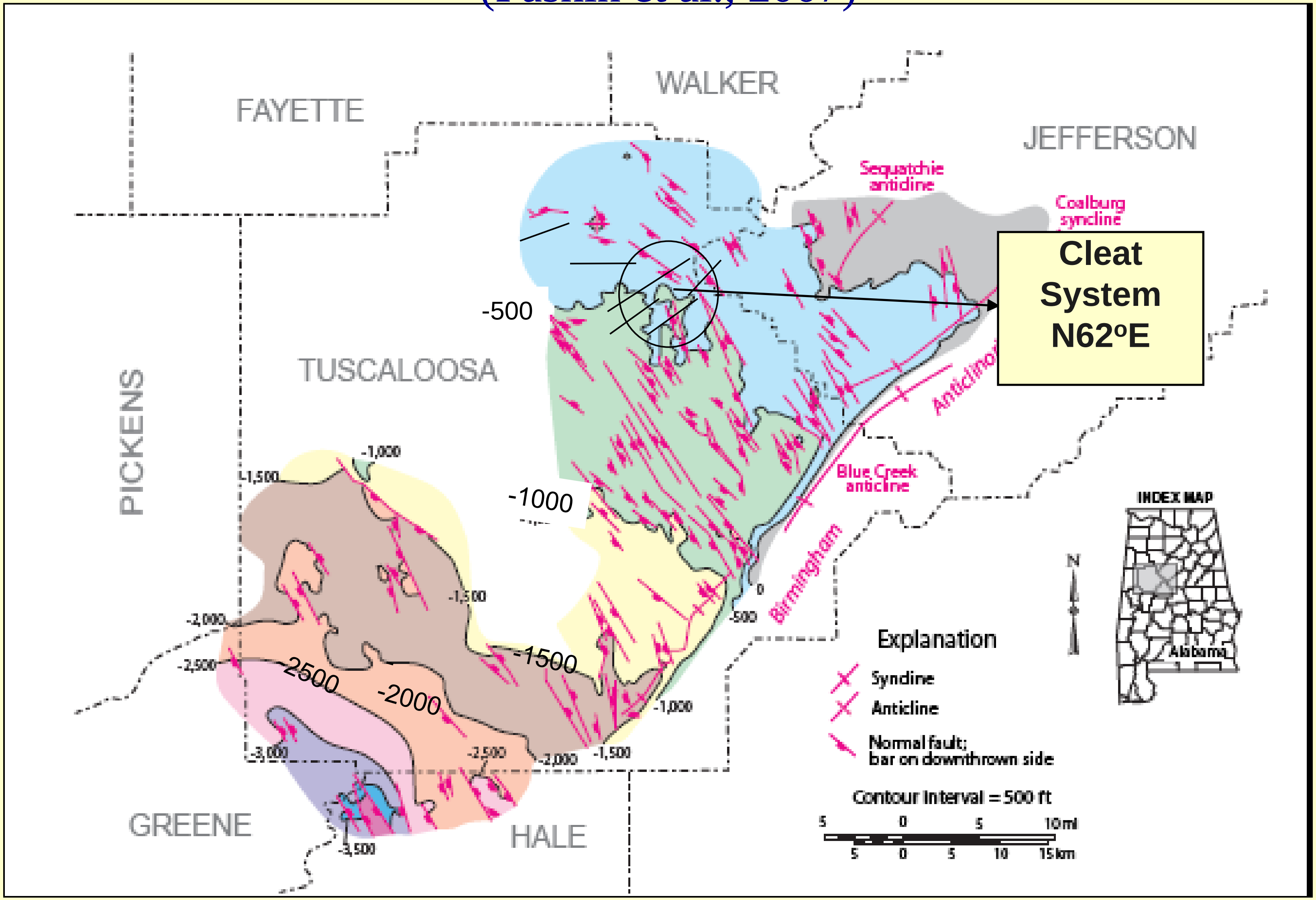
CBM Fields in Black Warrior Basin



Modified from Pashin et al., 2004

Structure, Top of Pottsville Fm

(Pashin et al., 2007)



Pottsville Stratigraphy and Coalbed Gas Content

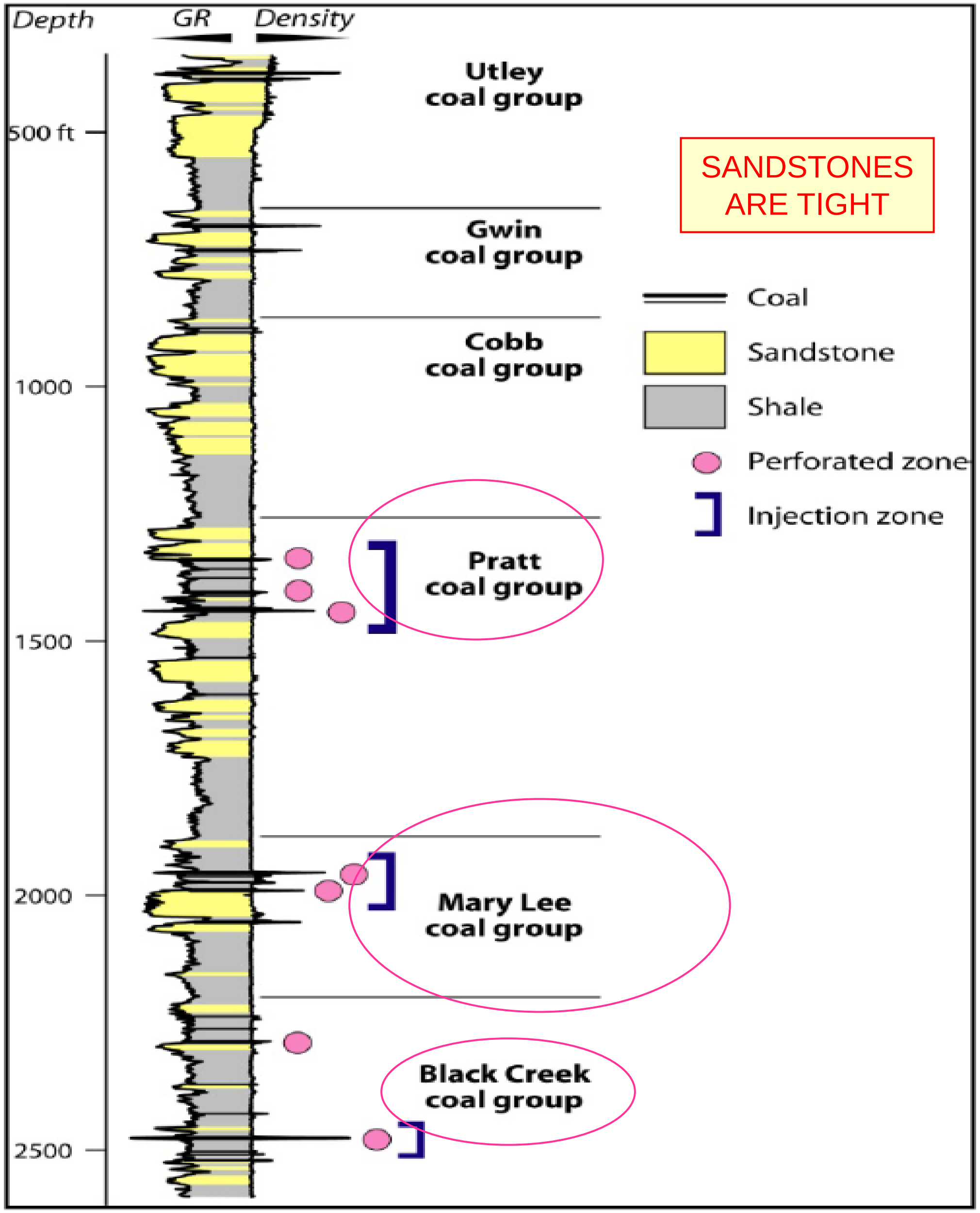
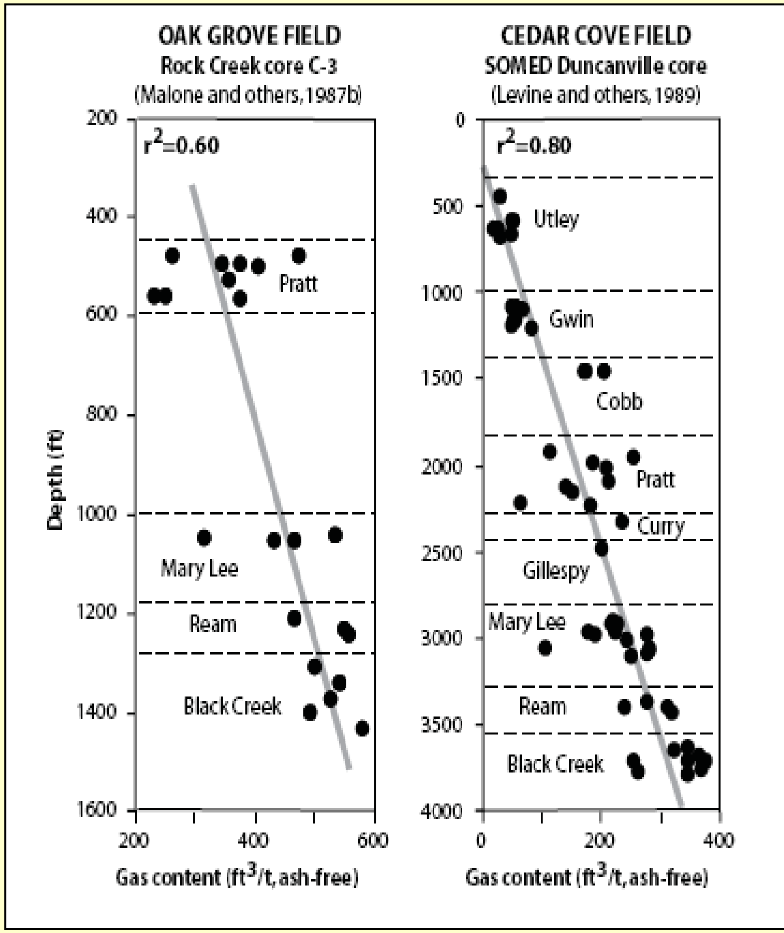


Figure 2. Well log showing stratigraphic section and injection zones in the test area



From Pashin, 2004

Thermal Maturity (Pashin 2004)

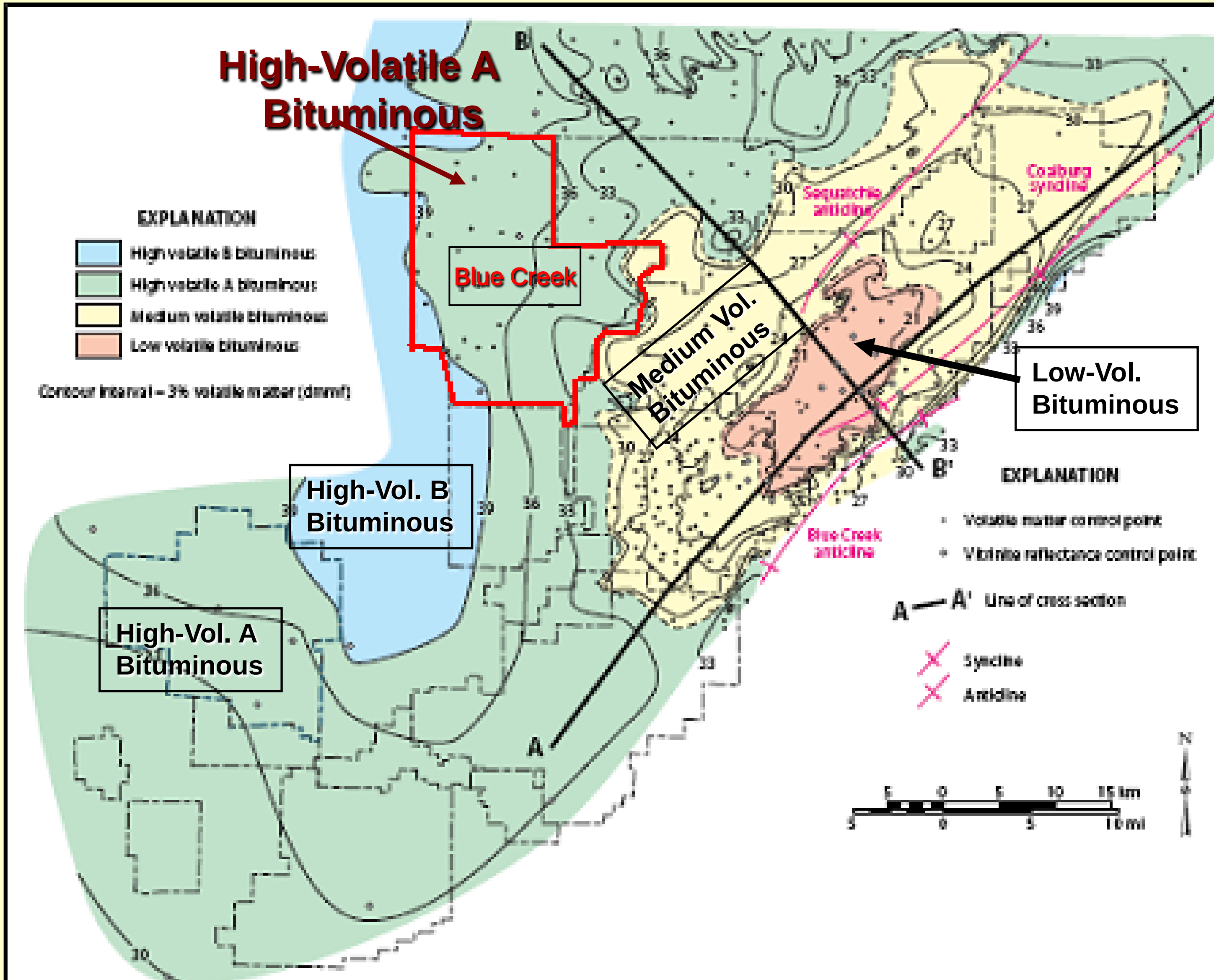
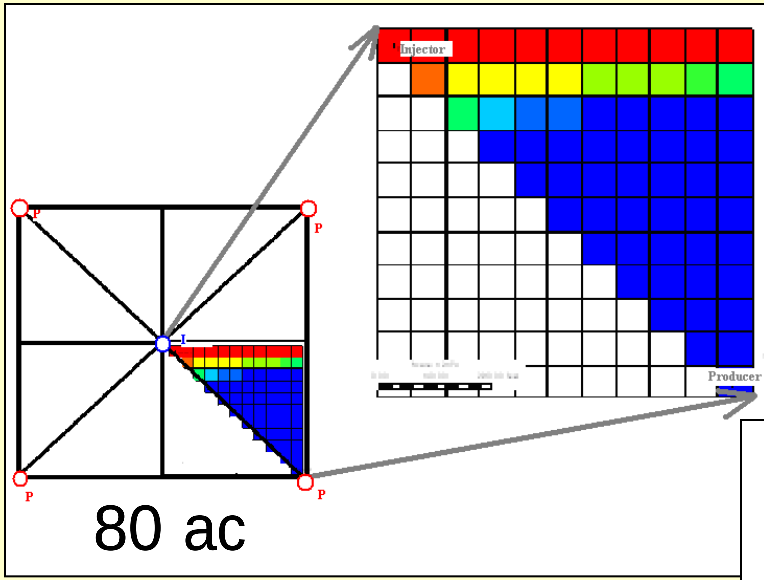


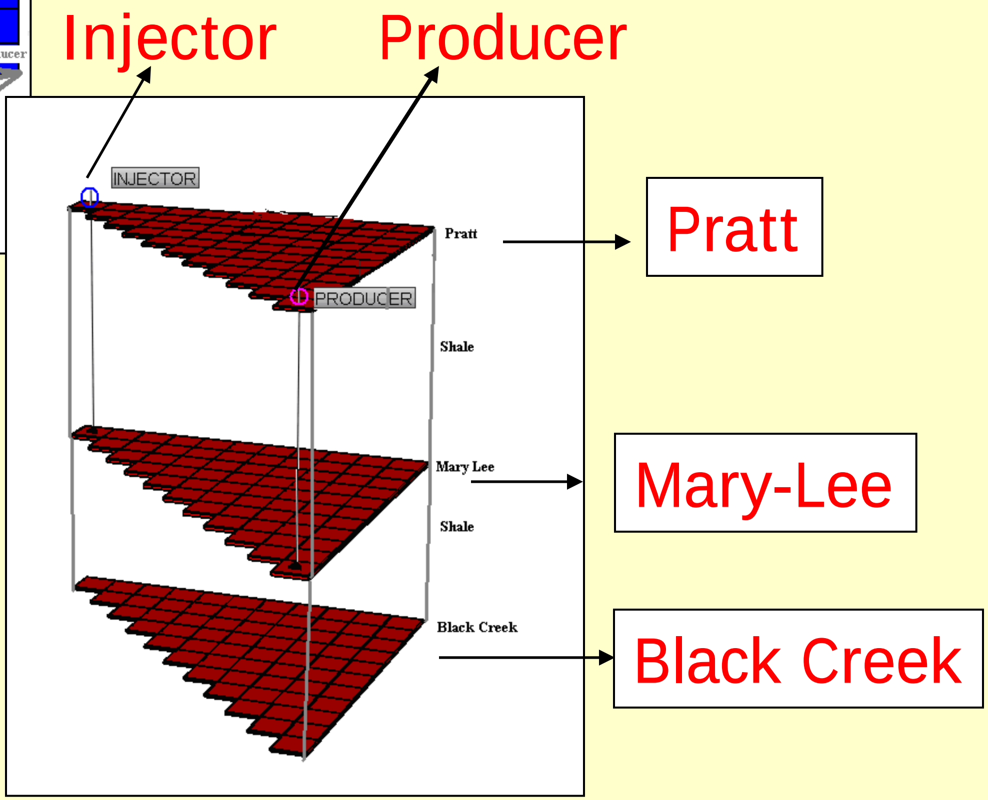
Figure 51.–Coal rank in the Black Warrior coalbed methane fairway based on volatile matter and vitrinite reflectance data from the Mary Lee coal zone.

Reservoir Grid Model



11*11*5

Five-Spot Well Pattern



Modeling Approach

- Dual porosity system
- Darcy flow of gas and water in the natural fracture system
- Pure gas diffusion and adsorption in the primary porosity system
- Coal shrinkage due to methane desorption and swelling due to CO_2 sorption on coal
- Mixed gas adsorption
- Mixed gas diffusion

Parameters in Model

Property	Coal Group		
	Pratt	Mary Lee	Black Creek
Depth (ft)	1,000	1,600	2,020
Thickness (ft)	6	8	4
Pressure (psi)	300	510	620
Temperature (^{o}F)	88.2	93.6	96.48
Cleat Spacing (inches)	0.55	0.98	0.28
Permeability (md)	100	10	1

Personal communication J. Pashin, 2009

Simulation Cases

- Base Case
- Effects of Injection and Production Rate
- Effects of Injection Gas Composition
- Effects of Coal Dewatering Prior to CO2 Injection
- Effects of Permeability Anisotropy
- Effects of Time to Soak
- Multi-Layer Completion
- Effects of Injector and Producer Well BHP Constraints

Constraints of Base Case	Value
Maximum Pressure at the Injector (psi)	1,500
Minimum Pressure at the Producer (psi)	50
Maximum Injector Rate (scf/D)	70,500
Maximum Producer Rate (scf/D)	35,250
Injected Gas Composition	100% CO_2
Percentage of CO_2 in the Producer when Breakthrough	5%

Results – Evaluation of Total Blue Creek Field

Estimated ECBM Production

Recoverable CBM Resources				
Coal Zones	Pratt	Mary Lee	Black Creek	Total
Coal Thickness, ft	6	8	4	18
Coal Density, ton/ac-ft	1,875.5	1,875.5	1,875.5	
Gas Content, scf/ton	198.18	251.1	270.7	
Pattern Area, ac	80	80	80	
GIP (per 80 ac), Bcf	0.179	0.301	0.162	0.642
Recoverable Resources (per 80 ac), Bcf	0.112	0.2	0.112	0.442
Recovery factor, fraction	0.62	0.66	0.691	0.688
Region Area, ac	**55,973**			
Number of 80-ac 5 spot patterns	**700**			
Potential CH_4 Recoverable (Blue Creek field)	**309 Bcf**			

Results – Evaluation of Total Blue Creek Field

Estimated CO_2 Sequestered

Potential Coalbed Sequestration of CO_2				
Coal Zones	Pratt	Mary Lee	Black Creek	Total
Coal Thickness (ft)	6	8	4	18
Coal Density, ton/ac-ft	1,875.5	1,875.5	1,875.5	
Gas Content, scf/ton	512.5	600.2	625.3	
Pattern Area, ac	80	80	80	
Theoretical Sequestration Capacity (per 80 ac), Bcf	0.461	0.72	0.375	1.56
Sequestered CO_2 Volume (per 80 ac), Bcf	0.398	0.577	0.298	1.27
Recovery factor, fraction	0.86	0.8	0.79	0.81
Region Area, ac	55,973			
Number of 80-ac 5 spot patterns	700			
Potential CO_2 Sequestered (Blue Creek field)	889 Bcf			

OBJECTIVES: Review and contrast potential for CO_2 sequestration in, and enhanced recovery of CH_4 from, coal beds in selected areas of the Black Warrior and Texas Gulf Coast basins.

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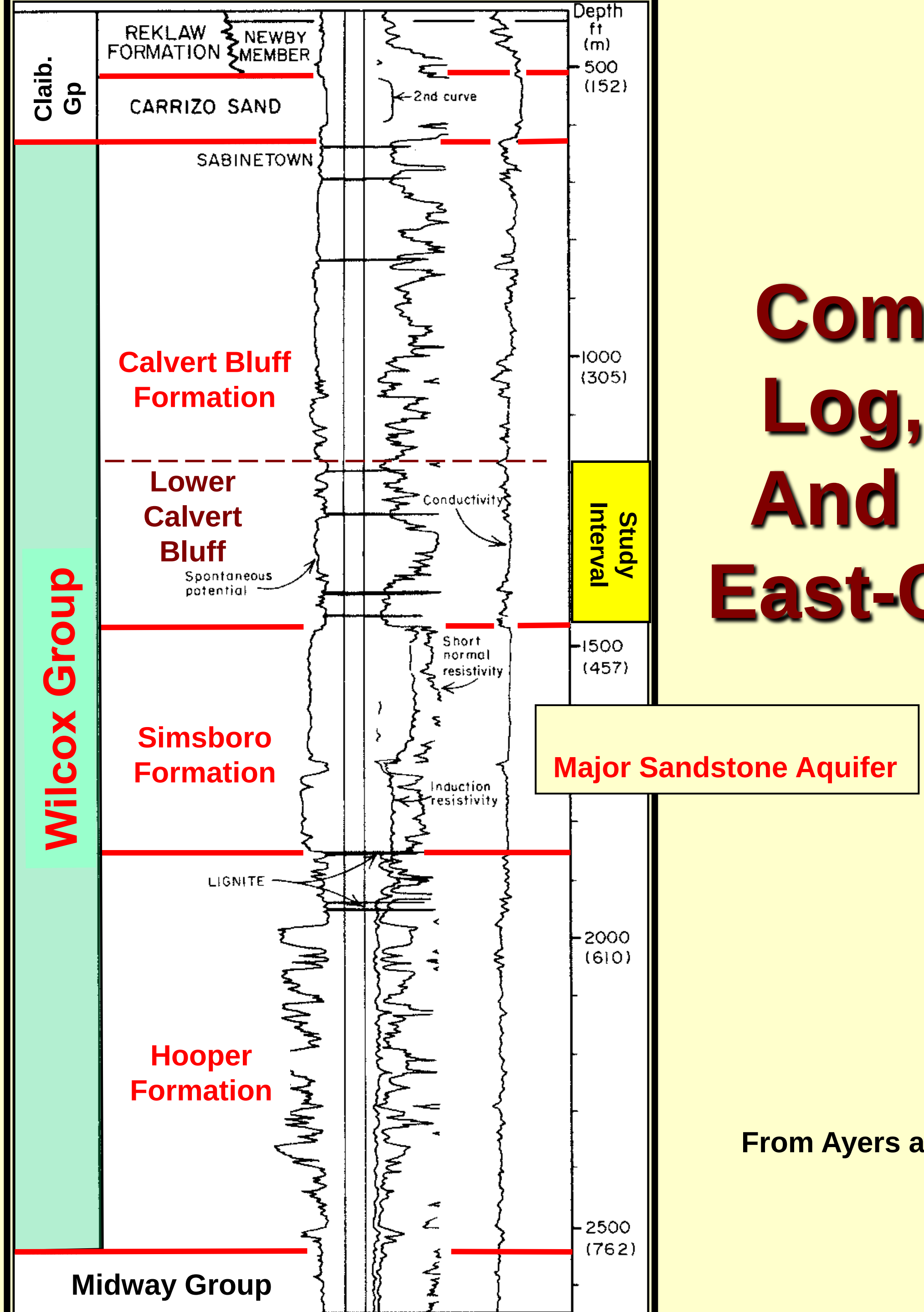
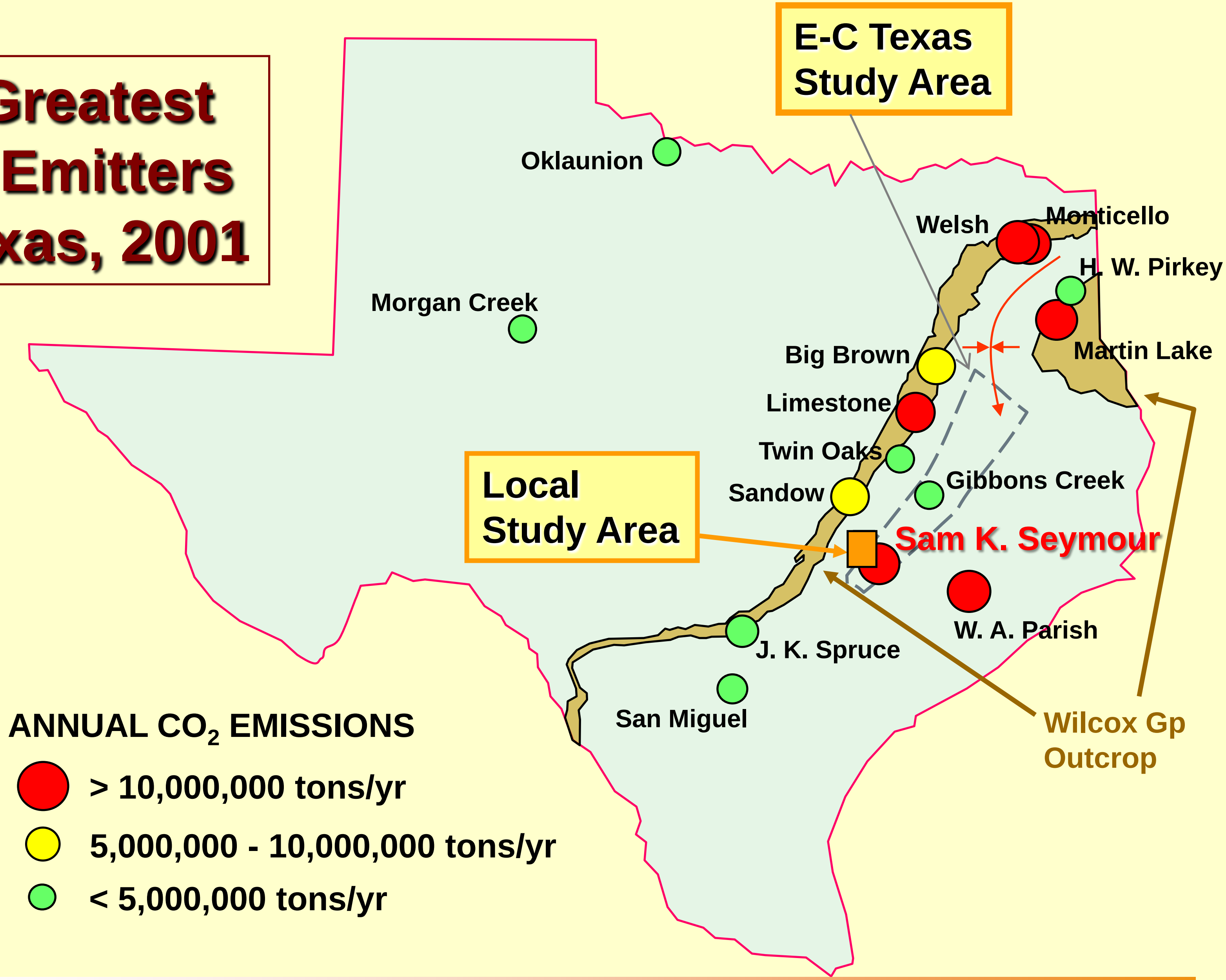
Composite Type Log, Wilcox Gp. And Carizzo Ss., East-Central Texas

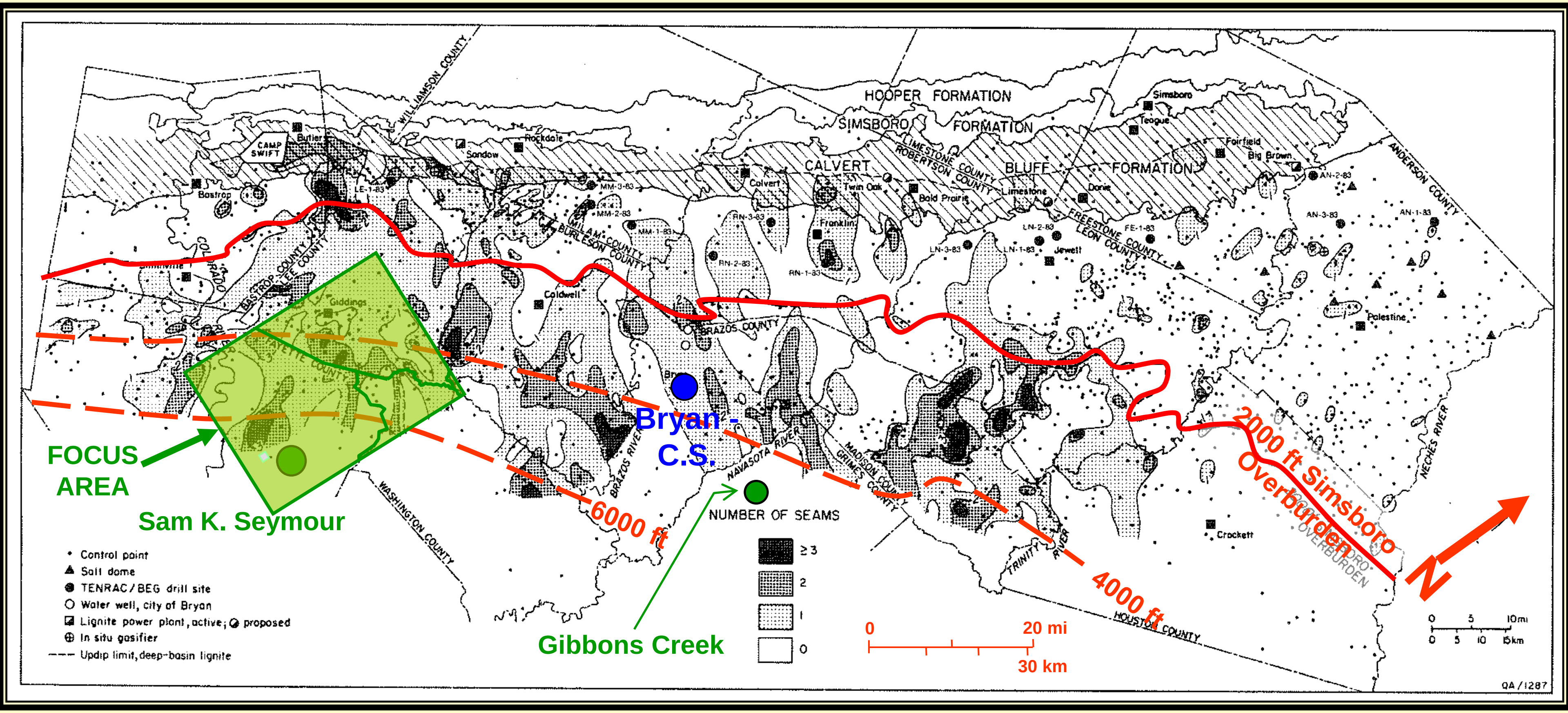


From Ayers and Lewis, 1985

15 Greatest CO_2 Emitters in Texas, 2001

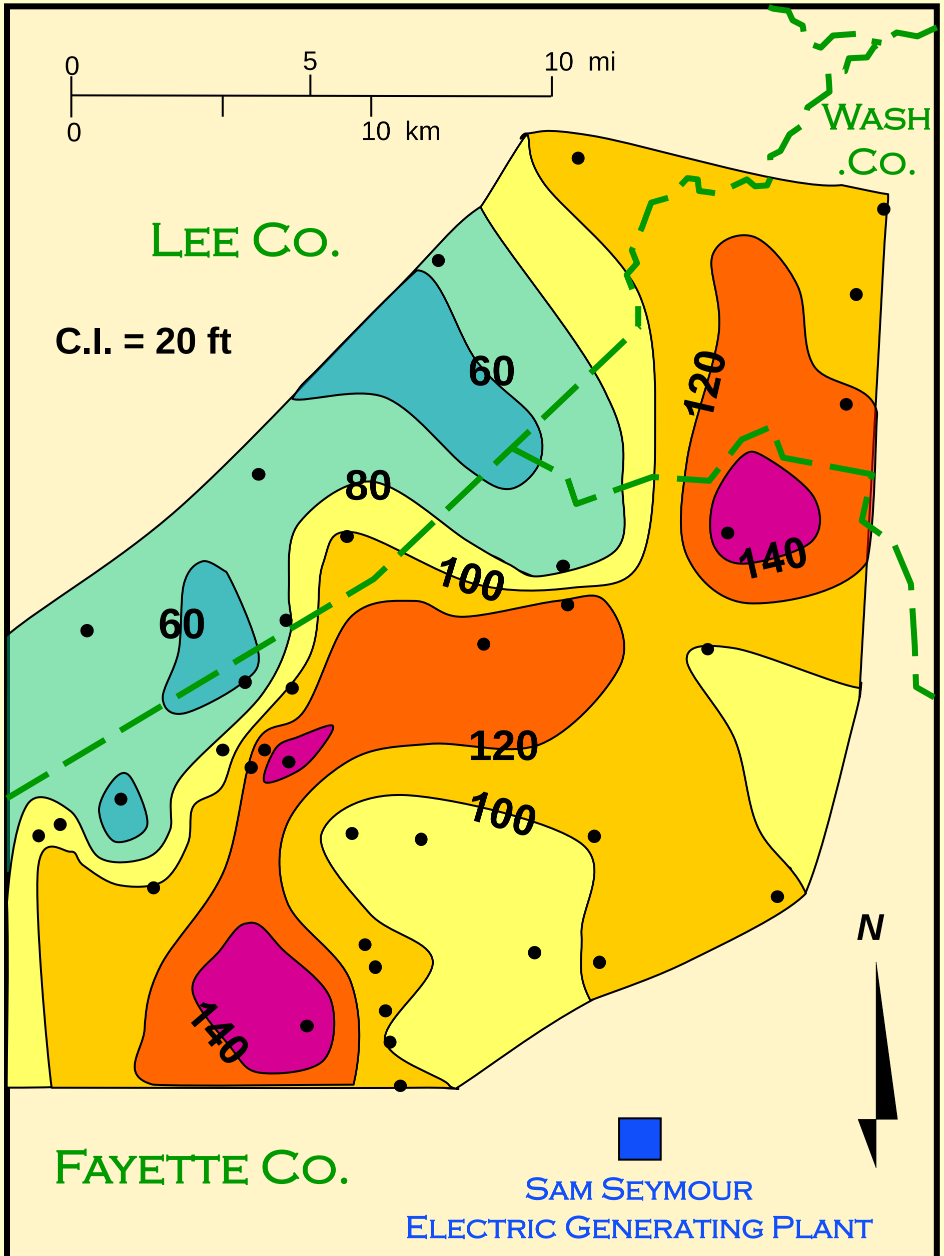


Number of Coal Seams > 5 ft (1.5 m) Thick, Lower Calvert Bluff Formation East-Central Texas

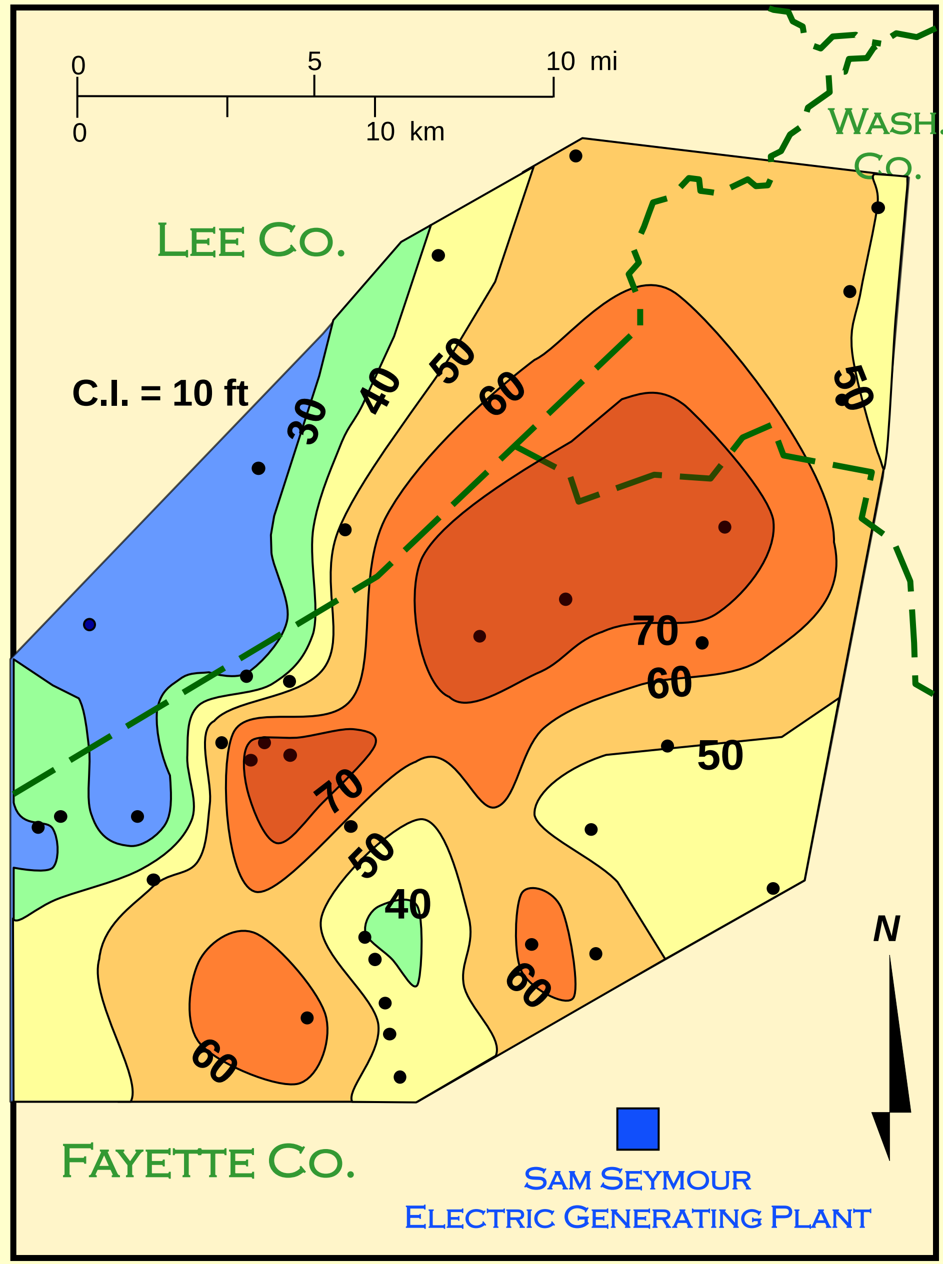


Modified from Ayers et al., 1986

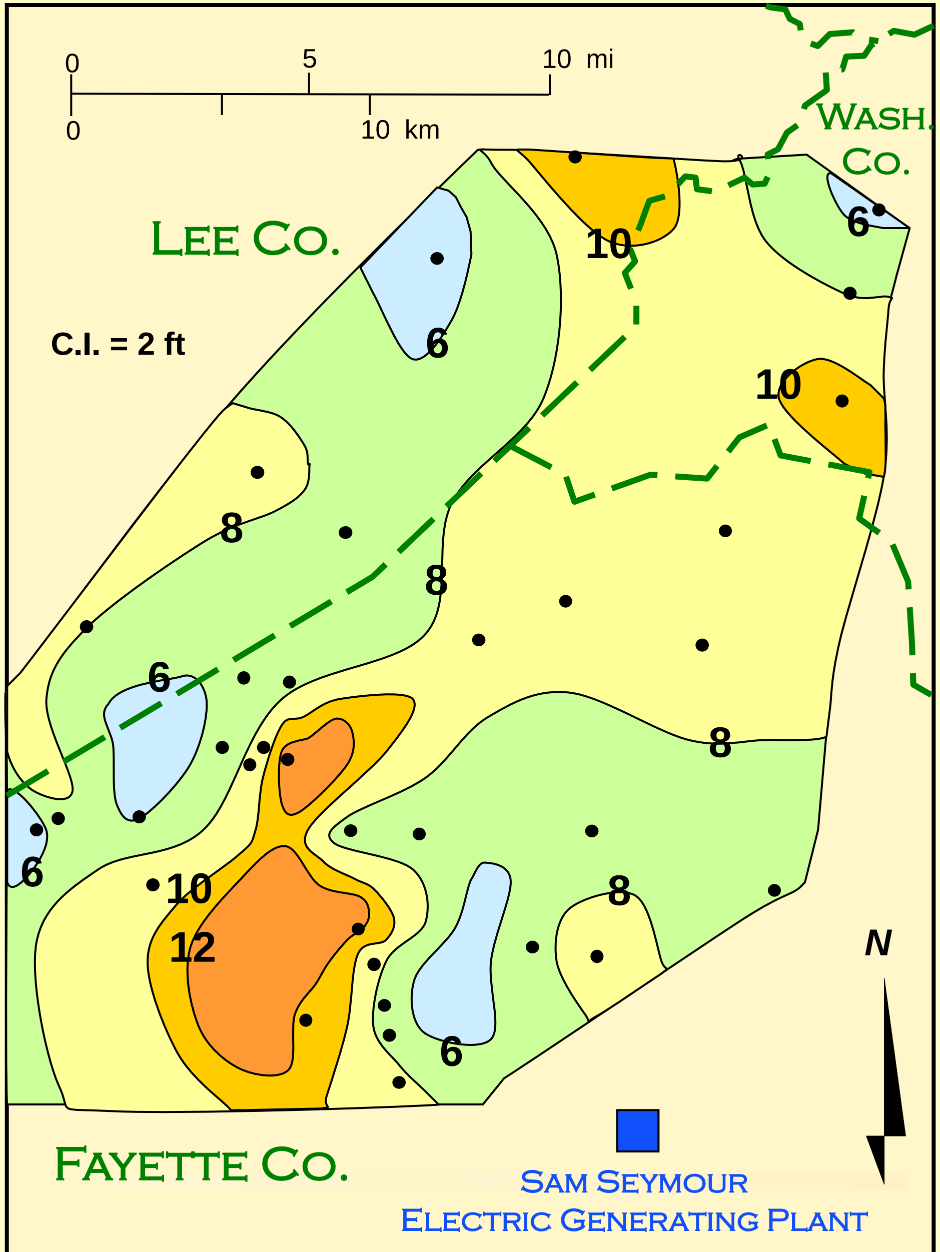
Wilcox Group, Total Coal Thickness



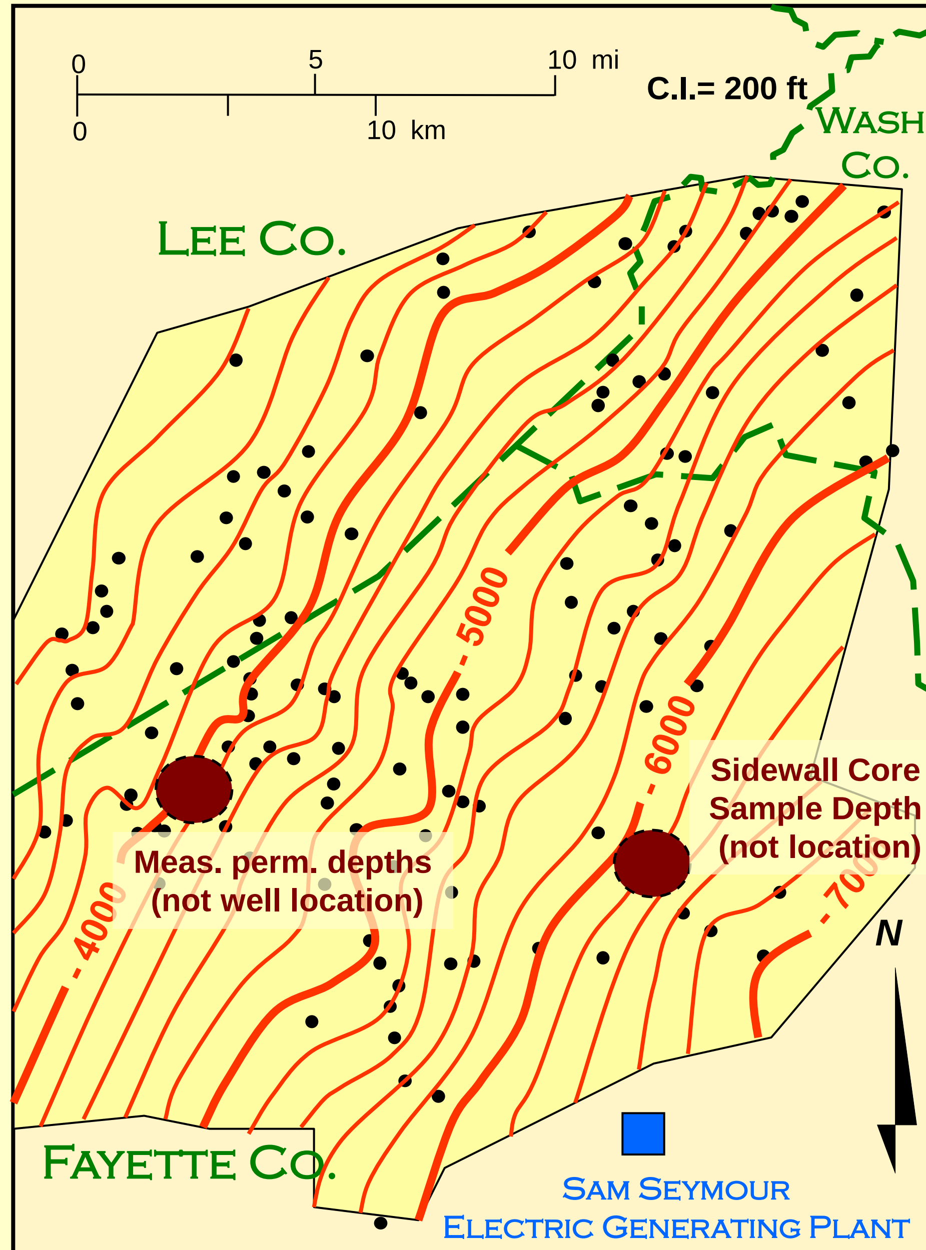
Lower Calvert Bluff Fm, Total Coal Thickness



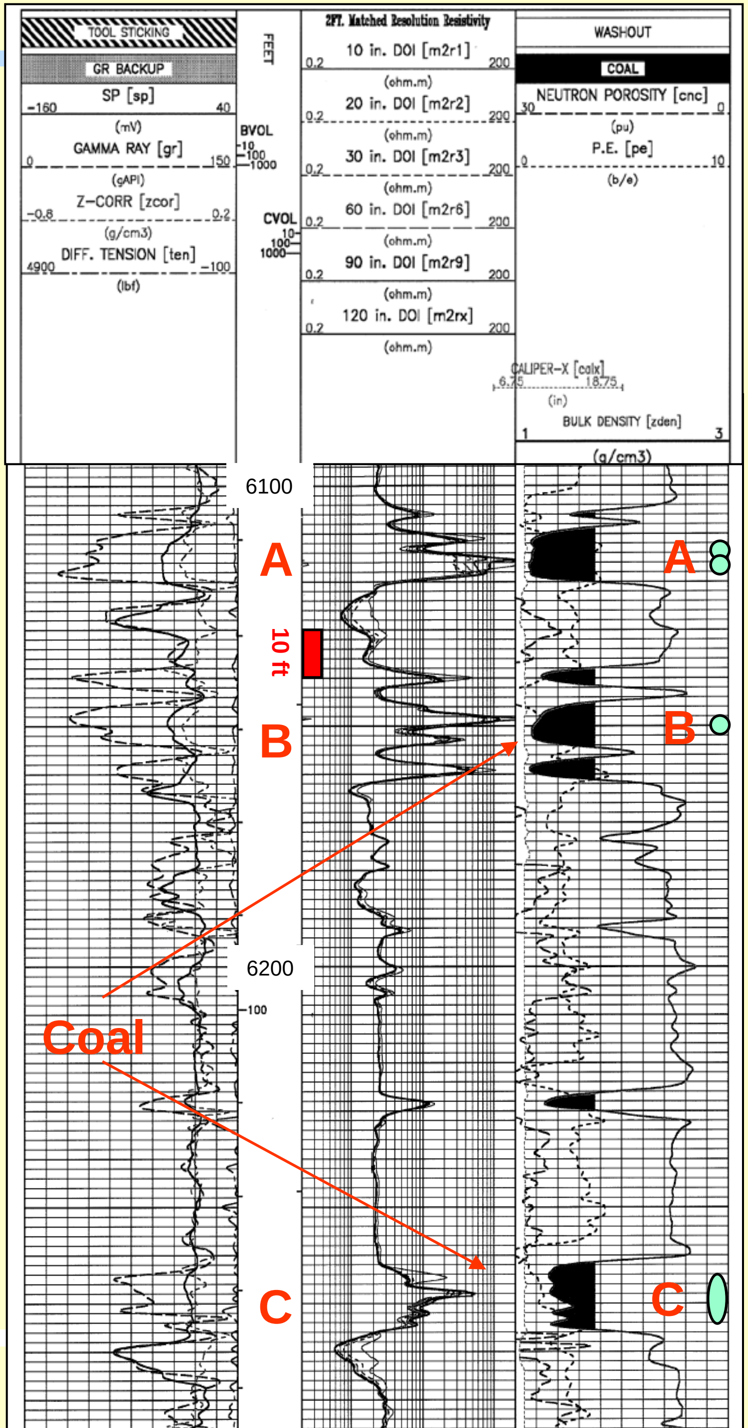
Lower Calvert Bluff, Thickest Coal Bed



Structure, Base of Calvert Bluff Formation



ANADARKO PETROLEUM CORP.



COOPERATIVE WELL 1

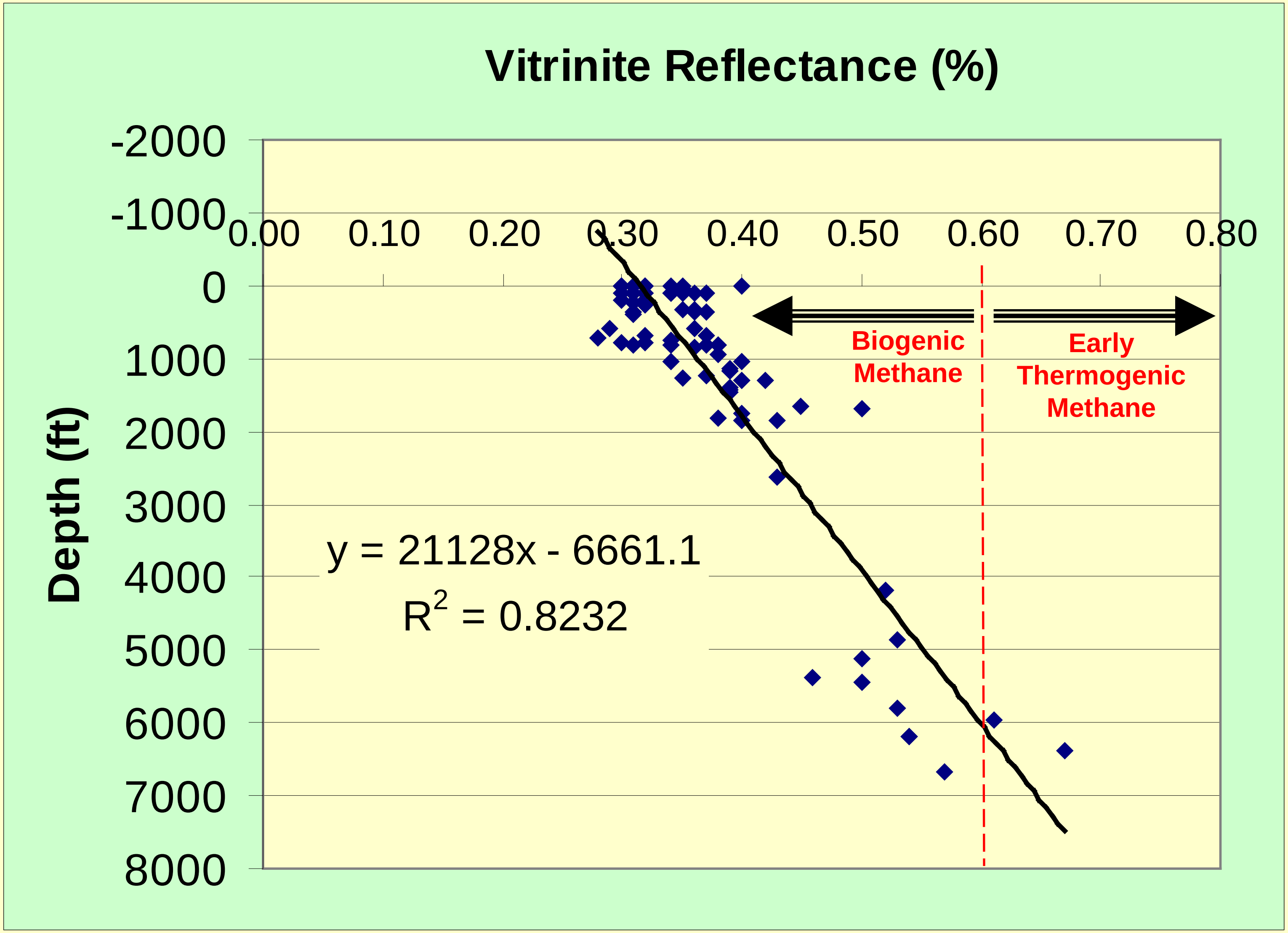
- 10 sidewall cores
- Desorbed in 4 canisters
- Adsorption isotherms
    - Carbon dioxide
    - Methane
    - Nitrogen
- Gas Composition
- Thermal maturity
- Proximate analysis

A = Coal bed cored

○ = Interval cored

SIDEWALL CORE SAMPLES

Vitrinite Reflectance vs. Depth (BEG, 2002, and This Study)

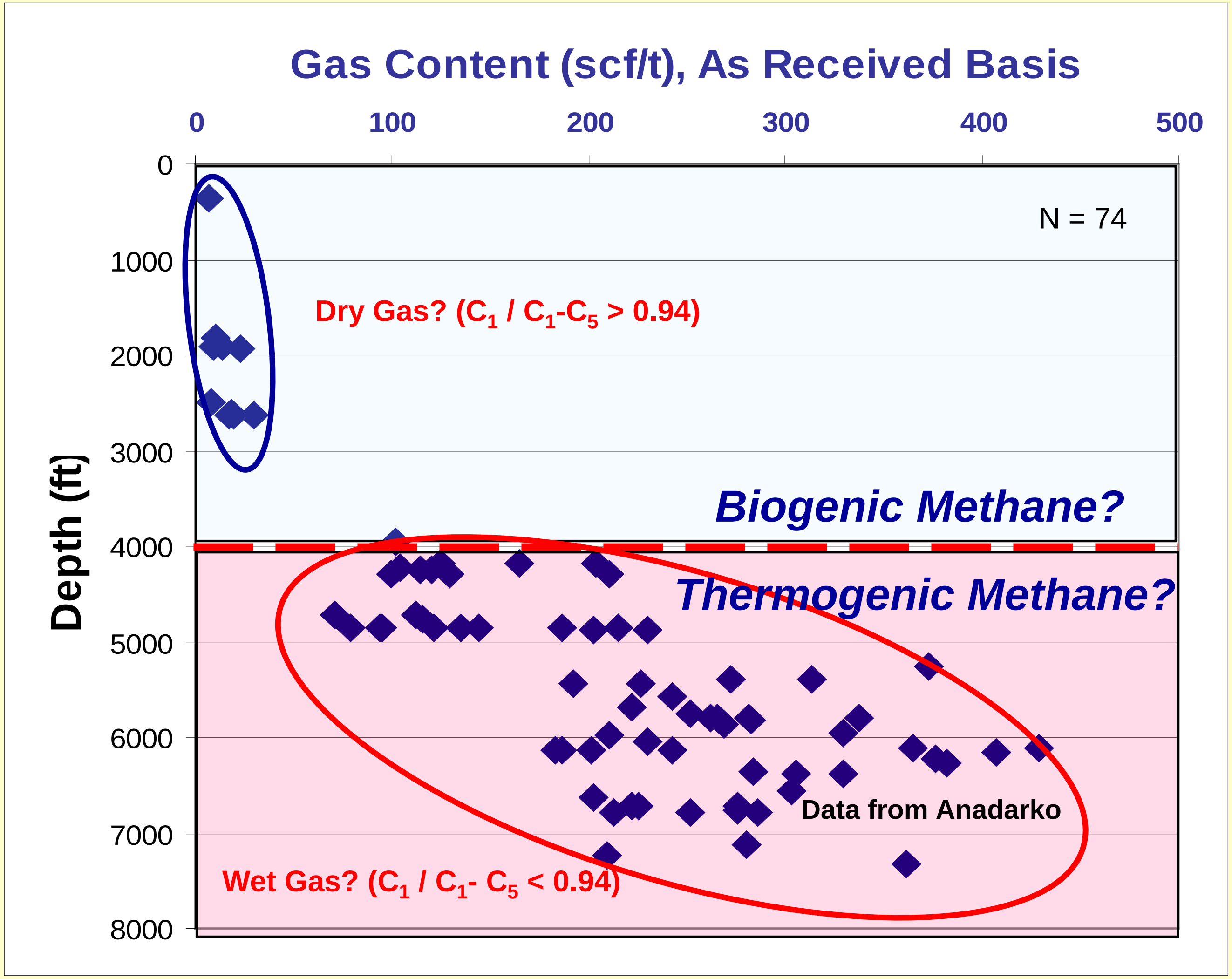


THERMAL MATURITY

WX Coalbed gas > 6,000 ft deep is "Early Stage" thermogenic gas <u>or</u> migrated gas

H-V C to H-V B Bituminous Coal

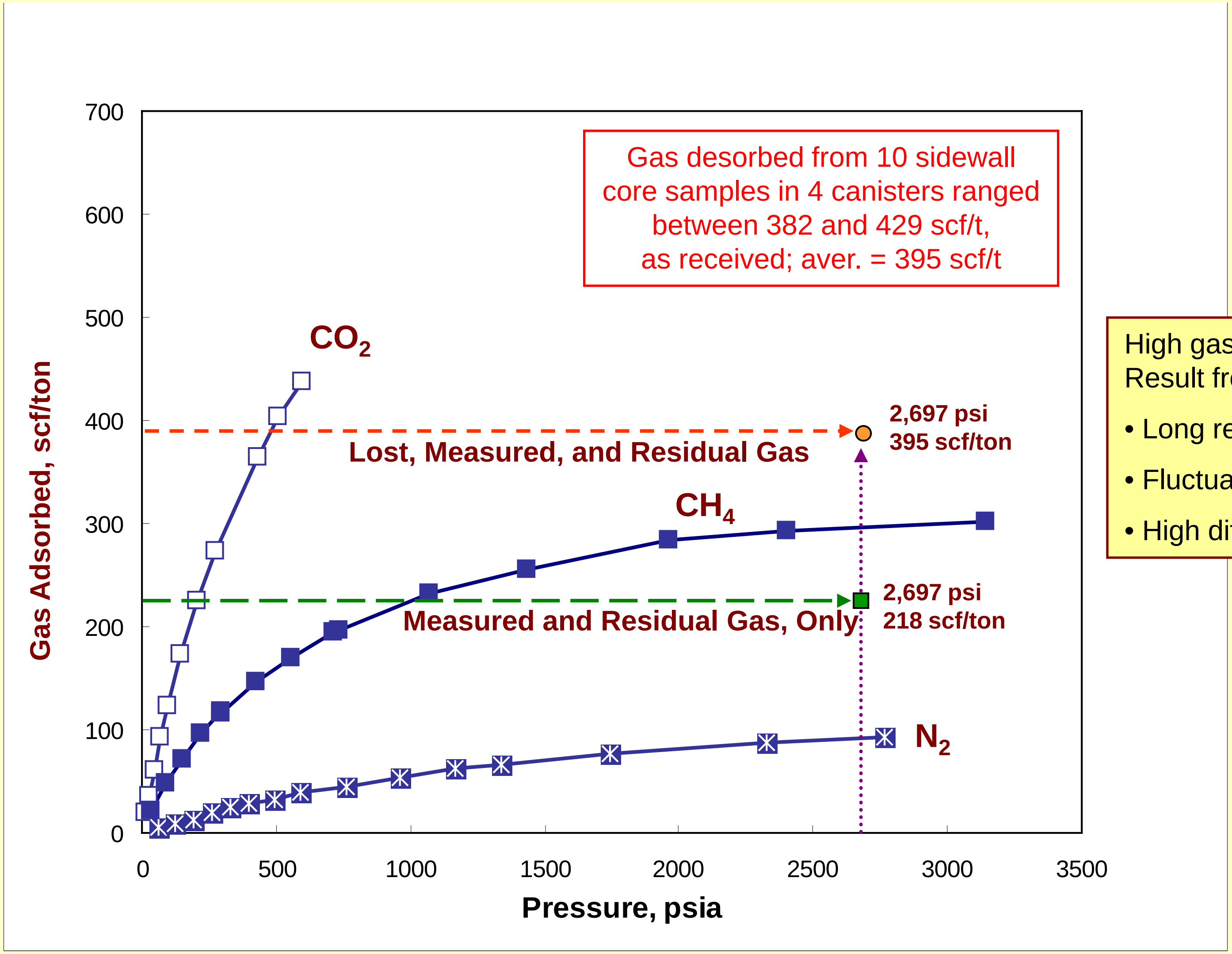
Gas Content vs. Depth , Wilcox Coals, E-C Texas



Pressure Injection/Fall-Off Tests Wilcox Coals, Anadarko Well

Depth, ft	4,200	4,000
Permeability, md	1.9	4.2
Pressure, psi	1,851	1,687

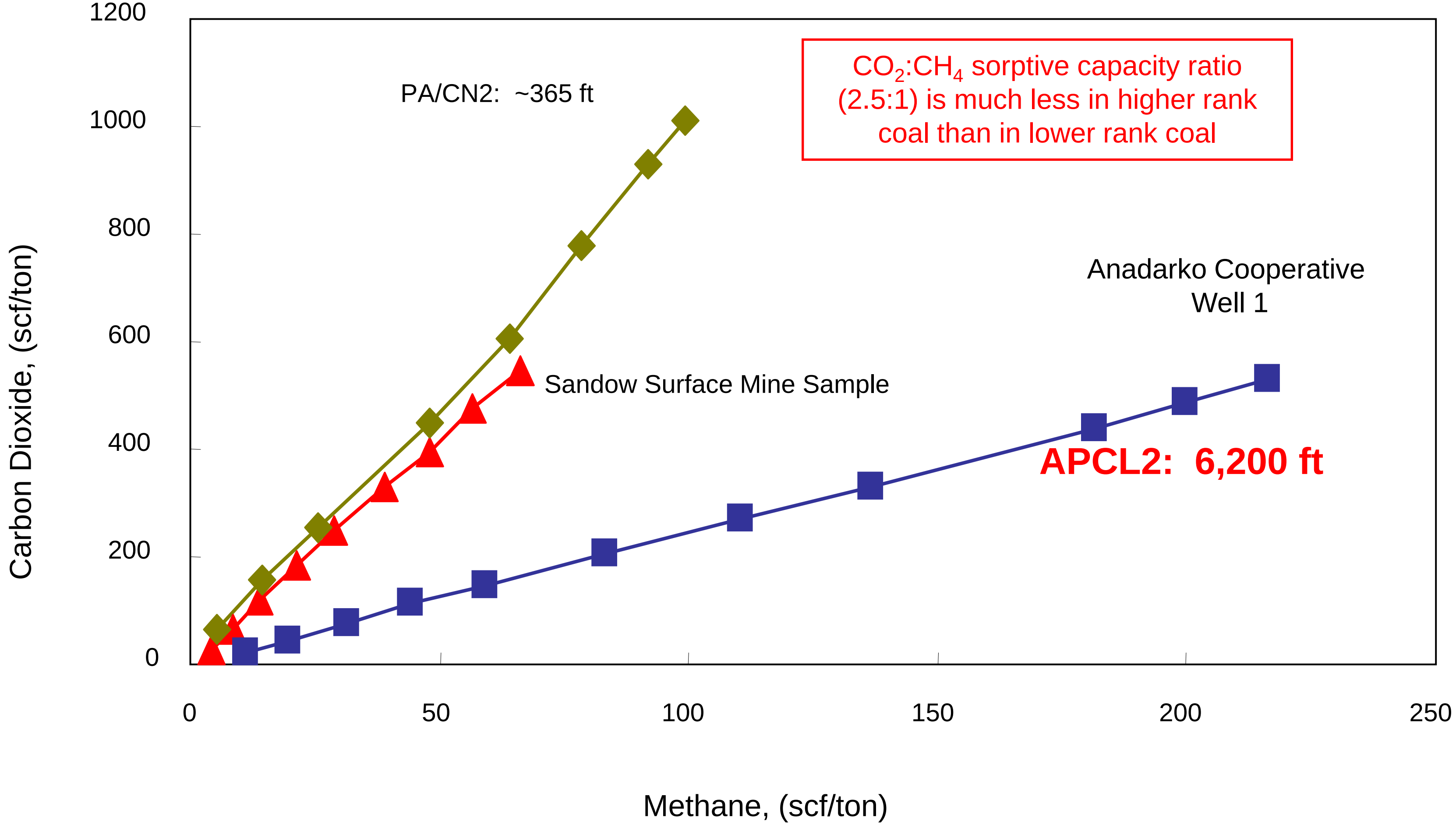
SORPTION ISOTHERMS AND GAS CONTENT, ANADARKO COOPERATIVE WELL 1, ~6,200 FT



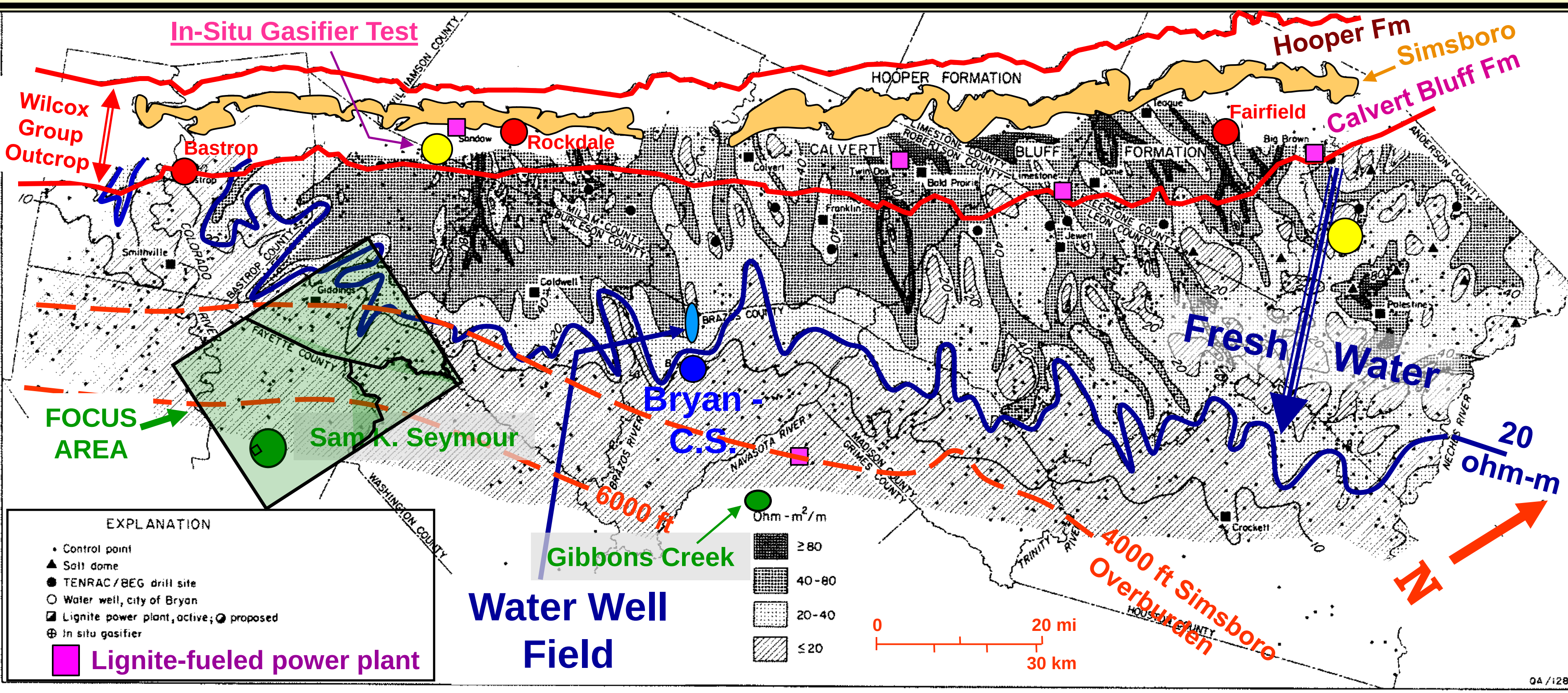
High gas measurement may Result from:

- Long retrieval time
- Fluctuation of ambient temp.
- High diffusivity

METHANE vs CARBON DIOXIDE ADSORPTION, 3 WILCOX GP COALS (Dry, Ash-Free Basis)



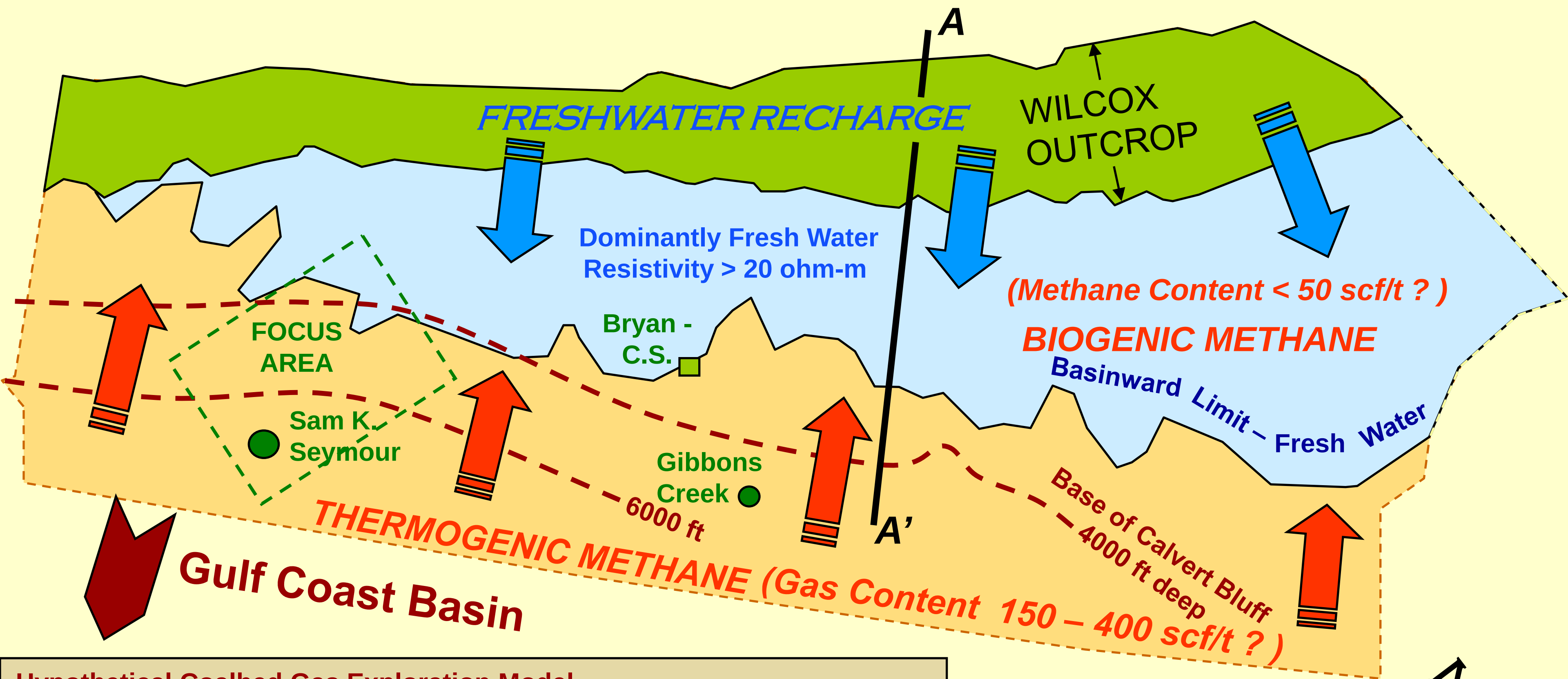
Resistivity of Maximum Sandstone, Simsboro Formation, E-C Texas



Modified from Ayers and Lewis, 1985

- Total dissolved solids of ground water varies inversely with resistivity
- Hydrologic setting helps clarify coalbed gas origins

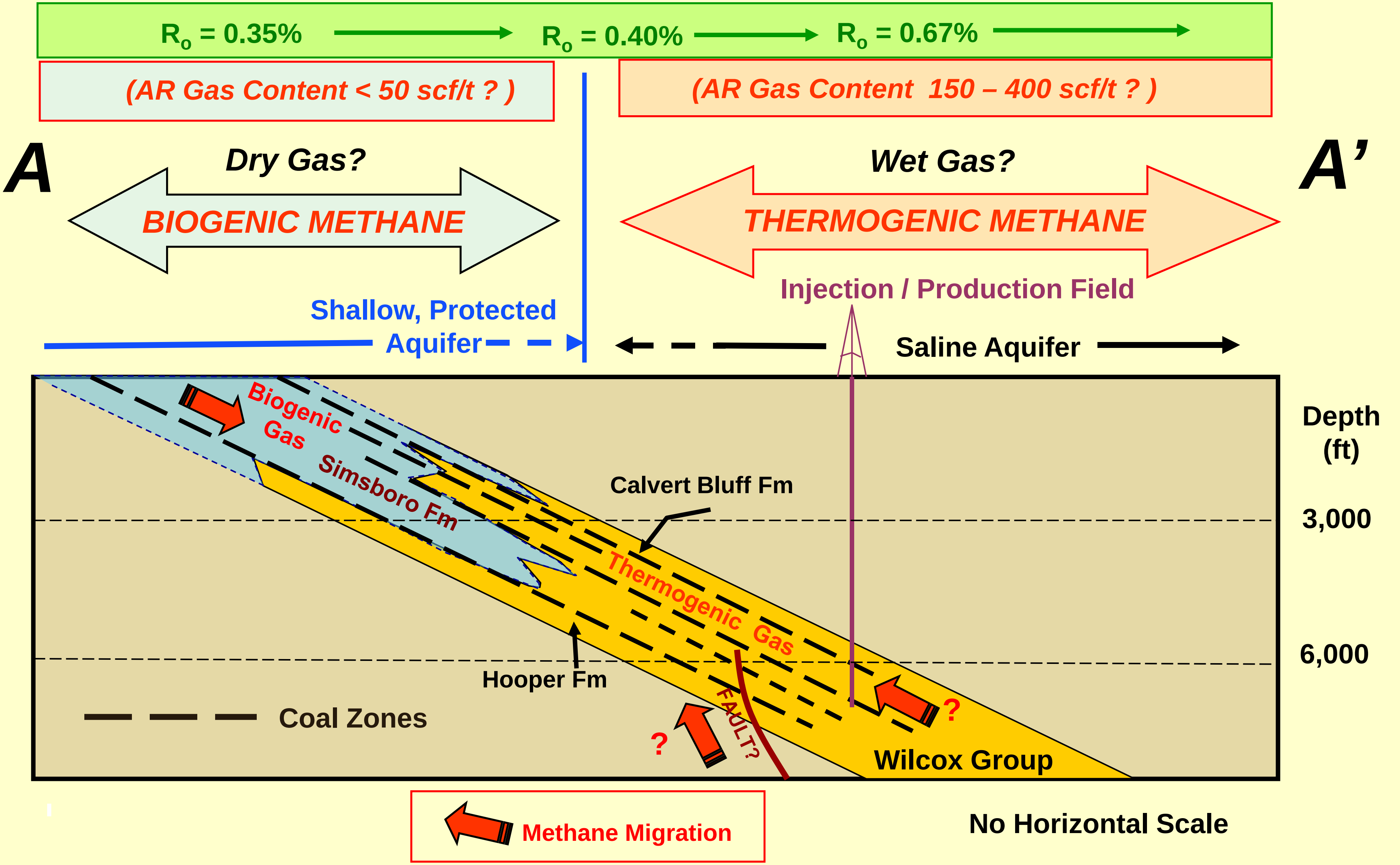
Wilcox Coalbed Gas Resources in E-C Texas – Hypothetical Exploration Model



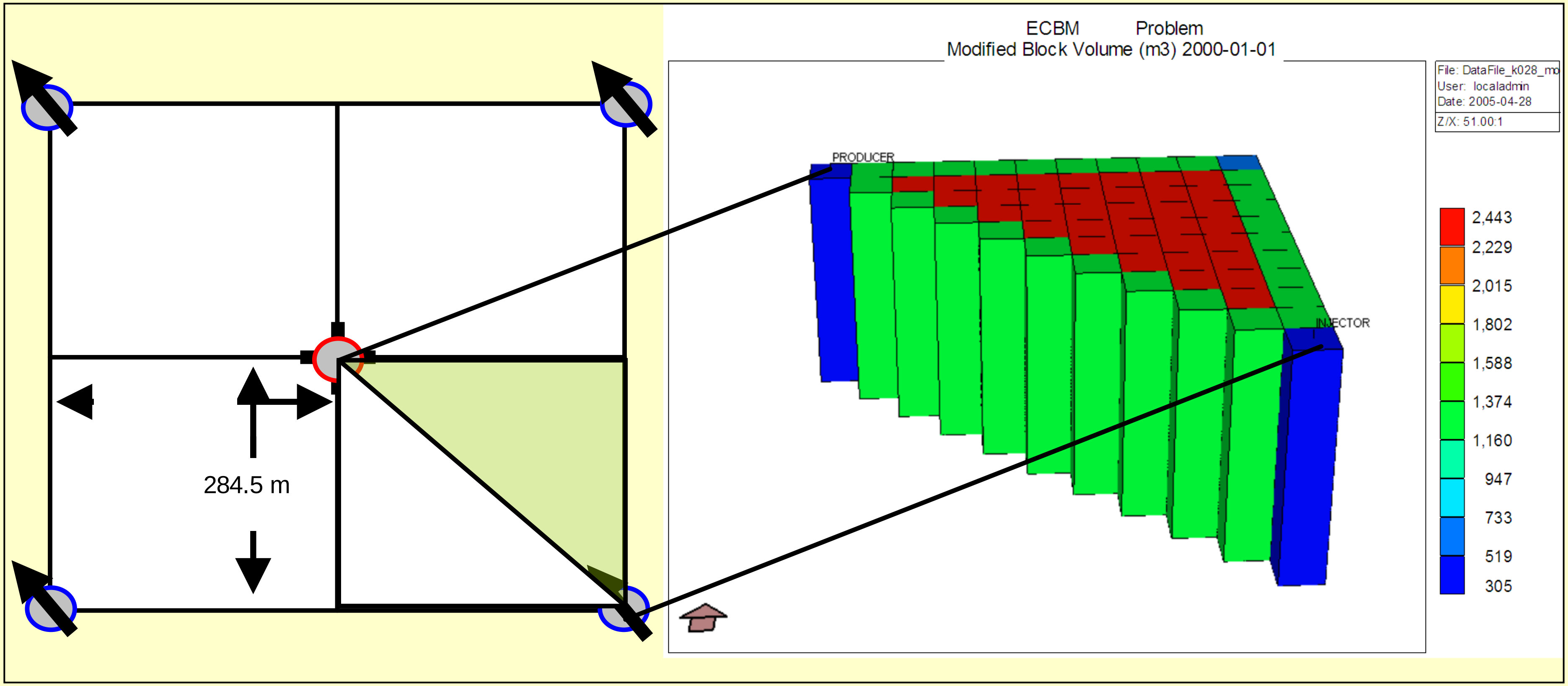
<u>Hypothetical Coalbed Gas Exploration Model</u>

- **<u>Biogenic Fairway</u>** - biogenic methane occurs in Wilcox Gp coal beds in the shallow, fresh-water interval; methane content of coal is low
- **<u>Thermogenic Fairway</u>** - methane content of the deeper Wilcox coals is high; thermogenic gas migrated from deeper in the basin to charge the coals

Wilcox Coalbed Gas Resources in E-C Texas – Hypothetical Exploration Model



Wilcox Reservoir Simulation Model of 1/8 of a 5-Spot Pattern



Wilcox Simulation Cases

Case	Parameter Investigated	Depth (ft)
Case 1a	Base Case - 4,000 ft	4,000
***Case 1b**	Base Case - 6,200 ft	6,200
Case 2	Well Spacing = 40 ac	6,200
	Well Spacing = 80 ac	6,200
	Well Spacing = 160 ac	6,200
	Well Spacing = 240 ac	6,200
Case 3a	Injected Gas Composition	6,200
Case 3b	Injected Gas Composition	6,200
Case 4	CO_2 Injection Rate (red. pres. drop)	6,200
Case 5a	Init. Dewatering @ 6 mos.	6,200
Case 5b	Init. Dewatering @ 18 mos.	6,200

***Cases 2 - 5 were modifications of Case 1b**

Uncertain Reservoir Property Estimates and Design Parameters

Parameter	Value
Coal Seam Thickness (1)	10, 20, 30 feet
Fracture Absolute Permeability (2)	0.8, 2.8, 10 mD
Coal Density (3)	1.289, 1.332, 1380 g/cm^3 (80.5, 83.2, 86.2 lb/ft^3)
Gas Phase Diffusion Time (4) (Sorption Time)	0, 1, 4 days
Injection Gas Composition	100% CO_2, 13% CO_2 - 87% N_2, 50% CO_2 - 50% N_2
Well Spacing	40, 80, 160, 240-acre well spacing

(1) Triangular Distribution

(2) Log-Normal Distribution

(3) Triangular Distribution

(4) Triangular Distribution

Base Case Coal Seam Scenarios

Parameter	4,000-ft depth	6,200-ft depth
Initial Reservoir Pressure	1,730 psia	2,680 psia
Reservoir Temperature	140 ^oF	170 ^oF
Langmuir Isotherm Parameters [(1)] :		
V_L, CH_4	458.5 scf/ton	363.6 scf/ton
P_L, CH_4	1,884 psia	608.5 psia
V_L, CO_2	1,375.5 scf/ton	961.9 scf/ton
P_L, CO_2	1,884 psia	697.5 psia
V_L, N_2	301 scf/ton	166.1 scf/ton
P_L, N_2	6,764 psia	2,060.7 psia
Operating Conditions - Pressure Control :		
Production Well, Pressure and Rate	40 psia, 3.5 MMscf/D	40 psia, 3.5 MMscf/D
Injection Well, Pressure and Rate	2,175 psia, 3.5 MMscf/D	3,625 psia, 3.5 MMscf/D

[(1)] As Received Basis

Economic Model Parameters

Parameters	Value	Units
Federal Tax Rate	35	%
Discount Rate	10	%
Gas Price [1]	2.00, 4.00, 12.00	\$/Mscf CH_4
Gas Price Escalation	3	%/yr
Texas Severance Tax	7.50	%
Net Revenue Interest [2]	75, 80	%
Carbon Market Price [2]	0.05, 1.58	\$/Mscf CO_2
Net to Gross CO_2 Injection Ratio for CO_2 Sequestration Credits	70	%
Area of field	30,000	acres
Area of 5-spot pattern	80, 160, 320, 480	acres
[1] Triangular Distribution [2] Uniform Distribution		

Costs – 1

Item	Cost	Units
Lease Acquisition Costs [1]	50.00, 300.00	\$/acre
CO_2 Pipeline CAPEX	53.33	\$/inch-mile, [*]
New Injection Well CAPEX	100.00	\$/ft
New Injection Well OPEX	1,500.00	\$/month
New Production Well CAPEX	100.00	\$/ft
New Production Well OPEX	1,500.00	\$/month
Gas Treatment and Compression Facilities CAPEX	21,153.13	\$, [*]
CO_2 /Flue Gas Compression OPEX	0.30	\$/Mscf CO_2
Produced Methane Processing	0.50	\$/Mscf
Produced Water Disposal	0.40	\$/bbl
Safety, Monitoring and Verification	10,000.00	\$/injector/yr
[1] Uniform Distribution [*] Cost computed for a single 80-acre pattern		

Costs – 2

100% CO2

Item	Cost	Units
CO_2 Capture Cost [(1)]	1.00, 2.00	$/Mscf
CO_2 Pipeline OPEX	0.01	$/Mscf

87% N2-13%CO2

Item	Cost	Units
Flue Gas Pipeline OPEX	0.50	$/Mscf Flue Gas
Produced Methane Processing (Nitrogen Rejection)	0.50	$/Mscf Wellstream

50% N2- 50%N2

Item	Cost	Units
Injected Gas Pipeline OPEX [(1)]	0.50, 1.00	$/Mscf Flue Gas
Produced Methane Processing (Nitrogen Rejection)	0.50	$/Mscf Wellstream

(1) Uniform distribution

Summary of Wilcox Reservoir Performance

- **Coal properties and reservoir parameters contribute significantly to uncertainties in potential performance of CO_2 injection and Methane produced, in LCB coalbeds in east-central Texas:**
  - **Increasing gas content at initial reservoir pressure** improves potential production
  - **CO_2 / CH_4 sorption capacity ratio** greatly controls the amount of CO_2 to be sequestered
  - **N_2 content in the injected gas increases methane recovery and decreases potential CO_2 sequestration**
  - **Cumulative methane produced and CO_2 sequestered** increase with increasing fracture permeability and coal thickness, and decreasing diffusion times

Summary of Wilcox ECBM Economics

- **Major economic parameters are:**
  - CO_2 capture cost
  - Gas price (methane production)
  - Carbon Market Price (sequestration credits)

- **At gas price ($2 - $12 per Mscf CH_4) and Carbon market price ($1 - $30 per ton CO_2), CO_2 capture cost has most dominant effect on investment which is greater than revenue realized from methane production and credits**

THEORETICAL CH_4 TO BE PRODUCED AND CO_2 TO BE SEQUESTERED

Area Basis	Total CH_4 Volumes, Bcf Produced			Total CO_2 Volumes, Bcf Sequestered		
	P_{10}	Mean	P_{90}	P_{10}	Mean	P_{90}
Pattern Area	0.270	0.418	0.580	1.160	1.621	2.100
East-Central Texas Area	6,330	9,790	13,600	27,190	38,000	49,220

East-Central Texas Total CO_2, MM tons		
1,570	2,195	2,690

WILCOX ECBM CONCLUSIONS

- Coalbed gas data are limited in the updip area; on the basis of available data, we suggest that there are two coalbed gas systems present in the East-Central Texas Wilcox Group.
  - The shallow coalbed gas system is characterized by thermally immature coal, low concentrations of compositionally dry, biogenic gas, and fresh formation water.
  - The deep coalbed gas system is distinguished by greater concentrations of compositionally wet, early thermogenic or migrated thermogenic gas and saline formation water.
- Methane resources and CO_2 sequestration potential of Wilcox coals in E-C Texas are significant.
  - ECBM production increases and CO_2 sequestration potential decreases with increasing N_2 content in the injected gas.
- With current gas prices and CO_2 sequestration credits, combined CO_2 sequestration and ECBM is uneconomic to marginally economic in Wilcox coals in E-C Texas.
  - Higher CO_2 sequestration credits and/or gas prices are required for economic projects.
  - Optimal injection gas is between 100% CO_2 and flue gas.

OBJECTIVES: Review and contrast potential for CO_2 sequestration in, and enhanced recovery of CH_4 from, coal beds in selected areas of the Black Warrior and Texas Gulf Coast basins.

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- **Coal beds as Geologic Media for CO_2 sequestration**

Comparison of the Pottsville and Wilcox Coalbed Gas Systems

Differences in geologic setting and coal reservoir parameters will greatly impact ECBM potential. Pilot projects should test range of coals for ECBM potential. Some differences between the Pottsville and Wilcox coals evaluated:

- **Geologic Age;**
- **Net Coal Thickness;**
- **Thermal Maturity;**
- **Depth;**
- **Permeability;**
- **Supercritical CO_2 and;**
- **Presence of adjacent aquifers**

OBJECTIVES: Review and contrast potential for CO_2 sequestration in, and enhanced recovery of CH_4 from, coal beds in selected areas of the Black Warrior and Texas Gulf Coast basins.

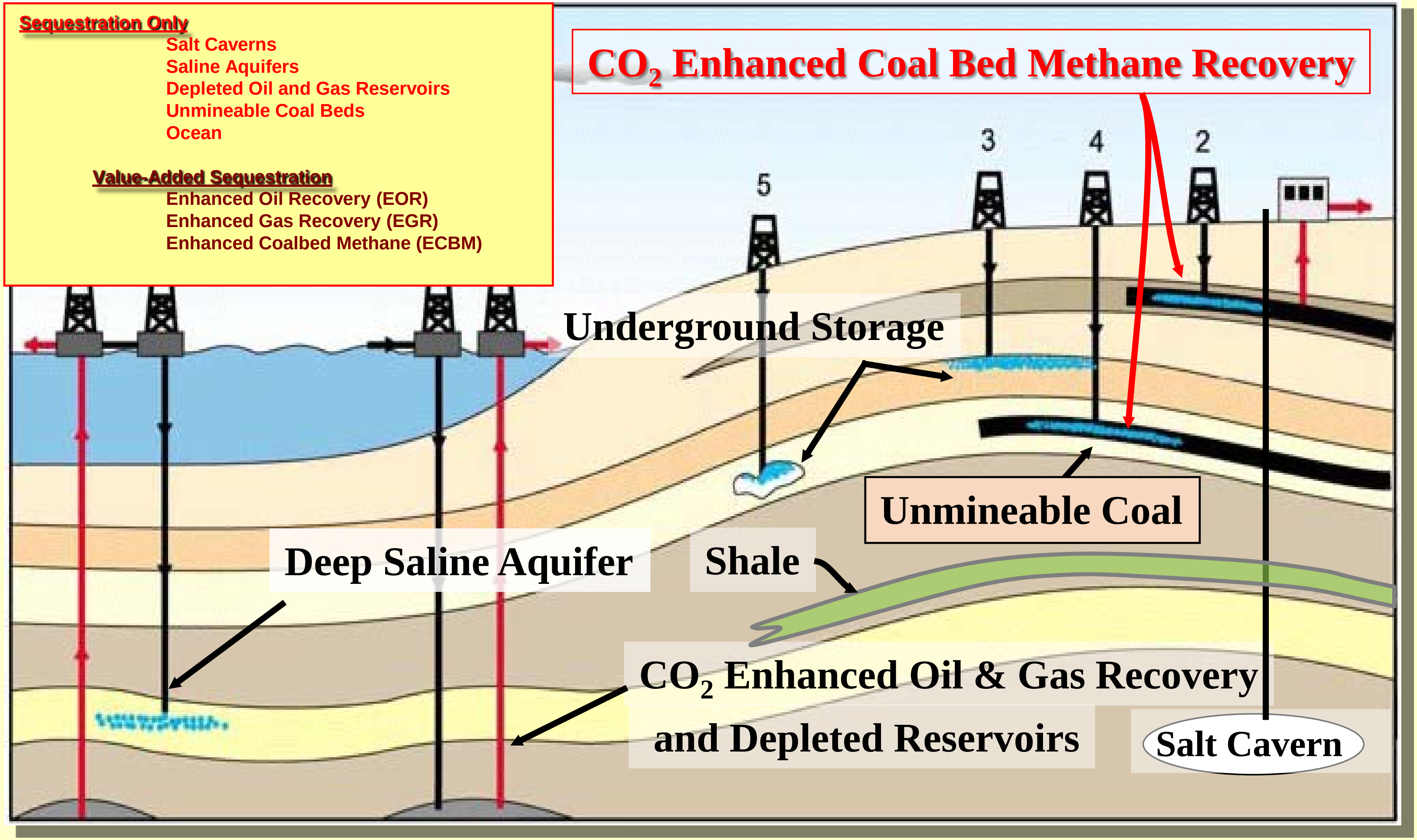
Outline

- Pottsville coal, Blue Creek Field, Black Warrior Basin (technical assessment, only)
- Wilcox Coal, East-Central Texas (technical and economic assessments)
- **Contrasts between the Coalbed Gas Systems**
- **Coal Beds as Geologic Media for CO_2 Sequestration**

CO_2 Geologic Sequestration Options

Sequestration Only
- Salt Caverns
- Saline Aquifers
- Depleted Oil and Gas Reservoirs
- Unmineable Coal Beds
- Ocean

Value-Added Sequestration
- Enhanced Oil Recovery (EOR)
- Enhanced Gas Recovery (EGR)
- Enhanced Coalbed Methane (ECBM)



Lawrence H. Wickstrom
AAPG Visiting Geologists Program

Modified from: http://www.spacedaily.com/news/greenhouse-00j.html

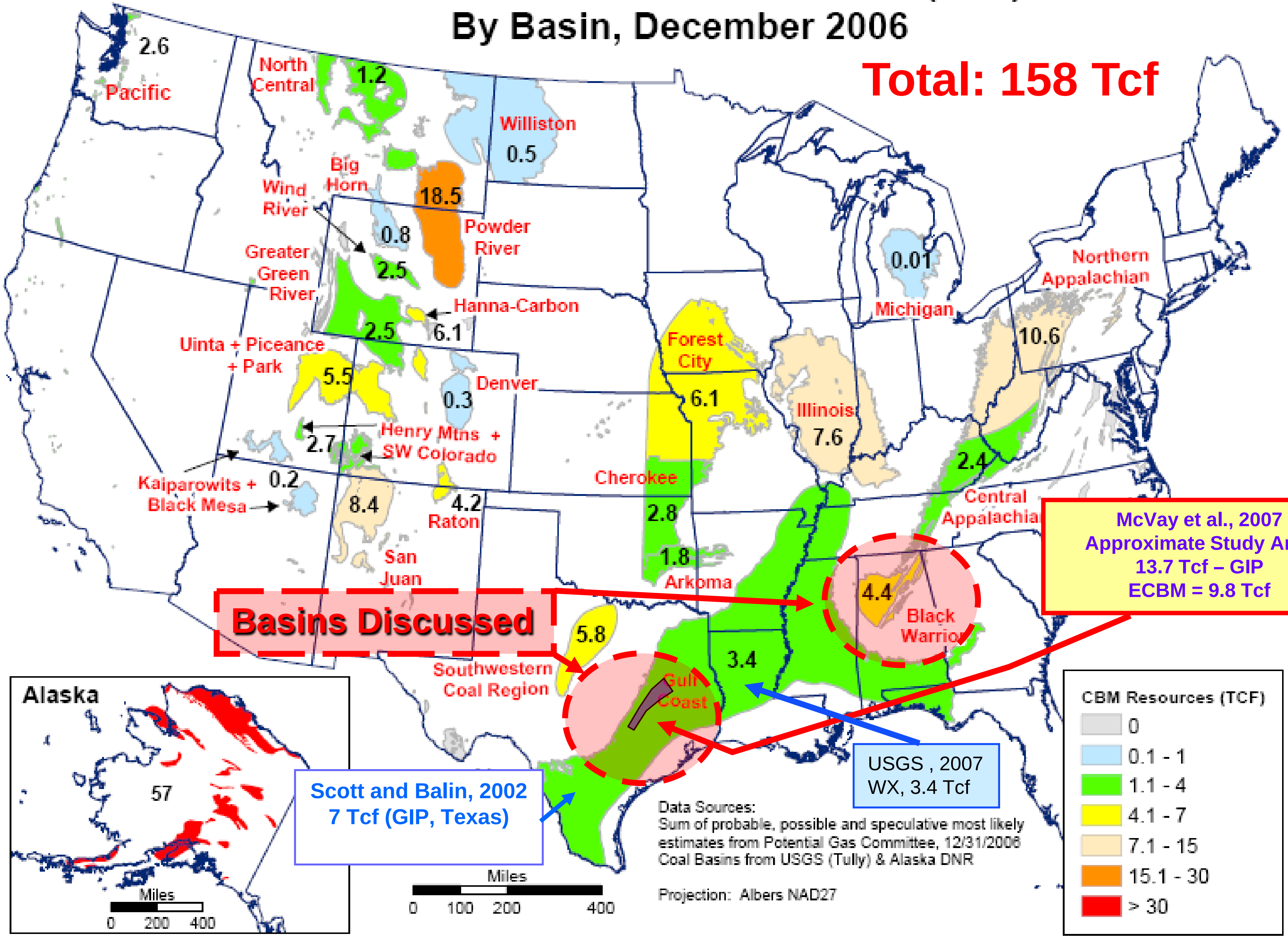
Expectations for CO_2 Storage Reservoirs

Reservoir Properties

- Adequate storage volume
- Injectivity – reasonable rates relative to sources
- Confining ability – leakage prevention (sealing caprock or confining unit)
- Sufficiently stable geological *environment* to avoid compromising the integrity of the storage site
  - Should expect 99% of CO_2 to be retained more than 1,000 yrs
  - Risk models should be established for various aspects of storage reservoirs
  - It is improbable that releases of CO_2 would endanger humans or ecosystems

From APEC, 2005; APCC, 2005

US Coalbed Methane Resources (TCF) By Basin, December 2006



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Research Areas and References

Bituminous Coal, Pottsville Gp, Black Warrior Basin, Alabama

He, Ting, 2009, Potential for CO_2 Sequestration and Enhanced Coalbed Methane Production, Blue Creek Field, NW Black Warrior Basin, Alabama: Texas A&M University, M.S. Thesis, 126 p.

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Wilcox Study Contract Report, M.S. Theses, Papers, and Abstracts