Enhanced Coalbed Methane Recovery and CO_2 Storage in Coal Seams

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OUTLINE

- Background
- Coalbeds as both the reservoir and source rock
- Retention and release of gas in coal
- Coal permeability, dynamic permeability modelling in coalbed reservoir simulation
- Reservoir simulation of enhanced Coalbed Methane recovery and CO_2 storage in coal seams
- Conclusions

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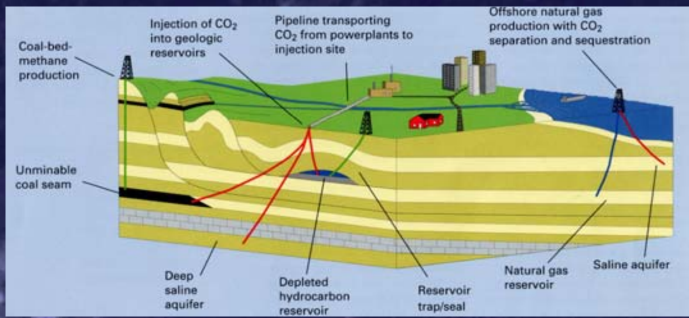
World Carbon Dioxide Storage Options

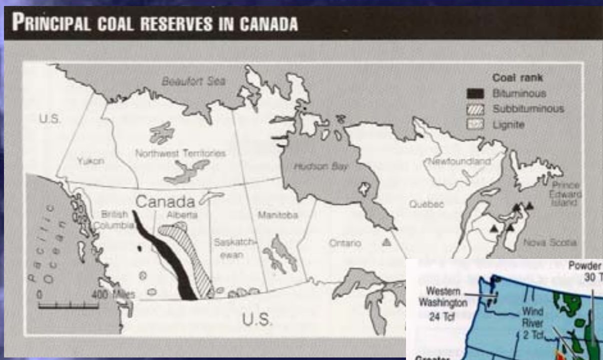
- Deep Ocean
- Saline Aquifers
- **Unminable Coal Seams** >15 Gt CO_2
- Depleted Oil Reservoirs
- Depleted Gas Reservoirs



Source: USGS

Major Coal Basins

Major Coal Basins



Major Coal Basins and Methane Resources

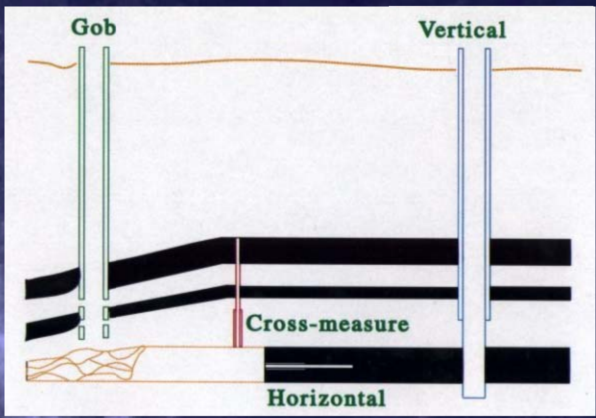
Continent	Country	Coal Resources x 10^9 tonnes	Methane Resources x 10^{12} m^3
Europe and the Russian Federation	Belgium		0.075
	France		0.600
	Germany	320	2.85
	Hungary		0.085
	Poland	160	2.85
	Russia	6,500	17-113
	Ukraine	140	1.7
	UK	190	1.7
North America	Canada	7,000	5.7-76
	USA	3,970	11
Asia	China	4,000	30-35
	India	160	0.85
	Indonesia	6	
	Kazakhstan	170	1.13
Australia		1,170	8.5-14
Africa		150	0.85
World Totals		~25,000	~84 - 262

Source: ARI, 1992

Methane Extraction from Coal Seams: Well Technology

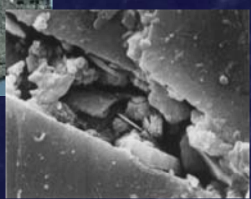
Underground Methane Drainage Practice

Coalbed Methane Technology



Coal as a Reservoir Rock: Structure

Uniform and orthogonal fracture (CLEAT) structure



microcleat

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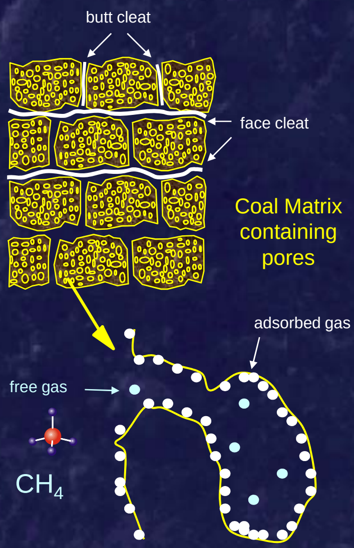
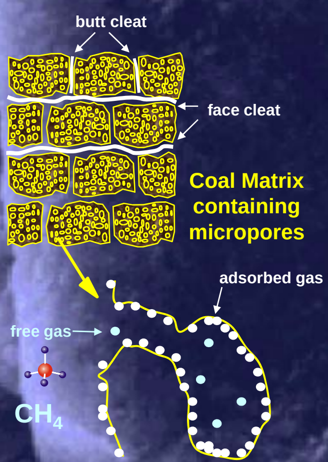
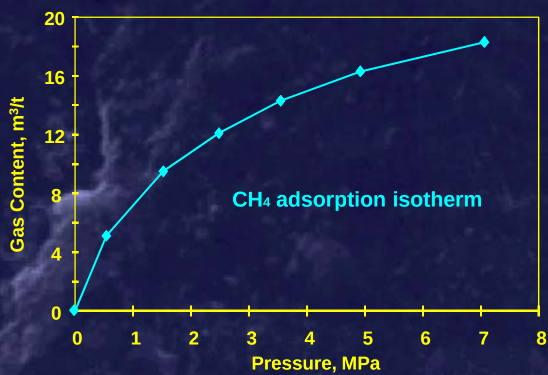
Coal as a Reservoir Rock: Structure



- Macropores > 50 nm
- Mesopores 2 – 50 nm
- Micropores < 2 nm
- Cleat system (2mm - 25 mm)
- Pore surface area 20 – 200 m^2

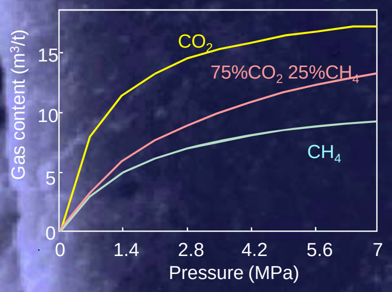
Coal as a Reservoir Rock – Gas Retention

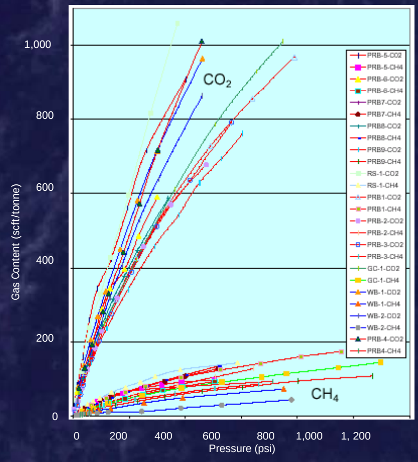




Coal as a Reservoir Rock:

CH_4 / CO_2 Retention in Coal - Adsorption Isotherm

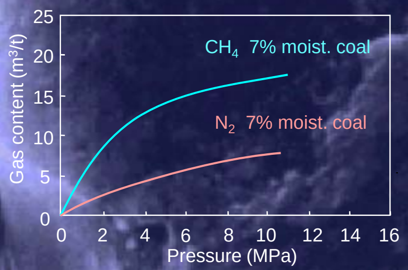


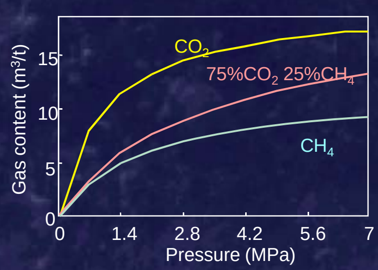


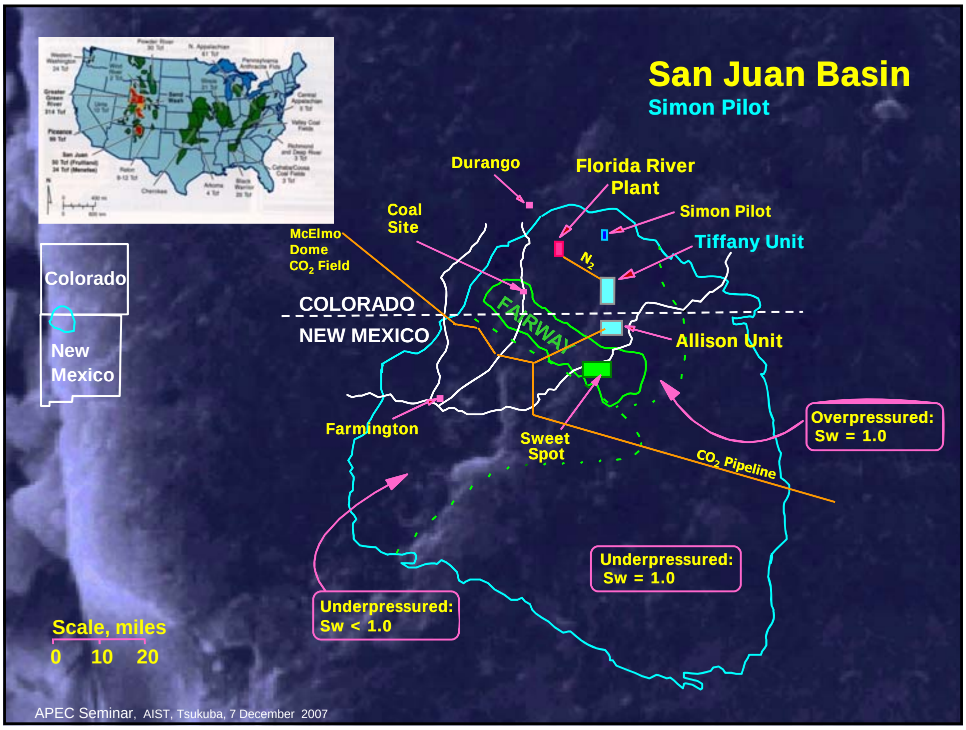
Langmuir equation: $V = \dfrac{V_L\, p}{P_L + p}$

Enhanced Coalbed Methane Recovery (ECBM)

- two principal methods of ECBM, namely N_2 and CO_2 injection (inert gas stripping and displacement sorption respectively)
- injection of nitrogen reduces the partial pressure of methane in the reservoir, thus promotes methane desorption without lowering the total reservoir pressure
- coal can adsorb approximately two to six times as much CO_2 by volume as methane, therefore, the assumption has been that the CO_2 injection stores 2-6 moles of CO_2 for every mole of CH_4 desorbed.






San Juan Basin
Simon Pilot
Colorado
New Mexico
Durango
Florida River
Plant
Coal
Site
Simon Pilot
Tiffany Unit
McElmo
Dome
CO_2 Field
COLORADO
NEW MEXICO
FAIRWAY
N_2
Allison Unit
Farmington
Sweet
Spot
Overpressured:
Sw = 1.0
CO_2 Pipeline
Underpressured:
Sw = 1.0
Underpressured:
Sw < 1.0
Scale, miles
0 10 20
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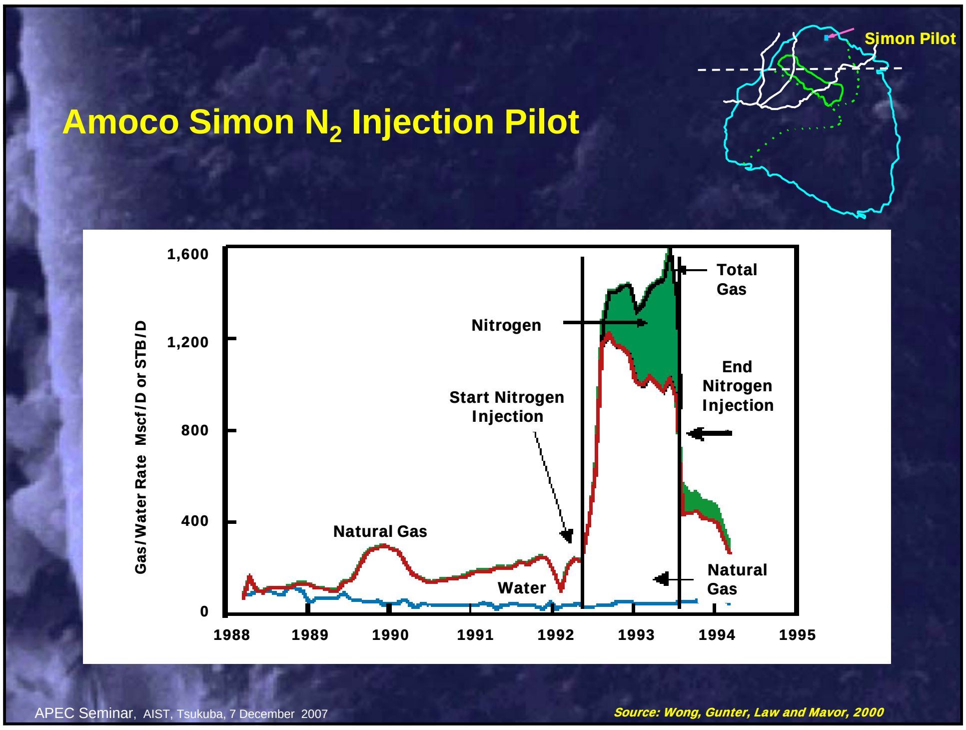
Amoco Simon N_2 Injection Pilot
Simon Pilot
Gas/Water Rate Mscf/D or STB/D
1,600
1,200
800
400
0
1988
1989
1990
1991
1992
1993
1994
1995
Total
Gas
Nitrogen
End
Nitrogen
Injection
Start Nitrogen
Injection
Natural Gas
Water
Natural
Gas
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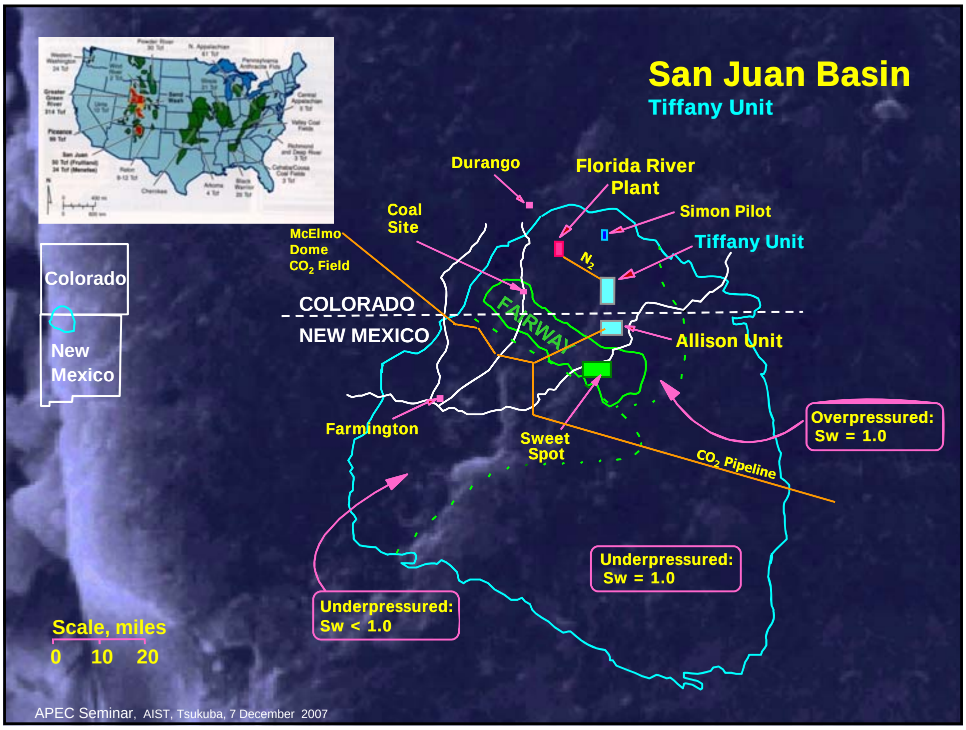
Source: Wong, Gunter, Law and Mavor, 2000



BP Tiffany Unit N_2 Injection (Full Scale Commercial Pilot)

9 Years of primary production,

12 N_2 injector wells,

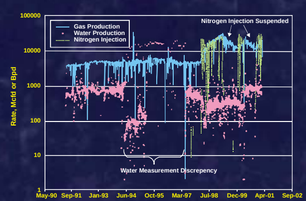
34 CH_4 production wells,

N_2 injection started in January 1998,

4-6 fold increase in production

early N_2 breakthrough

Source: Reeves and Peckot, ARI, USCBM Symp, 2001



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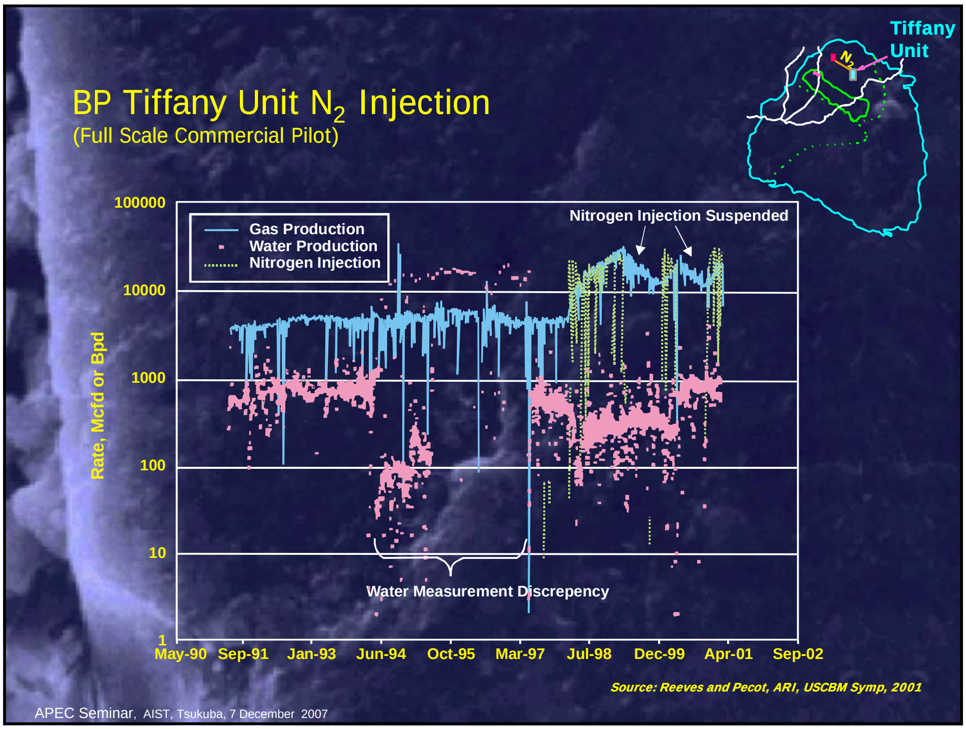
BP Tiffany Unit N_2 Injection
(Full Scale Commercial Pilot)
Tiffany Unit
Gas Production
Water Production
Nitrogen Injection
Nitrogen Injection Suspended
Rate, Mcfd or Bpd
100000
10000
1000
100
10
1
Water Measurement Discrepency
May-90 Sep-91 Jan-93 Jun-94 Oct-95 Mar-97 Jul-98 Dec-99 Apr-01 Sep-02
Source: Reeves and Pecot, ARI, USCBM Symp, 2001
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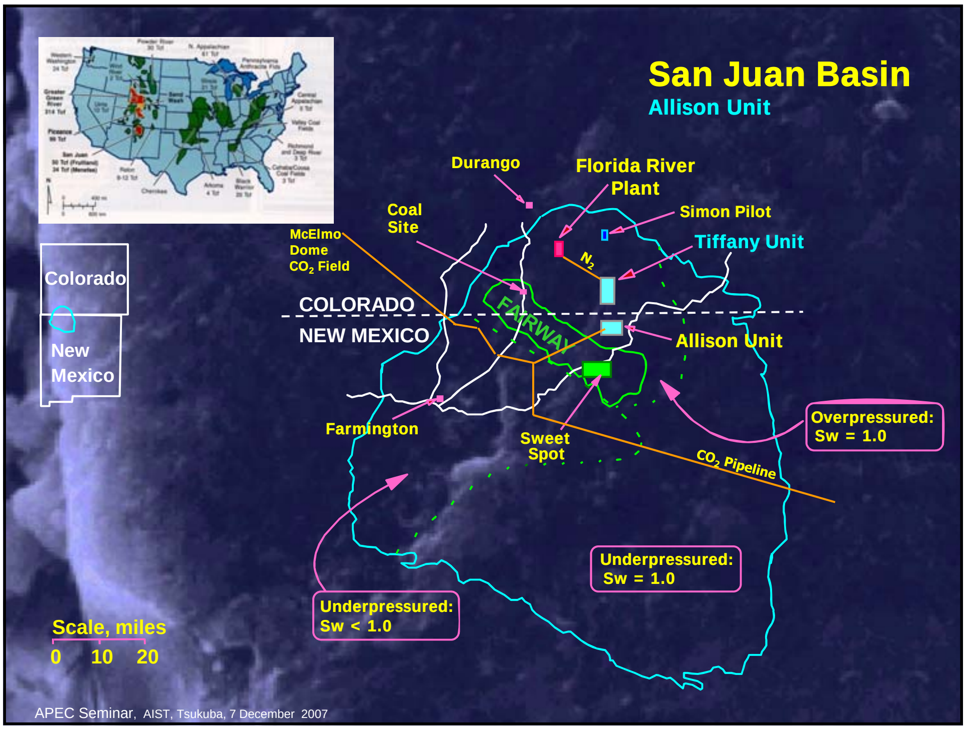
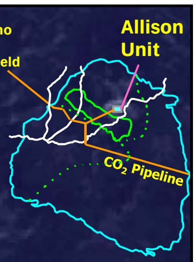

San Juan Basin
Allison Unit
Colorado
New Mexico
Durango
Florida River Plant
Coal Site
Simon Pilot
Tiffany Unit
McElmo Dome CO_2 Field
COLORADO
NEW MEXICO
FAIRWAY
Allison Unit
Farmington
Sweet Spot
CO_2 Pipeline
Overpressured: Sw = 1.0
Underpressured: Sw = 1.0
Underpressured: Sw < 1.0
Scale, miles
0 10 20
APEC Seminar, AIST, Tsukuba, 7 December 2007

Burlington Resources Allison Unit CO_2 Injection



6 Years of primary production (1988/89 – 1995),

4 CO_2 injector wells,

9 CH_4 production wells,

CO_2 injection started in May 1995,

reduced CO_2 injectivity with time

No significant CO_2 breakthrough

Source: Reeves and Pecot, ARI, USCBM Symp, 2001

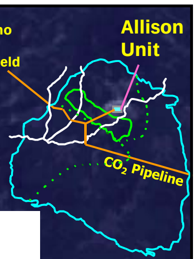
Alberta Research Council, Fenn Big Valley CO_2 Injection

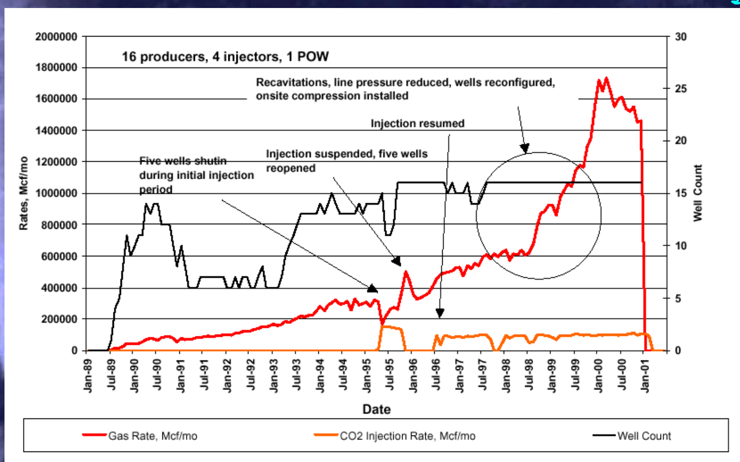
Field micro-pilot testing started in 1997

coal swelling and reduced permeability observed

Source: Wong and Gunther, 1999
Law, Van der Meer, Mavor and Gunter 2000

Burlington Resources Allison Unit CO_2 Injection





Source: Reeves, ARI, Coal-Seq Forum, 2002

Coal Permeability and Gas Flow

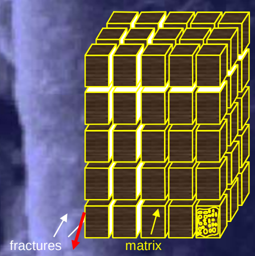
"… contrary to what is usually supposed, solid coal is extremely airtight, and lets very little air or gas through, even with a driving pressure of a whole atmosphere."

Ivor GRAHAM, 1916

"….that the rate of gas flow through the coal is a function of the difference in partial pressure of methane along the flow path. Therefore, the emission of methane from a lump of coal is not dependent on the total external pressure, but upon the partial pressure of the methane in the atmosphere and the pressure of the gas in coal."

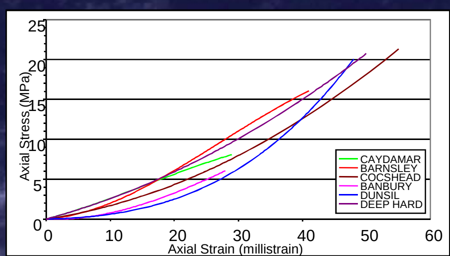
Ivor GRAHAM, 1919

Strength, Elastic and Flow Properties of Coal



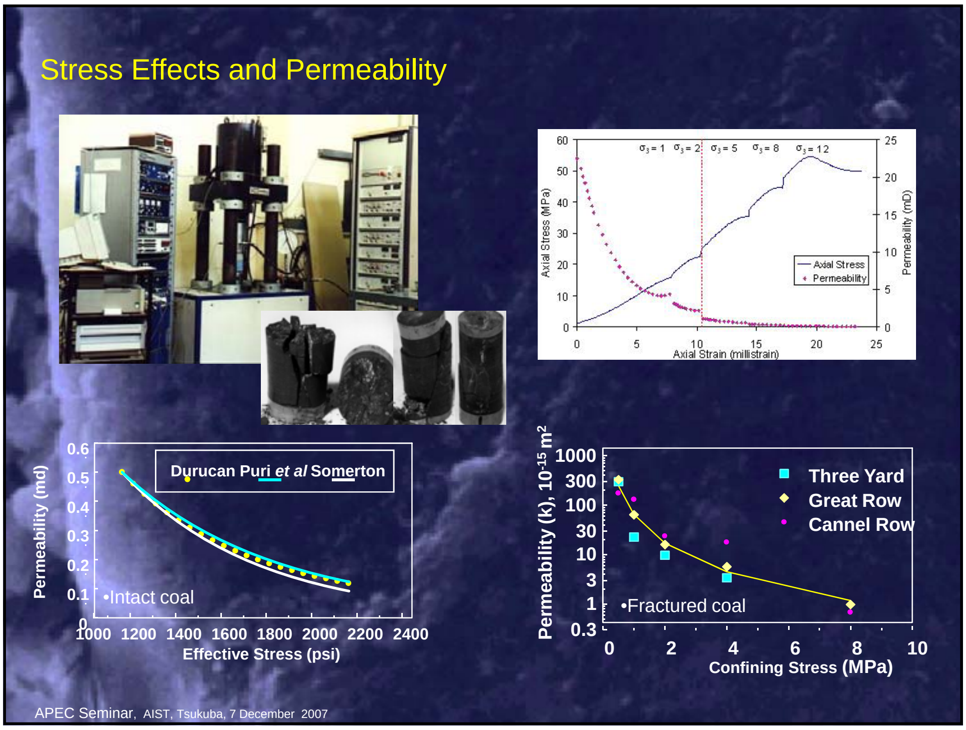
Coal structure is highly elastic

	Coal (Various)	Weak Reservoir Sandstone	Sandstone	Limestone	Shale
Young's Modulus, *E* (GPa)	0.86 - 3.9	0.4 – 1.8	10- 20	35 - 55	5 - 70



Coal permeability is

- Anisotropic
- Highly stress dependent


Stress Effects and Permeability
Axial Stress (MPa)
Permeability (mD)
Axial Strain (millistrain)
Axial Stress
Permeability
Permeability (md)
Durucan Puri et al Somerton
•Intact coal
Effective Stress (psi)
1000 1200 1400 1600 1800 2000 2200 2400
Permeability (k), 10^{-15} m^2
Three Yard
Great Row
Cannel Row
•Fractured coal
Confining Stress (MPa)
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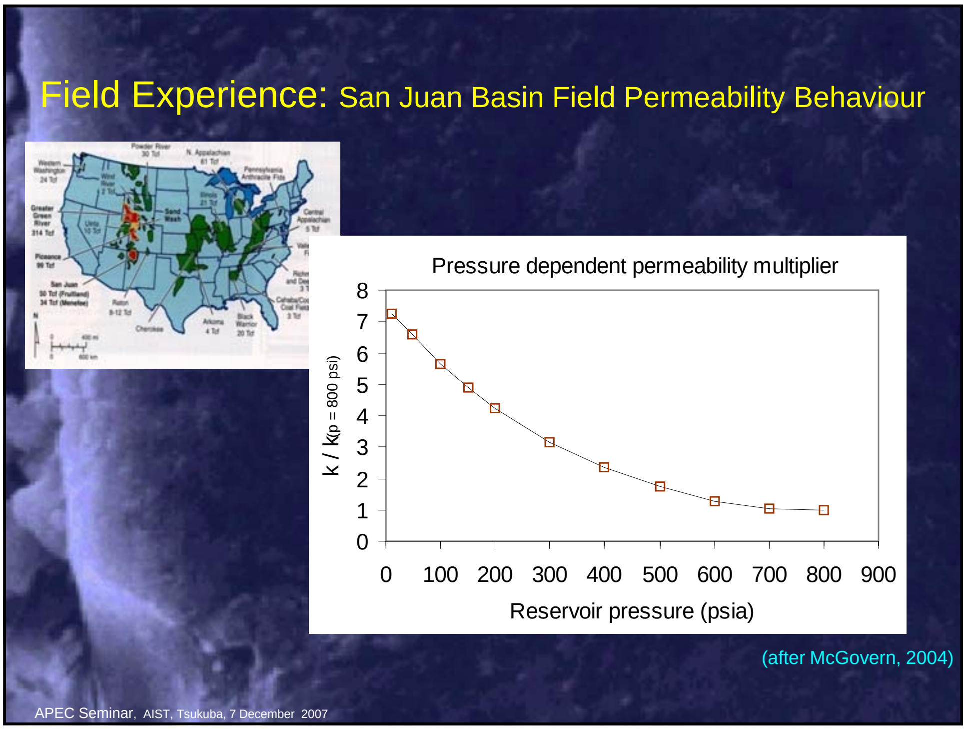
Field Experience: San Juan Basin Field Permeability Behaviour
Pressure dependent permeability multiplier
k / k(p = 800 psi)
Reservoir pressure (psia)
0 100 200 300 400 500 600 700 800 900
(after McGovern, 2004)
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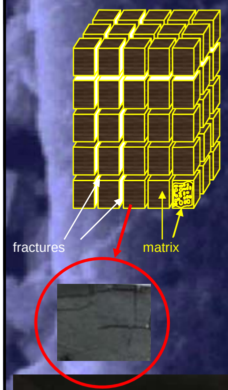
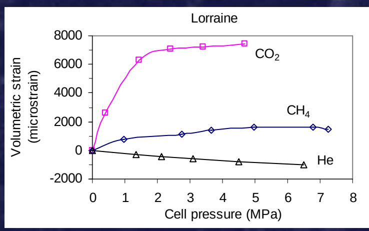
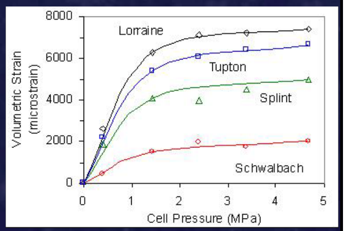
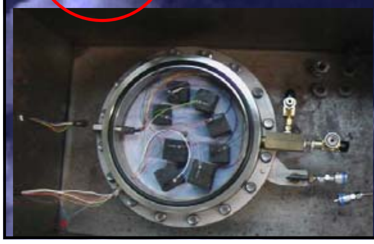
Pore Pressure Effects on Permeability: Matrix Shrinkage and Swelling

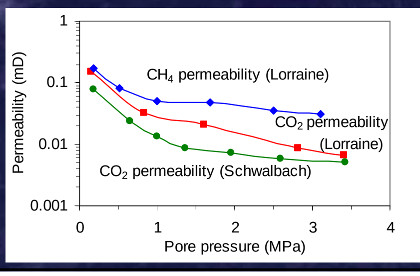






$$\varepsilon_s = \frac{\alpha_s V_L\, p}{P_L + p}$$





Primary and Enhanced Coalbed Methane Recovery Permeability Model

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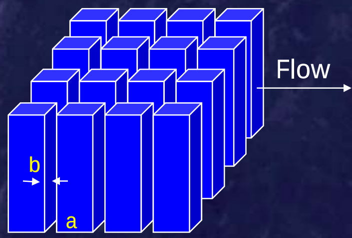
Model for Changes in Coalbed Permeability During Primary Recovery

Bundled matchstick model



(after Seidle et al., 1992)

$$k = k_0 e^{-3c_f(\sigma - \sigma_0)} \longleftarrow k = \frac{1}{12}\frac{b^3}{a}$$

c_f – cleat volume compressibility

$\sigma - \sigma_0$ - changes in effective horizontal stress

$$\sigma - \sigma_0 = -\frac{\nu}{1-\nu}(p - p_0) + \frac{E\alpha_S(V - V_0)}{3(1-\nu)}$$

compaction term — shrinkage term

α_S – shrinkage coefficient

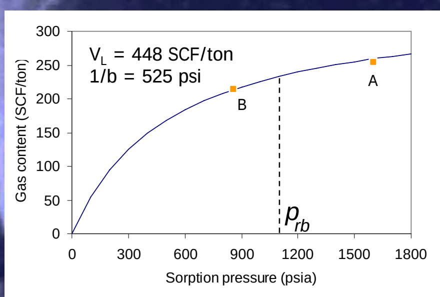
V – adsorbed gas volume

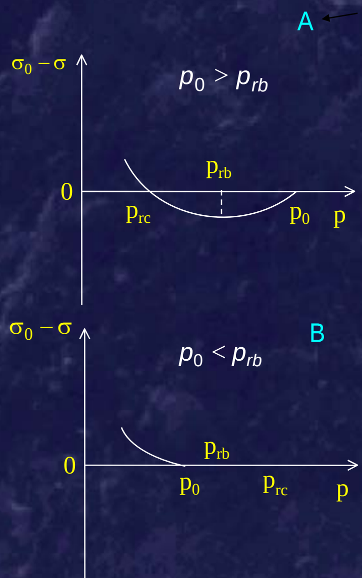
E – Young's modulus

ν – Poisson's ratio

Schematic Permeability Behaviour

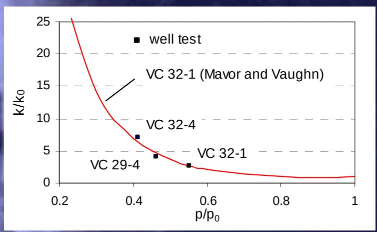
$$\sigma_0 - \sigma = \frac{E\alpha_S(V_0 - V)}{3(1-\nu)} - \frac{\nu}{1-\nu}(p_0 - p)$$

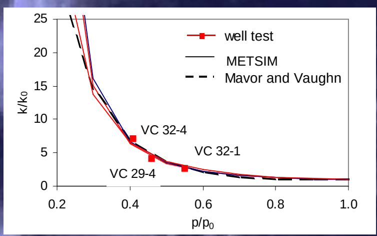




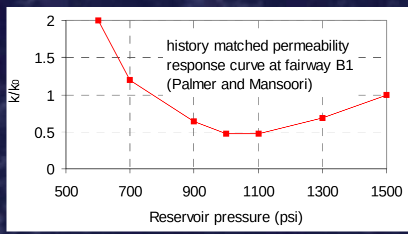
Model Validation: US San Juan Basin History Match

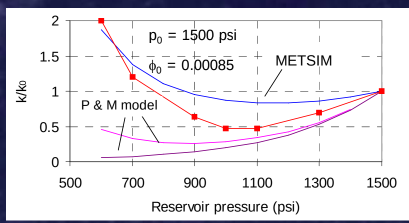
Valencia Canyon Wells:
Steady increase in permeability





Fairway B1 "boomer" Well:
Strong permeability rebound





Permeability Model For Enhanced Recovery

$$k = k_0 e^{-3c_f(\sigma-\sigma_0)}$$ Cleat permeability

Primary recovery

$$\sigma - \sigma_0 = -\frac{\nu}{1-\nu}(p-p_0) + \frac{E\alpha_S(V-V_0)}{3(1-\nu)}$$

Shrinkage/swelling term

Enhanced recovery

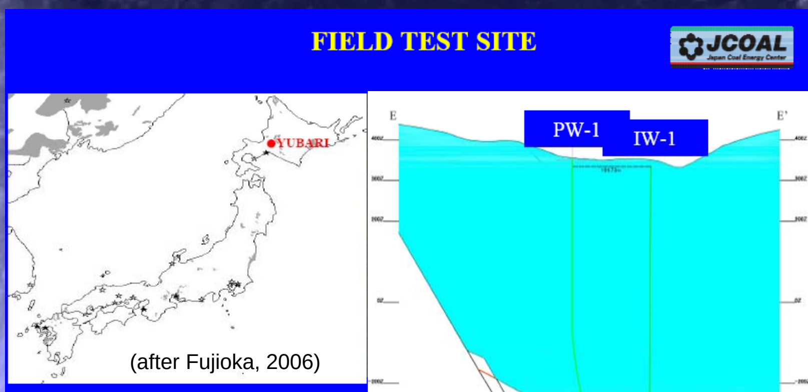
$$\sigma - \sigma_0 = -\frac{\nu}{1-\nu}(p-p_0) + \frac{E}{3(1-\nu)}\sum_{j=1}^{n}\alpha_{Sj}(V_j - V_{j0})$$

a_{Sj} – shrinkage/swelling coefficient for gas component j

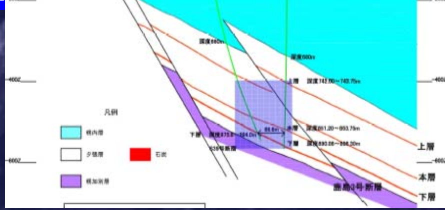
Imperial College in-house ECBM Simulator METSIM2

- 3D two-phase Darcy flow in cleats, Fickian diffusion in matrix (allows for bidisperse diffusion)
- multi-component gas mixture (CH_2, CO_2, N_2)
- matrix shrinkage/swelling effects one permeability
- mixed gas sorption and diffusion
- extended Langmuir model

Yubari Field Pilot, Hokkaido, Japan



(after Fujioka, 2006)

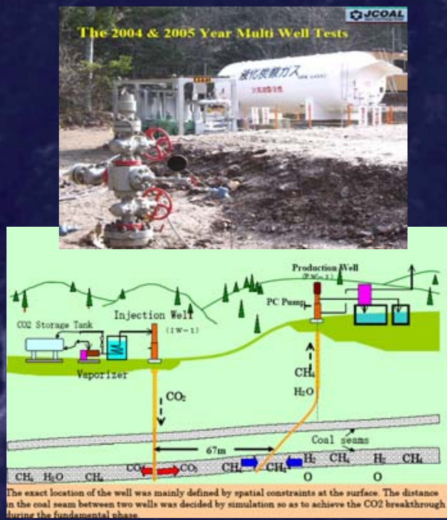


- In a mountainous national forest area
- Bounded by four major faults

Yubari Field Test

Three stages

- CO_2 injection huff-puff test (well IW-1, 7.5 tons CO_2)
- Multi-well CO_2 injection tests
  - 2004 (16 days, 35.7 tons CO_2)
  - 2005 (42 days, 115.4 tons CO_2)
- N_2 flooding test
  - 2006 N_2-flooding (9 days, 32 tons N_2)
  - 2006 Pre- and Post-N_2 flooding CO_2 injection

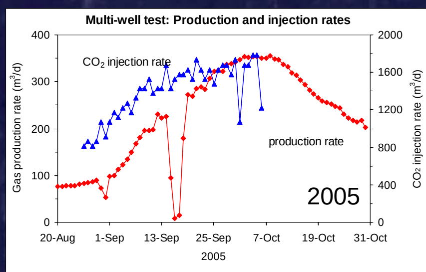


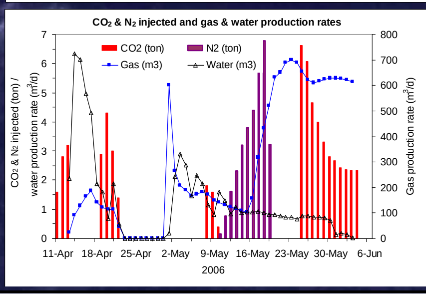
- Well tests prior to the test and after 2004 CO_2 injection
  - 1 -> 0.08 md

CO_2 Injection and N_2 Flooding Test Field Injection and Gas Production Rates

- 2004:
  - 15 days injection
  - 1.8 – 2.9 tones CO_2/day (1 ton = 506 std. m^3)
- 2005:
  - 40 days injection
  - 1.7 – 3.5 tones/day

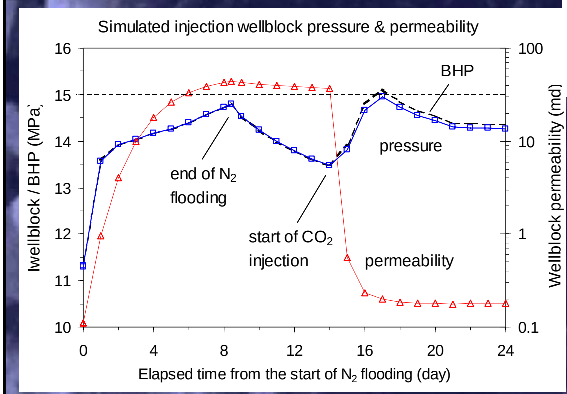
Low production rates: < 400 m^3/day

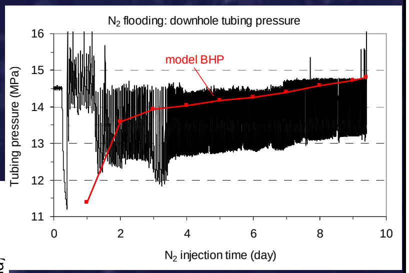




Reservoir Simulation of the 2006 N_2 Flooding Test

Simulated N_2/CO_2 injection wellblock permeability and BHP

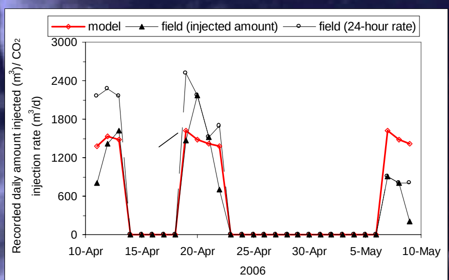


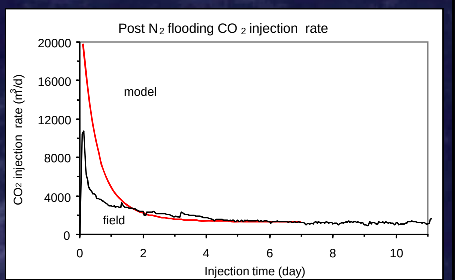


Simulated vs. field N_2 injection BHP

Model Prediction vs Field Data: Pre- and Post- N_2 Flooding CO_2 Injection Rates

Pre-N_2 flooding





N_2 flooding temporarily improved CO_2 injectivity, which declined quickly back to the pre-flooding level (~ 3 tones/ day) after two days.

Concluding remarks

- Coalbed reservoirs have unique characteristics: storage, transport and production mechanisms, permeability behaviour.
- Considerable advances in the reservoir simulation of ECBM, especially in permeability modelling have been made.
- While matrix shrinkage is desirable during primary recovery, CO_2 matrix swelling can have a severe impact on coalbed permeability and well injectivity.
- Long term fate of injected CO_2 in coalbeds is uncertain, as CO_2, especially at supercritical conditions, reacts with the reservoir rock and fluids.