

# Storing CO<sub>2</sub> in Coal Seams

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*Carbon Sequestration Leadership Forum  
Workshop*

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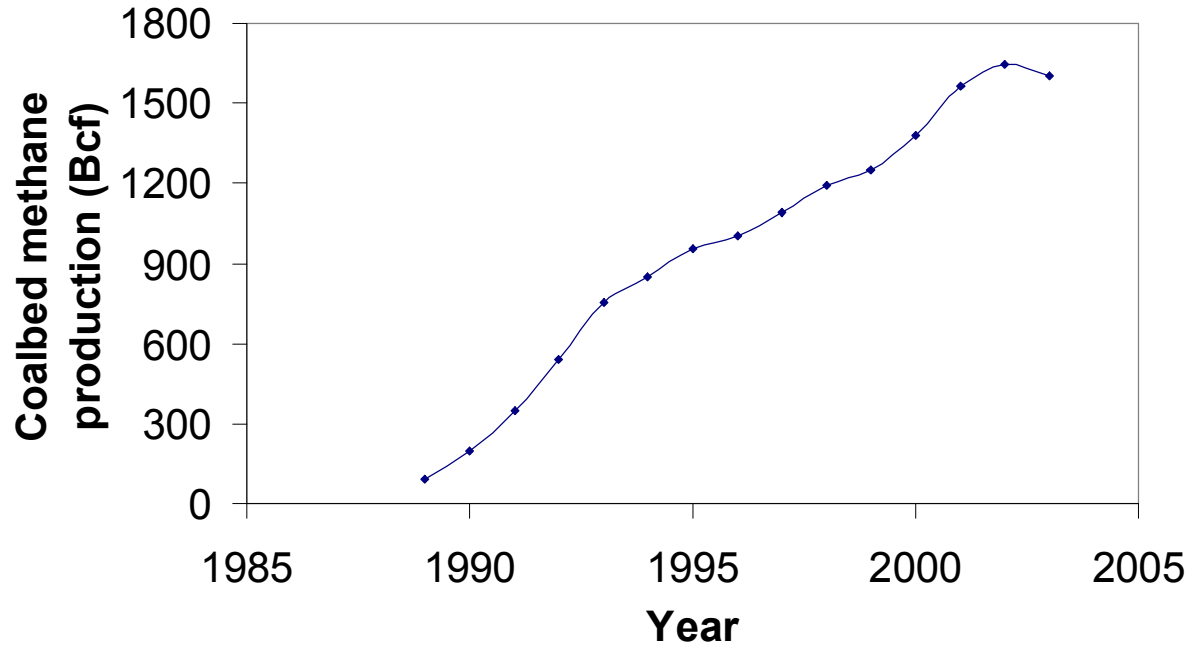
# Acknowledgements

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- Burcu Gorucu, Landmark



# Coalbeds are a major source of natural gas.\*

- 3000 to 9000 Tm<sup>3</sup> estimated global resource
- 8 to 17 Tm<sup>3</sup> estimated U.S. resource
- 0.444 Tm<sup>3</sup> (9%) of proven U.S. Reserves
- 1.4 Tcf (0.04 Tm<sup>3</sup>) U.S. production in 2000, ~10% of total gas production



Data from Energy Information Administration. U.S. Crude Oil, Natural Gas, and Natural Gas Liquids Reserves 2003 Annual Report, Table 12.



\*C.M. White, D.H. Smith, K.L. Jones, et al., "Sequestration of Carbon Dioxide in Coal with Enhanced Coalbed Methane Recovery--A Review," *Energy & Fuels* 19, 659-724 (2005).

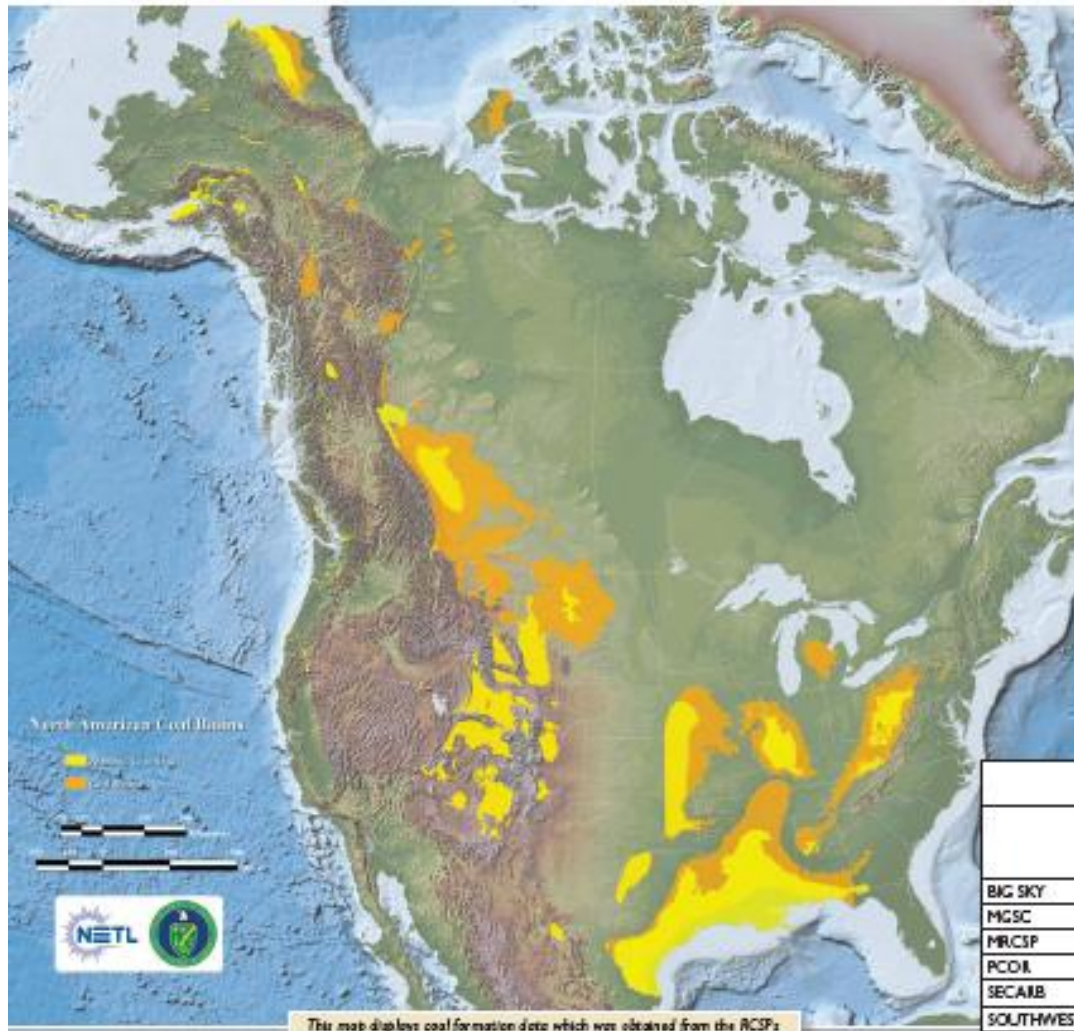
# Carbon sequestration will occur in unmineable coal seams.

- **What is unmineable coal?**
- **\*In-ground coal for which mining is economically infeasible given foreseeable technology, mining costs, and sales prices, due to:**
  - Inadequate seam thickness
  - Poor areal continuity
  - Adverse geology; e.g., steeply dipping, rolls, faults
  - Poor quality
  - Excessive depth
  - Other reasons



\* From R. Winschel, CONSOL ENERGY, Coal-Seq V Forum, Houston, TX, October 2006.

# Estimates of at least 150 – 180 Gtonnes of “theoretical” storage capacity in North American unmineable coals.



This map displays coal formation data which was obtained from the RCSPs and other external sources and compiled by NATCARB.

## Unmineable Coal Seams

Unmineable coal seams are too deep or too thin to be economically mined. All coals have varying amounts of methane adsorbed onto pore surfaces, and wells can be drilled into unmineable coalbeds to recover this coalbed methane (CBM). Initial CBM recovery methods, such as dewatering and depressurization, leave a considerable amount of methane in the formation. Additional recovery can be achieved by sweeping the coalbed with CO<sub>2</sub>. Depending on coal rank three to thirteen molecules of CO<sub>2</sub> are adsorbed for each molecule of methane released, thereby providing an excellent storage site for CO<sub>2</sub> along with the additional benefit of enhanced coalbed methane (ECBM) recovery. Similar to maturing oil reservoirs, unmineable coalbeds are good candidates for CO<sub>2</sub> storage.

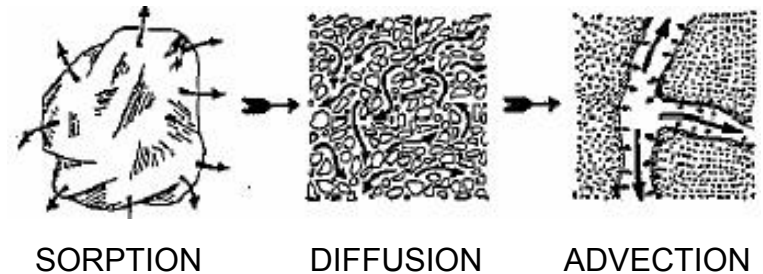
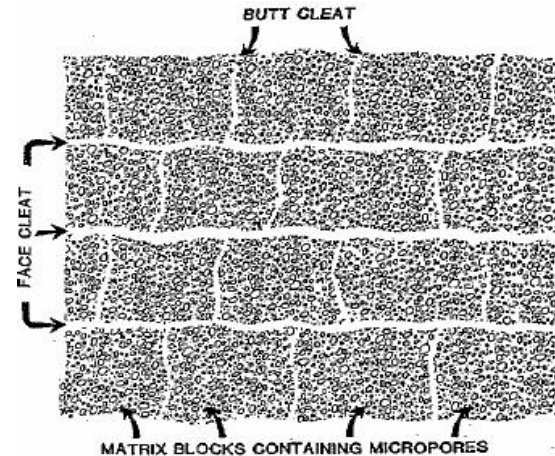
While not all potential areas of unmineable coal have been examined, the RCSPs have documented the location of 156–183 billion metric tons (172–202 billion tons) of CO<sub>2</sub> sequestration potential in unmineable coal seams.

	CO <sub>2</sub> Capacity Estimates by Partnership Unmineable Coal Seams			
	Low		High	
	(Billion Metric Tons of CO <sub>2</sub> )	(Billion Tons of CO <sub>2</sub> )	(Billion Metric Tons of CO <sub>2</sub> )	(Billion Tons of CO <sub>2</sub> )
BIG SKY	0.0	0.0	0.0	0.0
MGSC	2.3	2.5	3.3	3.6
MRCSP	0.7	0.8	1.0	1.1
PCDA	8.0	9.0	8.0	9.0
SECARB	57.4	63.3	82.1	90.5
SOUTHWEST	0.9	0.9	2.3	2.5
WESTCARB	86.8	96.1	86.8	96.1
<b>Total</b>	<b>156.1</b>	<b>172.6</b>	<b>183.5</b>	<b>202.4</b>



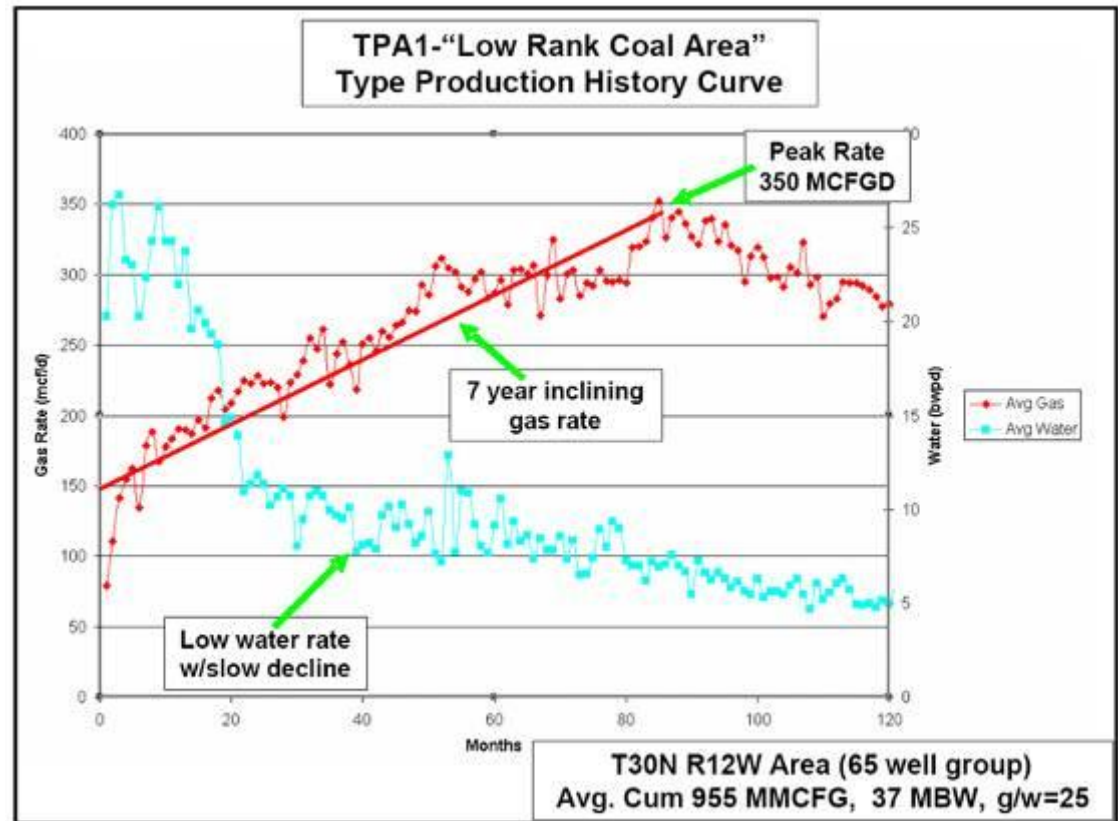
# Production from coal can be a complex process.

- Flow through coal is defined in large part by the cleat network.
- Methane sorbed on the coal is released by decreasing partial pressure.
  - May not be pure methane gas
- Water needs to be moved out of cleats before gas can flow.
- CO<sub>2</sub> injection causes reverse process (adsorption instead of desorption).



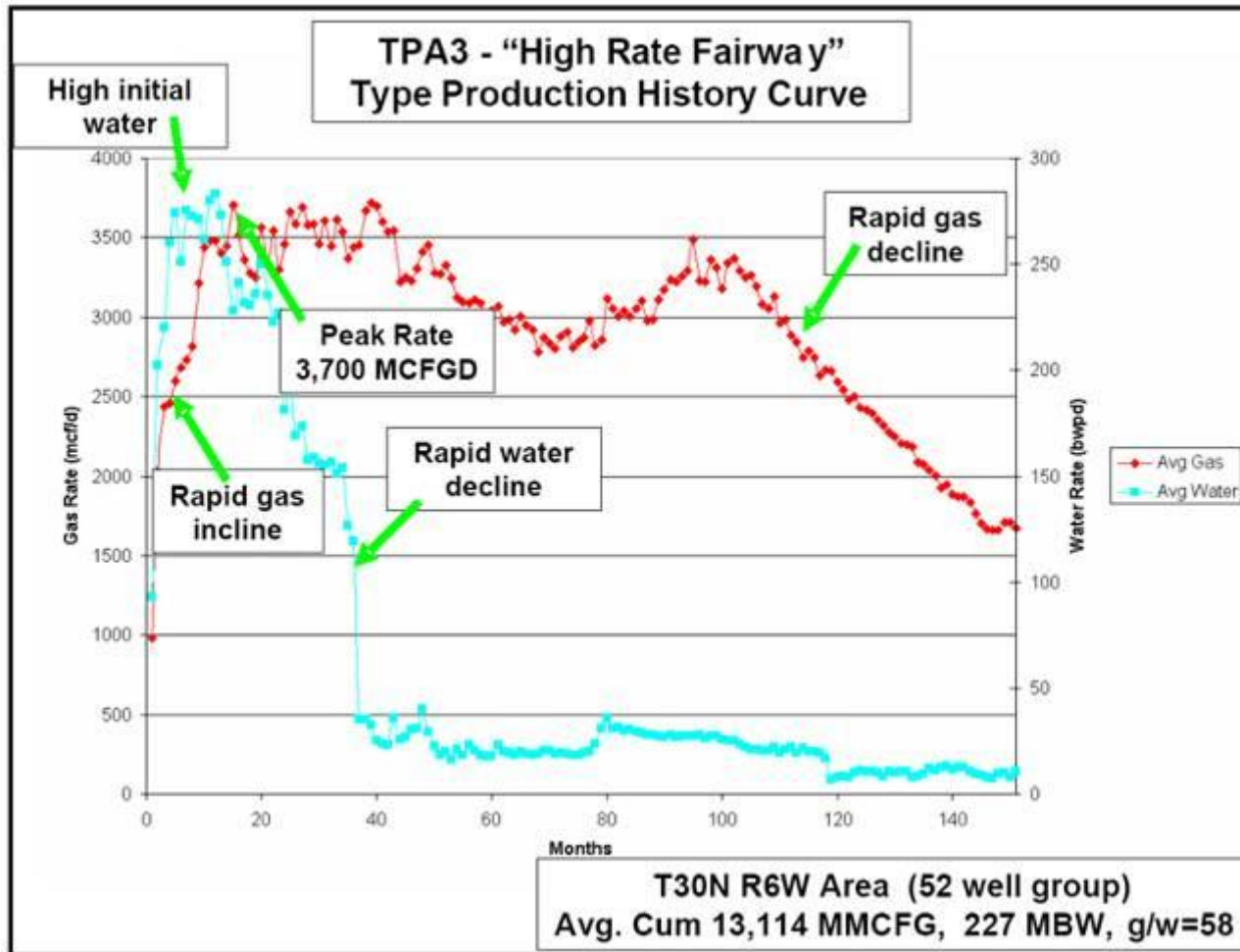
# Often, gas production is inhibited by initial water production.

- Relative permeability in the cleats affects flow of gas.
- Most of the water around the injection area should be removed before CO<sub>2</sub> is injected.



Meek and Levine, 2006

# However, sometimes water has short or little effect.

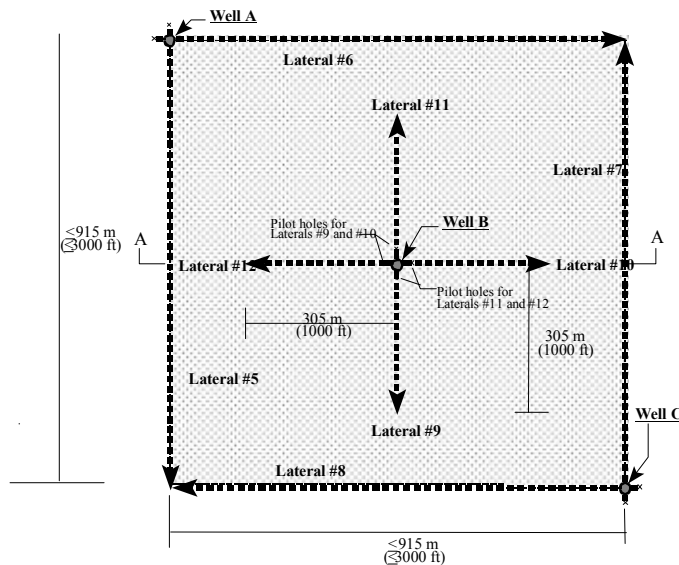


Meek and Levine, 2006

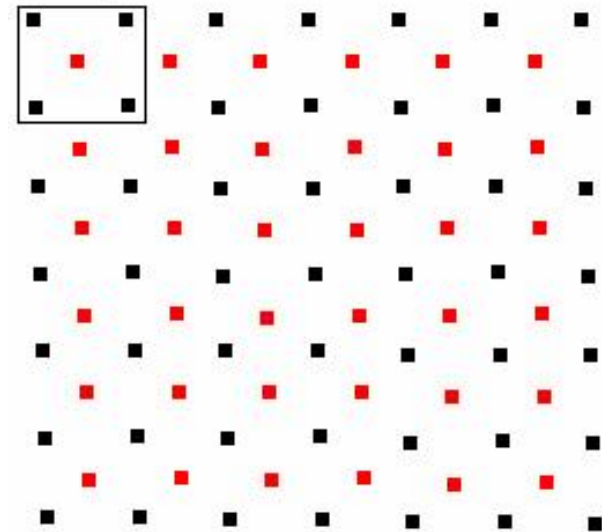


# CO<sub>2</sub> sequestration in coal will occur with ECBMR.

- Five-spot pattern for thick coals (San Juan Basin)
- For thinner seams, horizontal wells may be used.

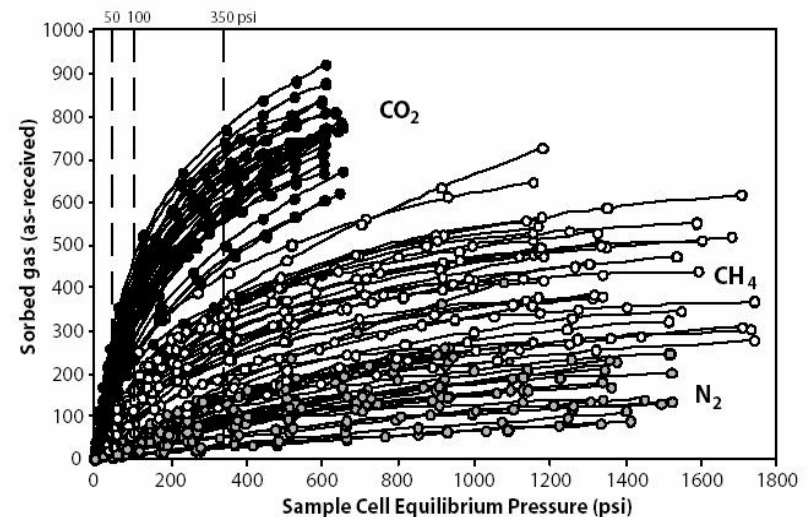
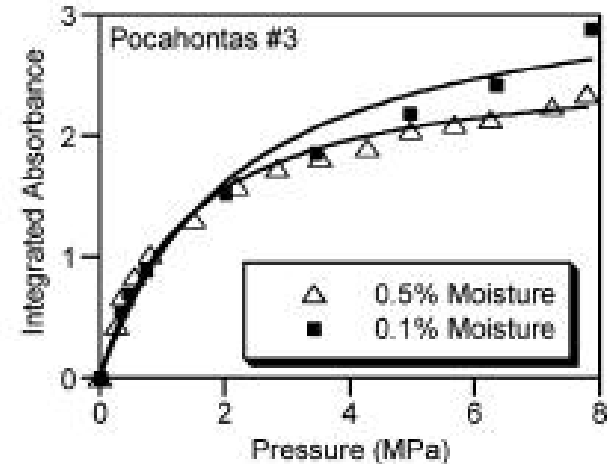


one pattern



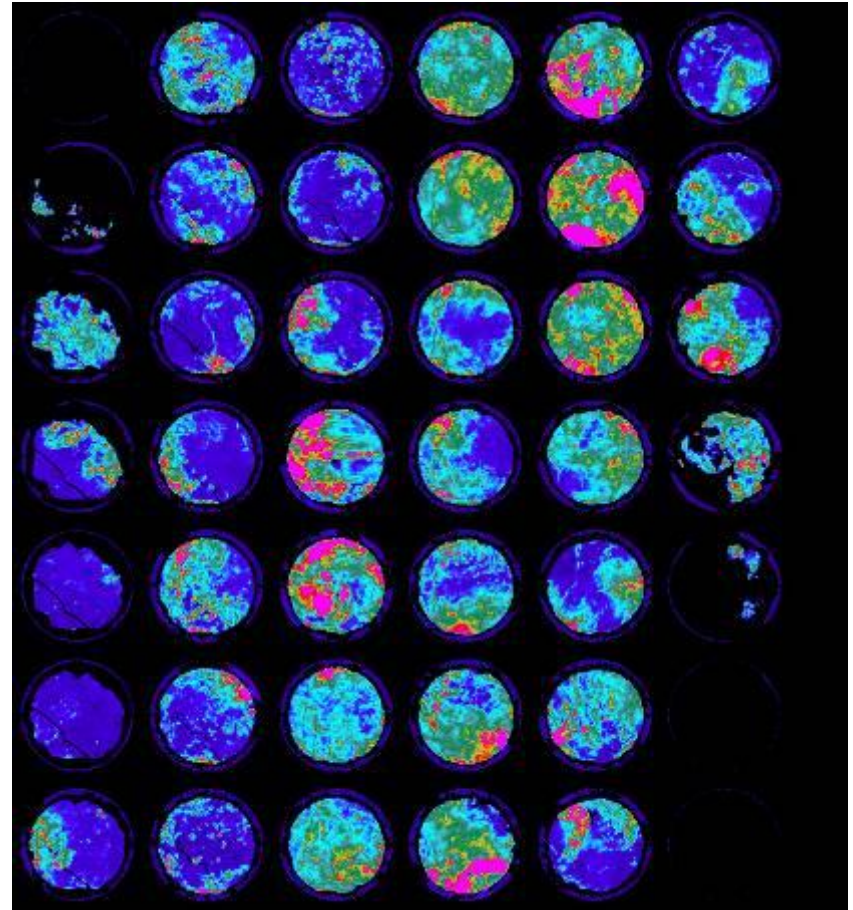
# How much CO<sub>2</sub> can be stored (and methane removed)?

- Sorption is typically considered to follow a Langmuir isotherm.
- Amount of sorbed gas is determined by:
  - Fluid pressure in the coal seam
  - Seam history (undersaturated seam)
- Gases other than methane may be sorbed.
- Dried coal gives different results than “wet” coal.
- CO<sub>2</sub> is preferentially sorbed to coal, compared to methane.



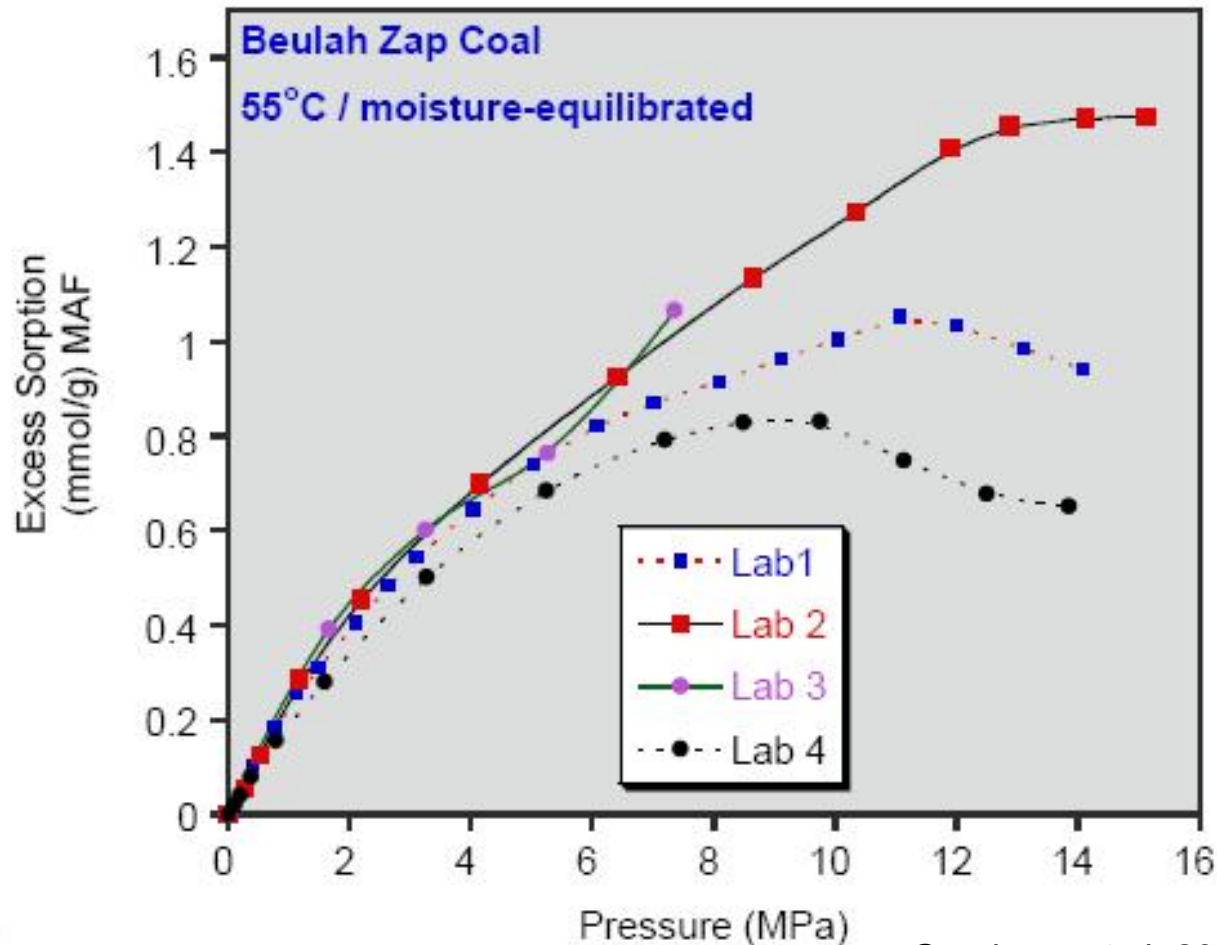
# Typical isotherms are taken on powdered samples.

- Powdered samples equilibrate quickly to produce isotherm points.
- But:
  - changes coal structure and available sorption sites
  - Doesn't allow for applied geomechanical pressure
- CT scanner can detect sorption on coal



# Some questions exist about amount of sorption at higher pressures.

## Interlab Results



Goodman et al, 2005, Coal-Seq IV.

# Diffusion time effects rates of production and sequestration.

- Time constant measures the rate at which gas diffuses through the coal matrix to the cleats and vice versa
- Helps determine how far ahead the CO<sub>2</sub> is in the cleats than in the matrix
- Cleat spacing is the major parameter.

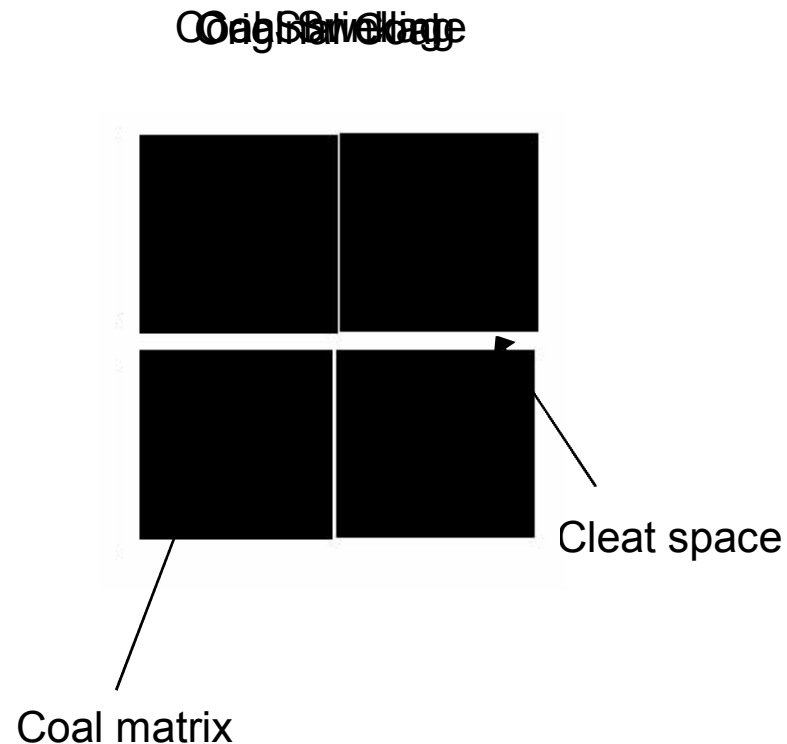
$$\tau = \frac{1}{D_{mi} \times a}$$

$D_{mi}$  (ft<sup>2</sup>/D) = micropore diffusion coefficient

$$a = \frac{5.7832}{R_{mi}^2}$$

$R_{mi}$  (ft) = cleat spacing

# Coal shrinkage and swelling can have significant impact on cleat permeability.



- Changes in cleat porosity lead to changes in permeability

# Fluid pressure affects changes in permeability.

- **Modified Palmer-Mansoori equation:**

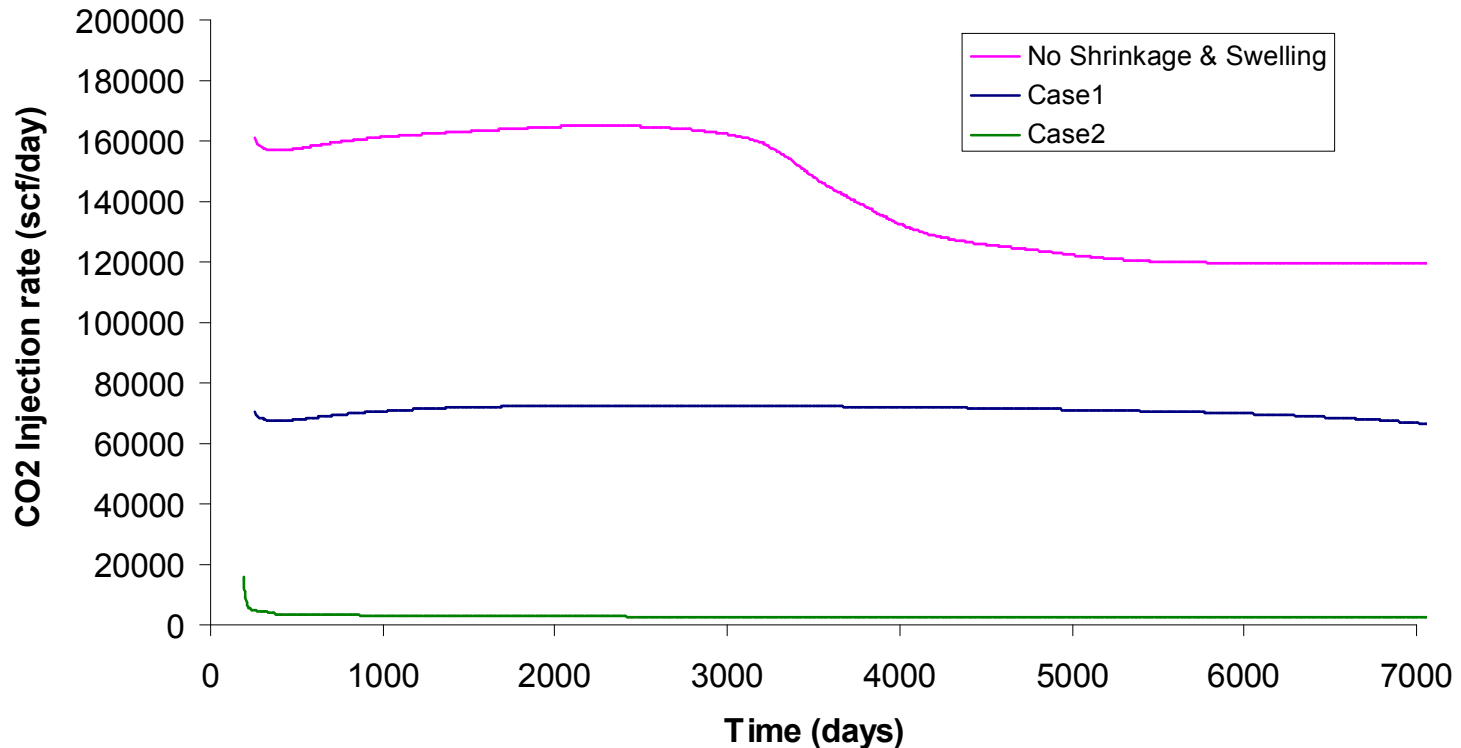
$$\phi = \phi_o^* + c_m P + \left( \frac{K}{M} - 1 \right) \sum_j^J s_{m,j} a_i$$

porosity change due to  
matrix compressibility

porosity change due to  
sorption

- **Most important coal properties for shrinkage and swelling:**
  - Porosity ( $\phi$ ), Young's modulus (E), Poisson's ratio ( $\nu$ )

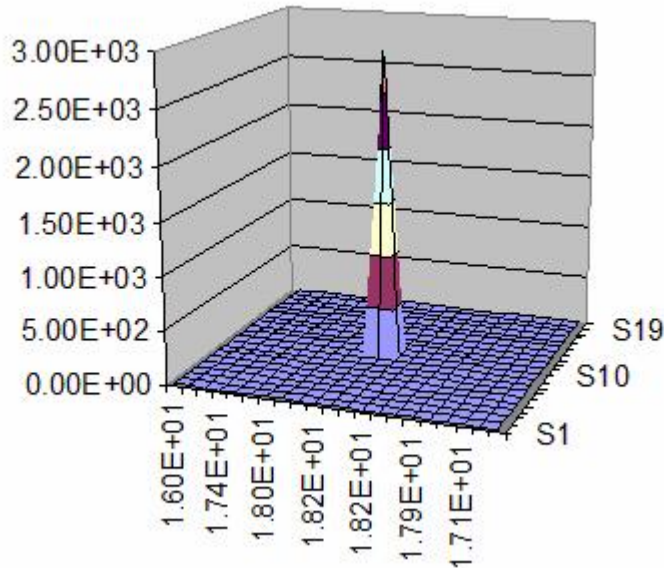
# Swelling may significantly reduce cleat permeability and therefore injectivity.



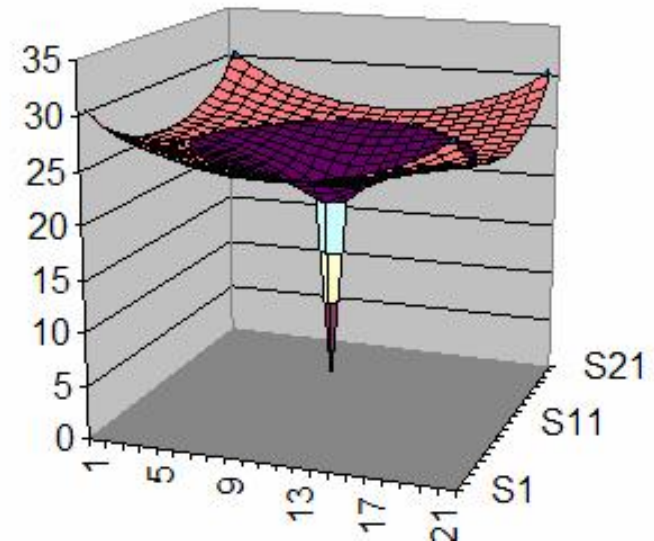
# Injectivity may or may not suffer significantly from coal swelling.

- Coal seam may undergo permeability increases at production wells while decreases at injection wells.
- Horizontal wells may help reduce effects on injectivity.

Pressure distribution (psi)



Permeability distribution (md)



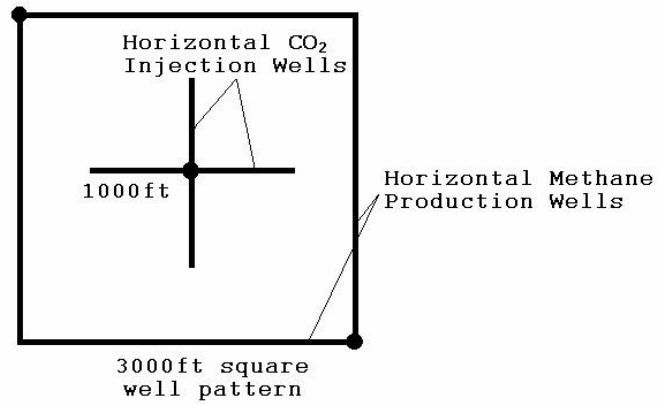
# How might injectivity be improved?

- **Fracturing coal seams (RECOPOL)**
  - **Drilling horizontal wells (CONSOL)**
  - **Injecting with other gas???** (JCOAL)
  - **Stop and start injection**
  - **Others???**
- 
- **Note: Not all injectivity reduction will be from swelling; some will be from near-wellbore damage.**

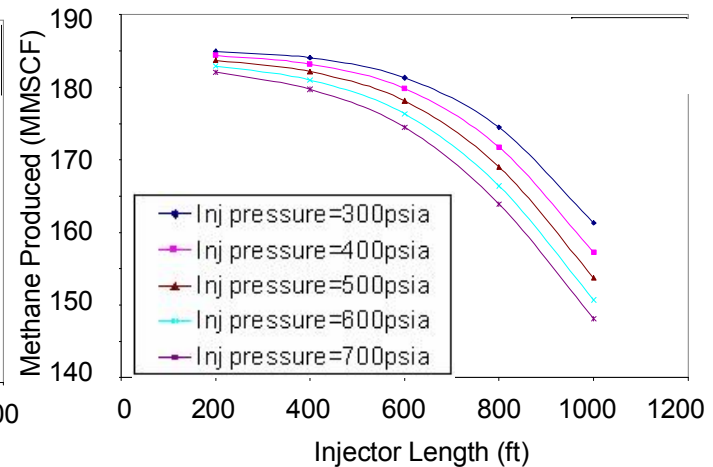
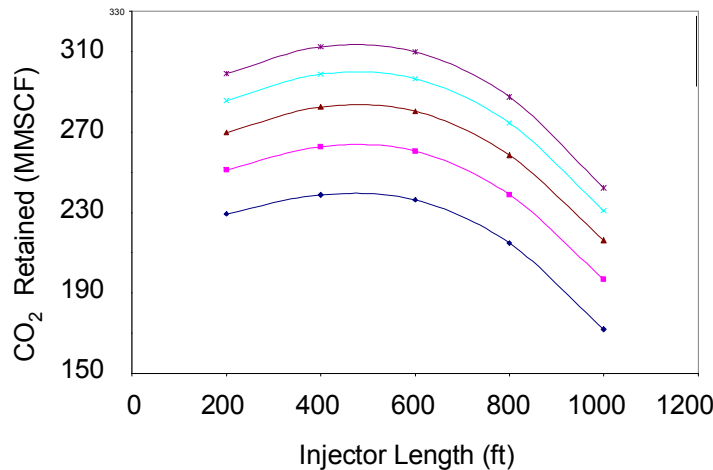
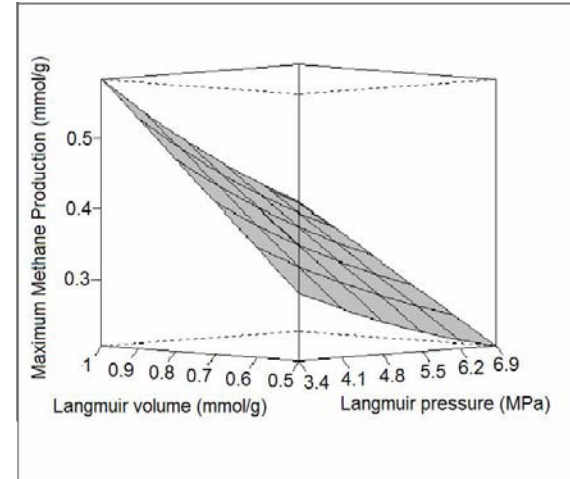
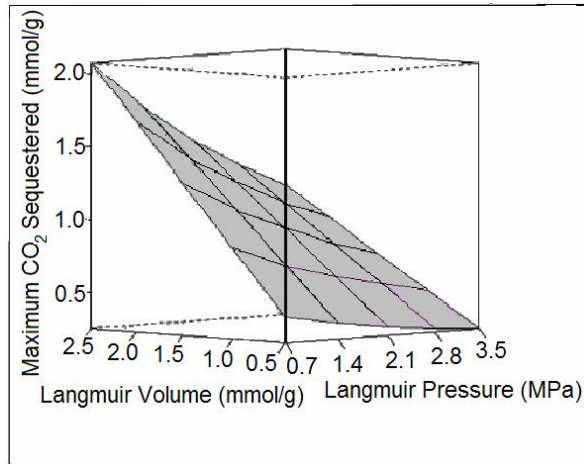
# Long-term storage in coal seams

- **Has not been proven.**
- **But:**
  - CO<sub>2</sub> is in the sorbed state
  - Coal seams have held methane and CO<sub>2</sub> for geologic time
  - If cleats filled with water, escape mechanism is through dissolution.
- **Still need a good caprock.**

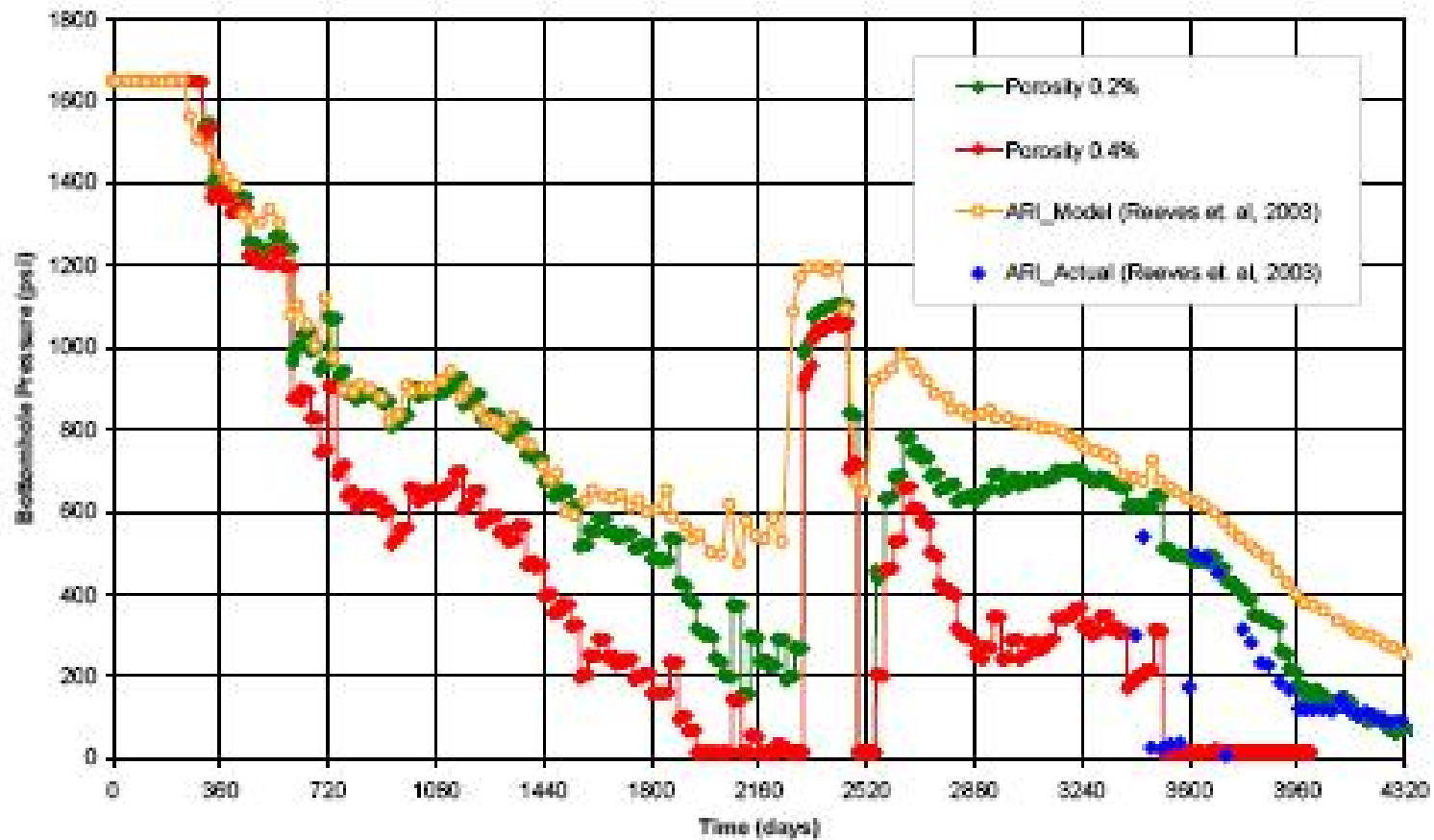
## Proposed Well Pattern for Coal Seam Sequestration



# Simulation can help optimize project design.



# History matching gives the opportunity to calibrate simulator to the coal seam.



Smith and Siriwardane, Coal-Seq V, 2007.

# Several simulators compared as part of GEOSEQ.

- **Several codes compared on synthetic and actual data.**
- **Simulators tested from CMG, TNO, ARI, BP, Shell, Imperial College, NETL/PSU.**
- **Tested ability to handle multiple gas components, dual porosity approach, mixed gas diffusion and sorption, and stress-dependent permeability and porosity.**
- **See Gunter, Law, Mavor, ICBM, 2005.**



# **Coal-Seq consortium is addressing several research issues related to coal seam sequestration.**

- **Sorption on coal cores under lithostatic pressure vs. powdered coal**
  - **Sorption with gas mixtures**
  - **Bi-directional diffusion**
  - **Coal swelling in presence of CO<sub>2</sub>**
- 
- **[www.coal-seq.com](http://www.coal-seq.com)**



# Some recent and upcoming projects in coal seam sequestration.

- **Allison Field ECBM project (San Juan Basin)**
  - Clear evidence of reduced injectivity
  - Increased methane production from ~77% to ~95% OGIP
  - 3:1 ratio of injected CO<sub>2</sub> to produced CH<sub>4</sub>
- **Southwest Regional Partnership San Juan Basin Project**
  - Upcoming injection of >75,000 tonnes
  - Field being monitored and modeled
- **CONSOL horizontal well pilot**
  - Injecting >10,000 tons into horizontal wells



# Some recent and upcoming projects in coal seam sequestration (cont).

- **RECOPOL – Poland**
  - Injected >700 tonnes
  - Methane production enhanced 55-70%
  - Could not continuously inject
  - Frac job helped increase injectivity
- **Canada-China ECBM pilot**
  - 192 ton injection
  - saw slight injectivity decreases over time
  - Simulator did admirable job of matching injection
- **JCOP – Japan**
  - ~100 ton liquid CO<sub>2</sub> injection
  - Clear ECBMR
  - Lower injectivity caused by swelling
  - Suggested nitrogen “WAG”



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# Questions?

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