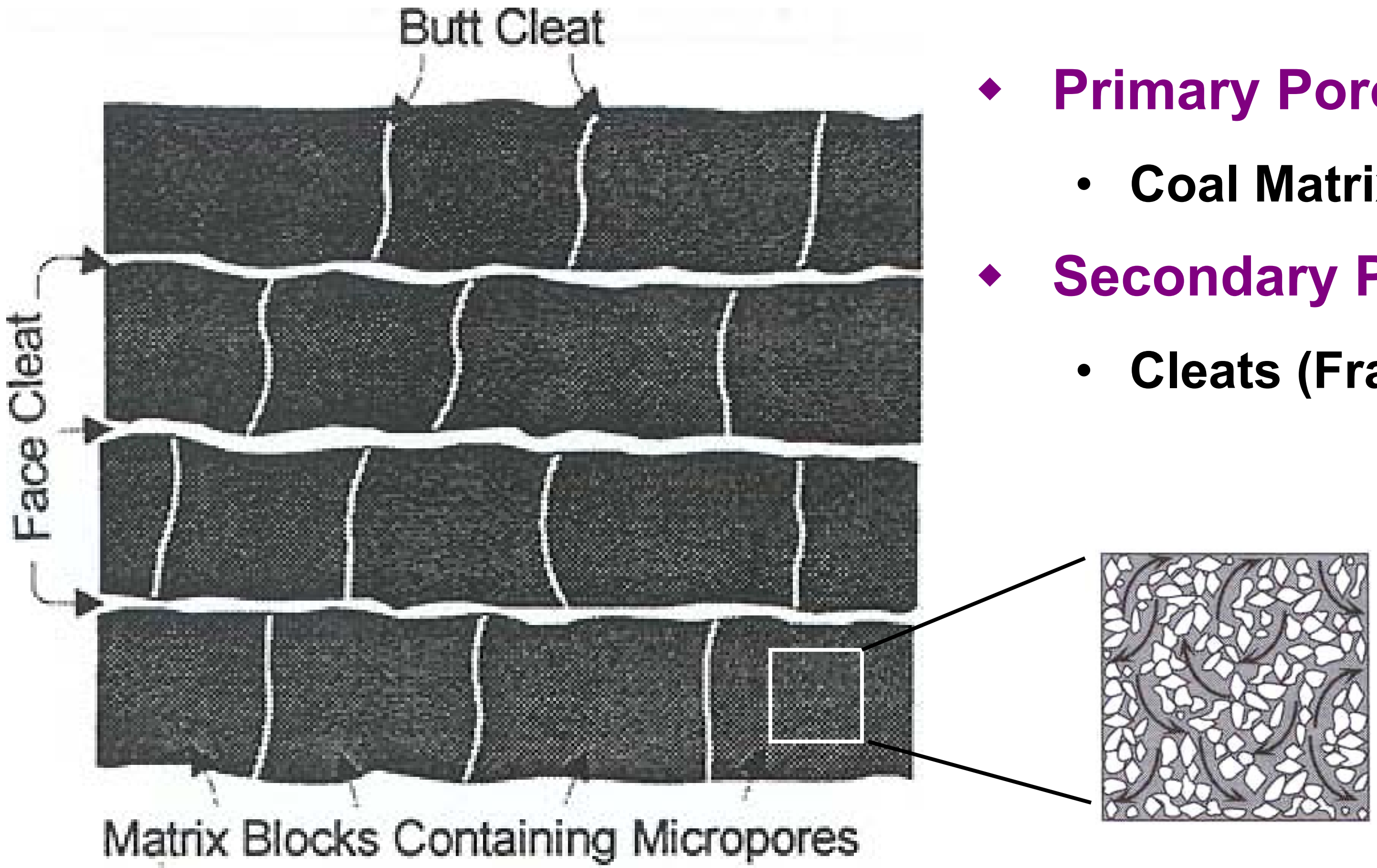
CBM & ECBM Reservoir Simulation

Computer Modelling Group Inc.

Acknowledgements

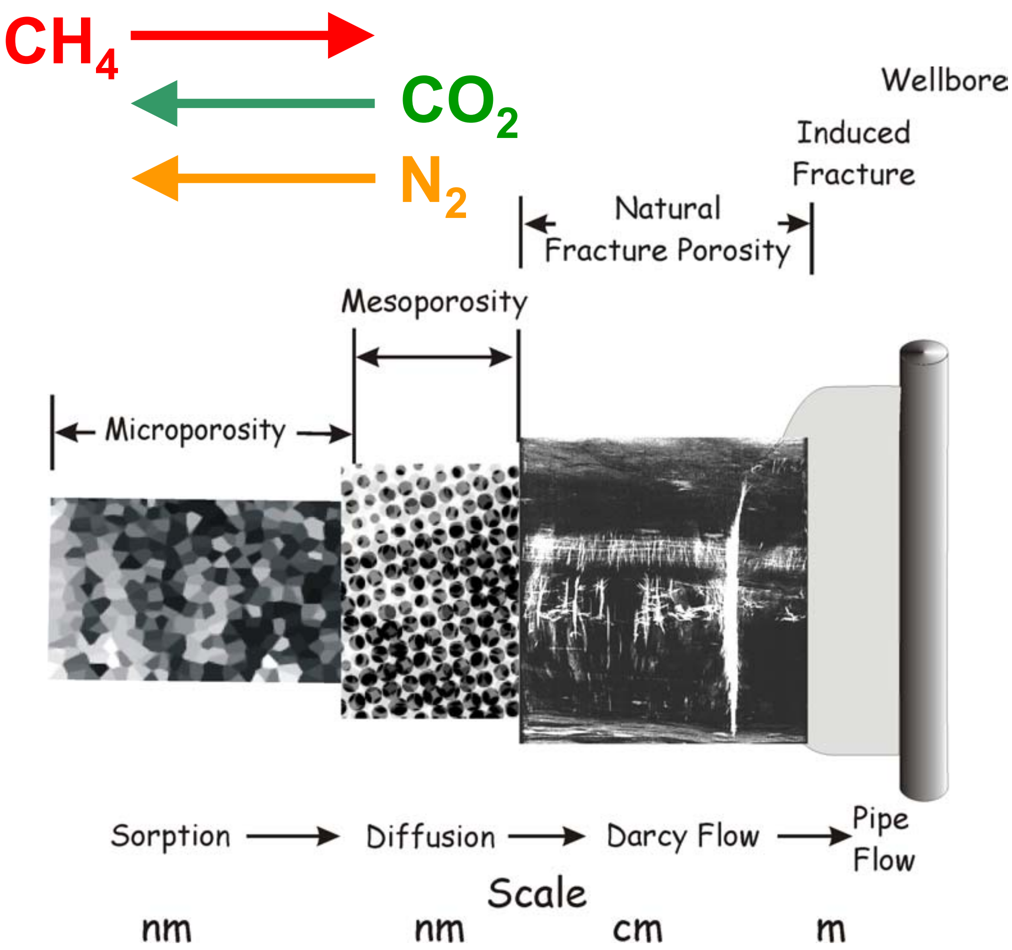
- Presentation Created by
  - Peter Sammon (CMG, Ltd.) – Technical Coordinator of GEM development team
  - Mohamed Hassam (CMG, Ltd.) – member of GEM development team
- Work performed with assistance from
  - David H.-S. Law (Alberta Research Council) – Head of CBM Consortium
  - Bill Gunter (Alberta Research Council) -
- Multi-component extension to Palmer-Mansoori Theory
  - Matt Mavor (Tesseract) - Consultant

Structure of Coal



- **Primary Porosity**
  - **Coal Matrix**
- **Secondary Porosity**
  - **Cleats (Fractures)**

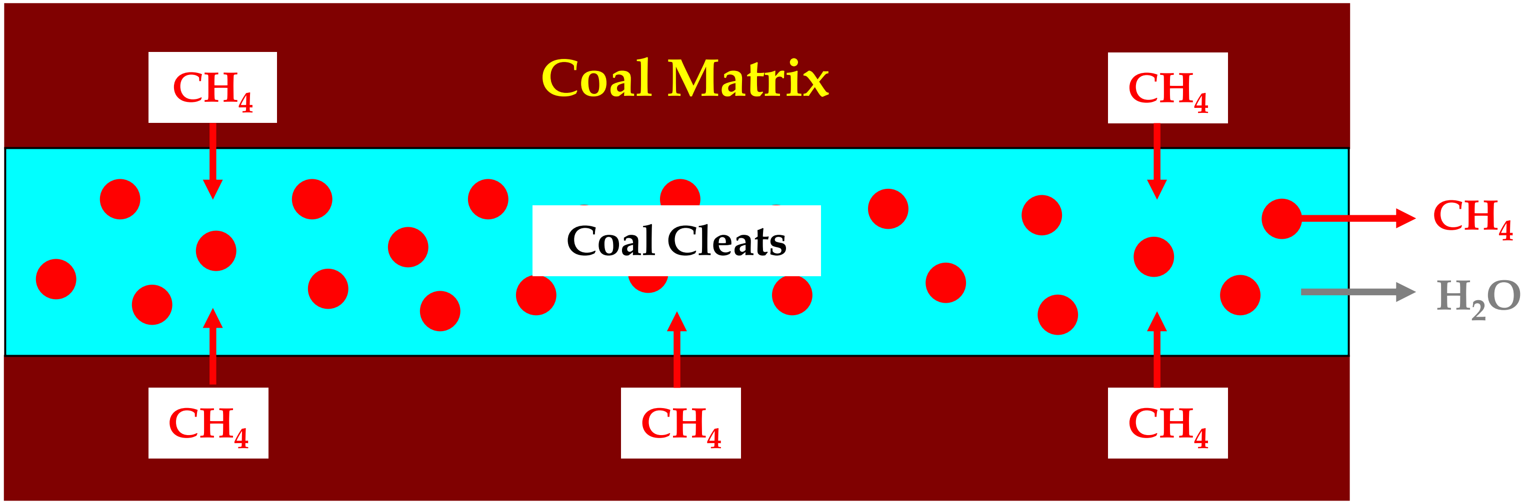
Flow in Coal



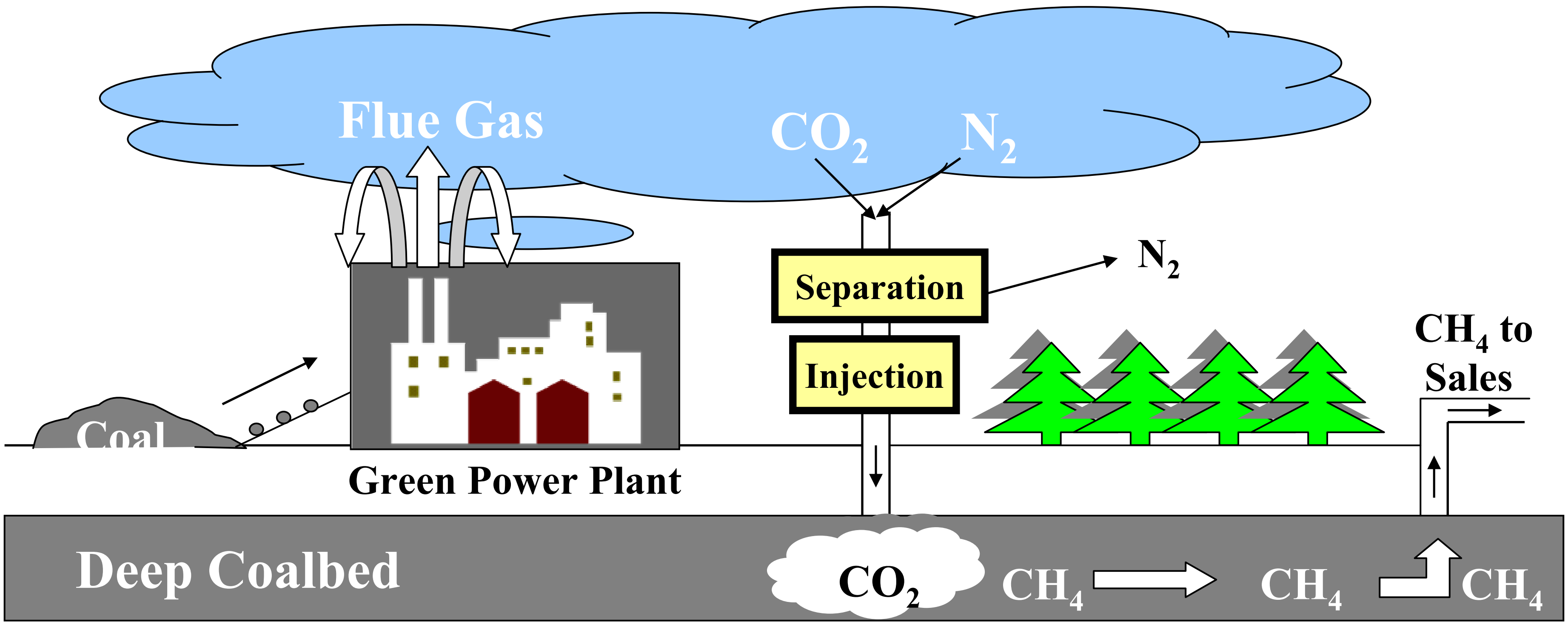
- Primary CBM recovery
- CO_2 enhanced recovery (CO_2-ECBM)
- N_2 enhanced recovery (N_2-ECBM)
- Flue gas enhanced recovery

Primary CBM Recovery Mechanisms

- Reduce cleat pressure by producing water
- Methane desorbs from matrix, diffuses to cleats
- Methane and water flow to wellbore
- Cleat permeability affected by matrix responses



ECBM Processes



- Enhanced Coalbed Methane (ECBM) Recovery
- Green House Gas (GHG) Sequestration

Modelling Issues: Properties of Coal

- Primary porosity system (coal matrix)
  - Microporosity (< 2 nm)
  - Mesoporosity (2 – 50 nm)
  - Very low flow capacity: perms in microDarcy range
- Secondary porosity system (coal cleats)
  - Macroporosity (> 50 nm)
  - Natural fractures
  - Much greater flow capacity: perms in milliDarcy range

Issues for CBM Modelling

- Multiple porosity model required
  - Allows standard Darcy flow in fracture (Cleat) system
- Diffusion process for gas from matrix to fracture
  - No Darcy flow required here
- Adsorption/desorption of gas in the matrix
  - Pressure-dependent isotherms
- Coal shrinkage due to gas desorption and swelling due to cleat depressurization
  - Alters fracture permeability
- Water Blockage Issues
  - Water in cleats can interfere with gas flow from/to matrix

Issues for ECBM Modelling

- All the above for CBM but add
  - Multi-component gas (CH_4, CO_2, N_2, …)
    - Need to calculate accurate gas properties
  - Multi-component adsorption/desorption isotherms
  - Multi-component diffusion modelling
    - Can have bi-lateral diffusion
  - Coal mechanics become more complicated
    - Additional coal swelling due to CO_2 adsorption competing with other effects
  - Could take place in an non-isothermal environment

GEM: ECBM capabilities

- **How GEM addresses these issues**
  - **Start with a multi-component, multi-phase reservoir simulator: GEM (CMG's EOS Reservoir Simulator)**
  - **GEM uses an Equation of State (EOS) formulation**
    - **Accurate fluid properties**
    - **Can use library components**
    - **Can tune to lab data**
    - **For instance, could tune to viscosities for CO_2 mixtures measured near the critical point of CO_2**

GEM: Adsorption Definition

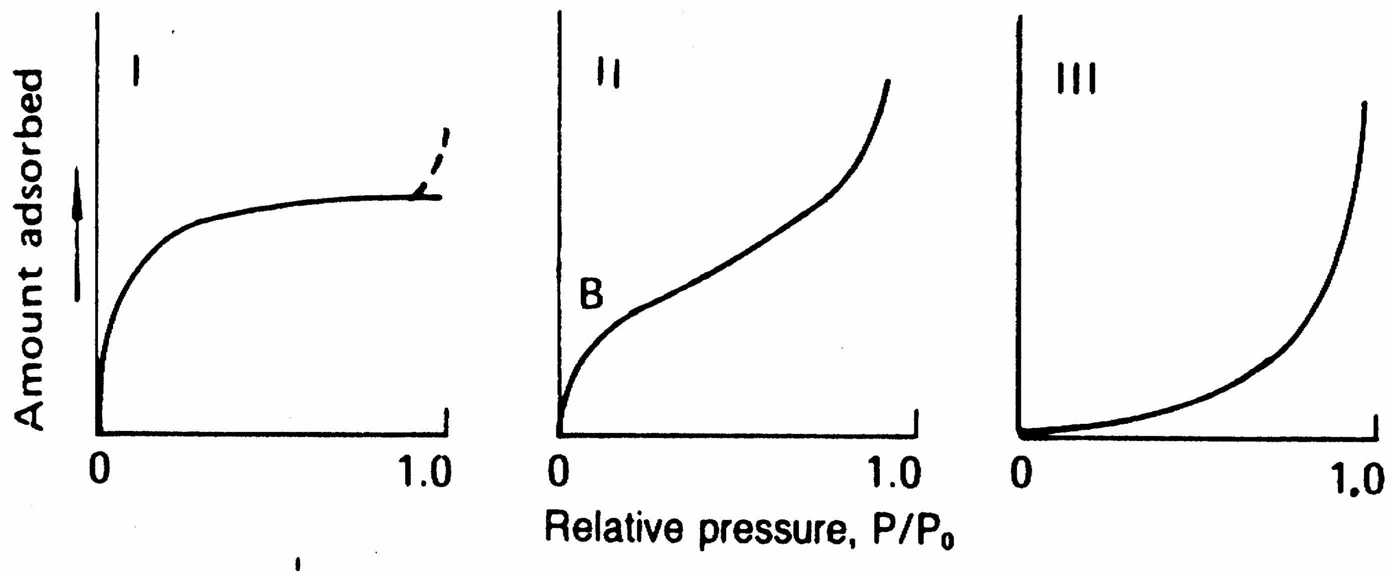
- GEM has different adsorption models
  - Extended Langmuir model

$$\omega_i = \omega_{i,max} \left(\frac{(y_{ig}\, p / p_{Li})}{1 + \sum_j (y_{jg}\, p / p_{Lj})} \right)$$

    - Based on Langmuir isotherm for single components
    - Provides a multi-component extension
  - Tabular input for binary systems
    - Allows direct input of measured lab data

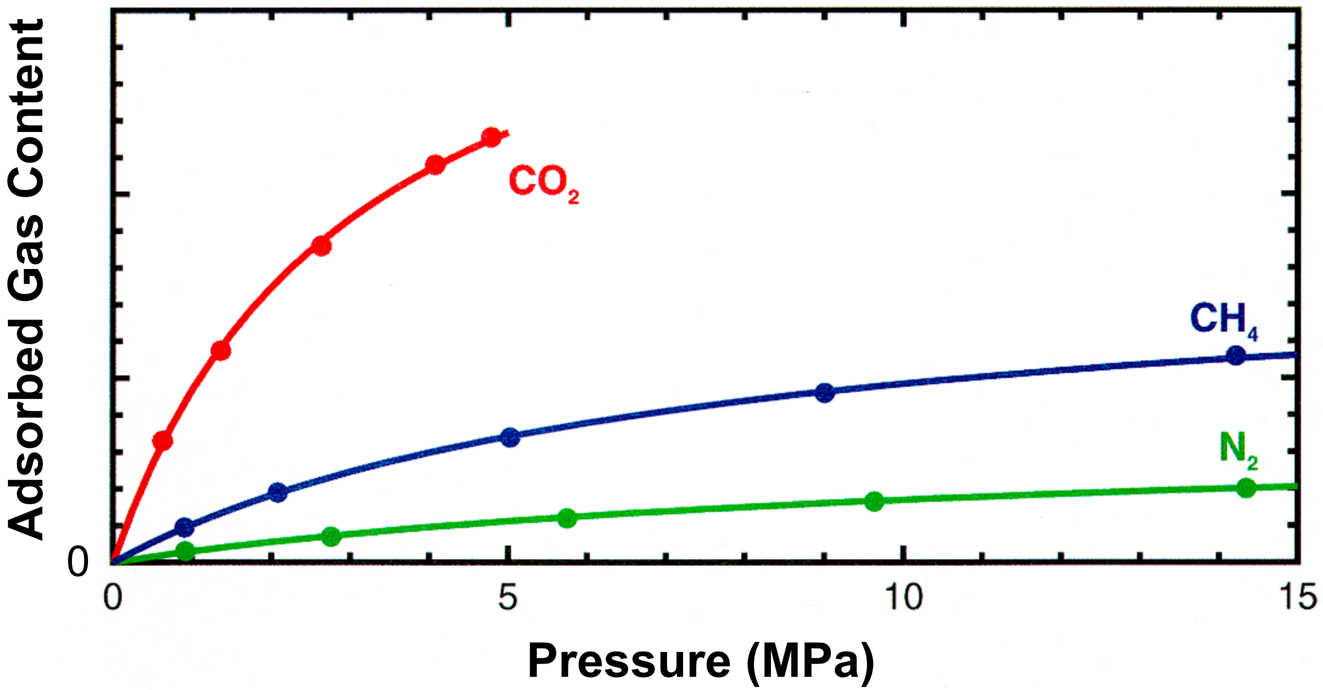
GEM: Adsorption Definition

- GEM uses different adsorption models
  - General tabular input
  - For more complicated systems



GEM: Adsorption Definition

- Adsorption isotherms (Langmuir type)



GEM: Diffusion Modelling

- Input of coal diffusion "times"
  - Use measured coal desorption times (days) directly
    - Can be component dependent
  - Internally calculates diffusive flow
- Direct input of gas phase diffusion "rates"
  - Enter diffusion constants (cm^2/sec)
  - Enter estimated coal cleat (fracture) spacings
    - Leads to an effective inverse area: Shape Factor
  - Flow based on product of the two terms

GEM: Diffusion Modelling

Direct input of gas phase diffusion "rates"

- Specify {$DiffCoeff_i$} for each component
- Specify fracture spacings: $DFrac_i$, $DFrac_j$, $DFrac_k$
- These imply the following shape factor:

$$\text{Shape} = 4 \sum_{l} \frac{1}{(\text{DFrac}_l)^2}$$

- Used to find diffusional flow from bulk coal $\leftrightarrow$ cleats
  - Diffusion Constant = Shape $\times$ $DiffCoeff_i$

GEM: Matrix Swelling and Shrinkage

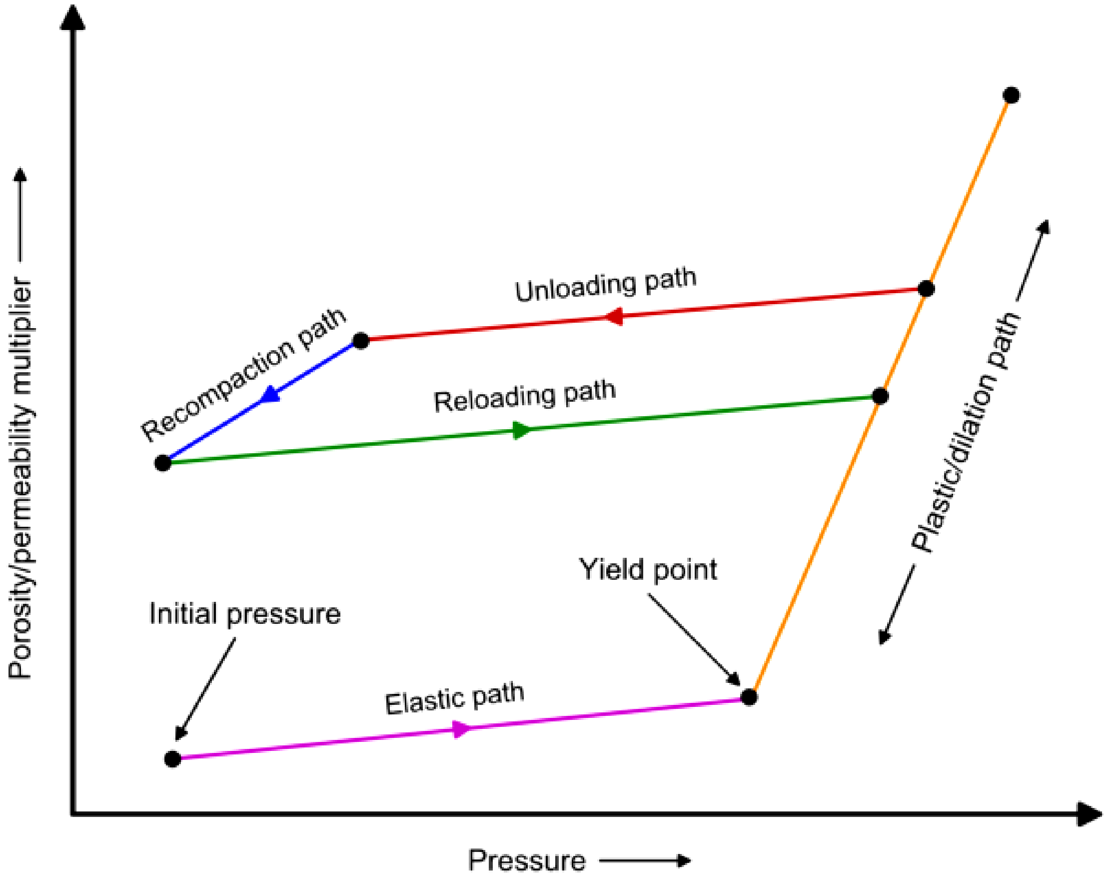
- When gas/water is produced initially
  - Pressure in cleats decreases, alters effective stresses
  - Cleats close, lowering permeability
- But desorbing methane
  - Causes matrix shrinkage, opening cleats, increasing k
  - Reduces water saturation
- Injecting other gases
  - Causes matrix swelling
- Offsetting effects requires simulation to resolve

GEM: Matrix Swelling and Shrinkage

- GEM has capabilities for shrinkage/swelling
  - Input for a “compaction/dilation” option
    - Porosity/permeability multipliers
    - Functions of pressure
    - Uses tabular input

GEM: Matrix Swelling and Shrinkage

- Compaction/dilation scanning curves



Tables of ϕ and/or k multipliers as functions of pressure

GEM: Matrix Swelling and Shrinkage

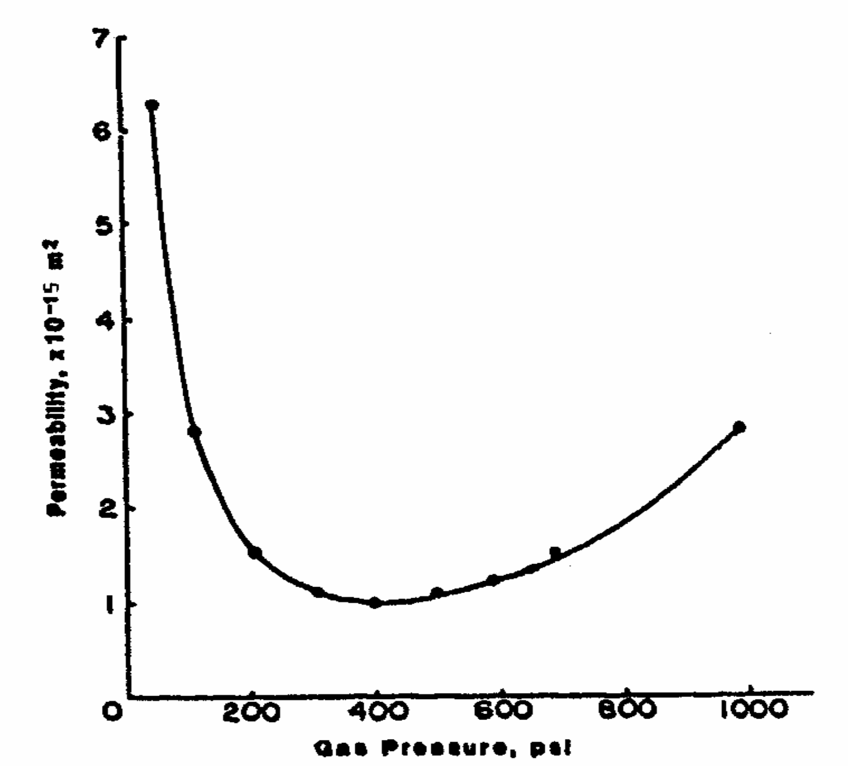
- GEM also has Palmer/Mansoori models
  - Basic model uses relevant rock mechanics
    - Initial pressure (p_{init}) and porosity (ϕ_{init})
    - Young's modulus (E) and Poisson's Ratio (ν)
    - Max strain at inf pres (ε_L) and half-strain pressure (p_ε) (amounting to a Langmuir-type model for strain)

$$\frac{\phi}{\phi_{init}} = 1 + c_f(p - p_{init}) + \frac{\varepsilon_L}{\phi_{init}}\left(1 - \frac{K}{M}\right)\left(\frac{p_{init}}{p_\varepsilon + p_{init}} - \frac{p}{p_\varepsilon + p}\right)$$

Function of ν and $1/(E\phi_{init})$ — Function of ν

GEM: Matrix Swelling and Shrinkage

- Typical cleat permeability plot for methane
  - Using $(k/k_{init}) = (\phi / \phi_{init})^{pwr}$



GEM: Matrix Swelling and Shrinkage

❒ Multi-component Palmer/Mansoori models

- **Problem: CO_2 injection causes coal matrix to swell**
  - **Swelling much greater than shrinkage due to CH_4 desorption**
  - **Expect that wells might seriously lose injectivity**
- **Need compositionally-dependent P&M parameters**
  - **Improvement over the user needing to input one "average" set of parameters**
  - **Specifying composition-dependent ε_L and p_ε**

GEM: Matrix Swelling and Shrinkage

- Multi-component Palmer/Mansoori models
  - Max strain at inf pres (ε_L) and half-strain pressure (p_ε) have been made component dependent, Based on work by Mavor & ARC
  - Law and Mavor used to match FBV field tests
  - Law using to match CUCBM pilot test

$$\frac{\phi}{\phi_{init}} = 1 + c_f\left(p - p_{init}\right) + \frac{1}{\phi_{init}}\left(1 - \frac{K}{M}\right)\left(\sum_{j=1}^{nc} \frac{p_{init}\,\varepsilon_{Lj}\left(y_{init,j}/p_{\varepsilon j}\right)}{1 + p_{init}\sum_{k=1}^{nc}\left(y_{init,k}/p_{\varepsilon k}\right)} - \sum_{j=1}^{nc} \frac{p\varepsilon_{Lj}\left(y_j/p_{\varepsilon j}\right)}{1 + p\sum_{k=1}^{nc}\left(y_k/p_{\varepsilon k}\right)}\right)$$

Other GEM features

- ❐ Many other possibilities available with GEM
  - Can model gas solubility in water, water vapourization
  - Non-isothermal problems
  - Non-Darcy flow models available
    - Forchheimer modifications, in reservoir and at wells
  - Diffusion/Velocity-Dependent Dispersion modelling
    - In cleat system
  - Numerical dispersion reduction (TVD schemes)
- ❐ Geochemical reactions being tested for CO_2 sequestration in saline aquifers
  - Application to ECBM (e.g.carbonic acid dissolving minerals in coal)?

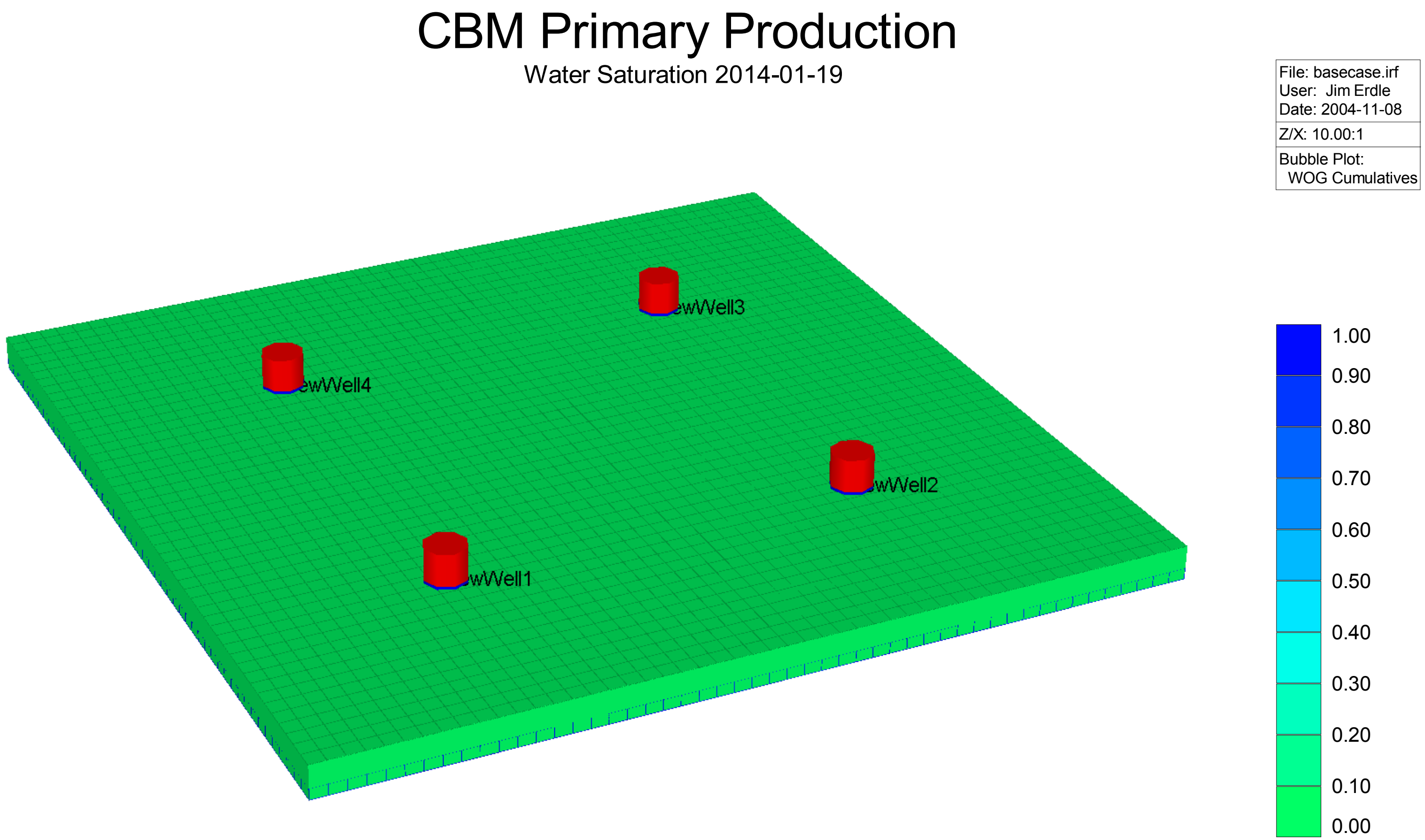
Other GEM features

- Typical full-field simulator features
  - Can specify spatially dependent properties, including those for adsorption, rock mechanics, …
  - Various initializations, including saturated and under-saturated coals
- Full Windows-based input processing and graphics

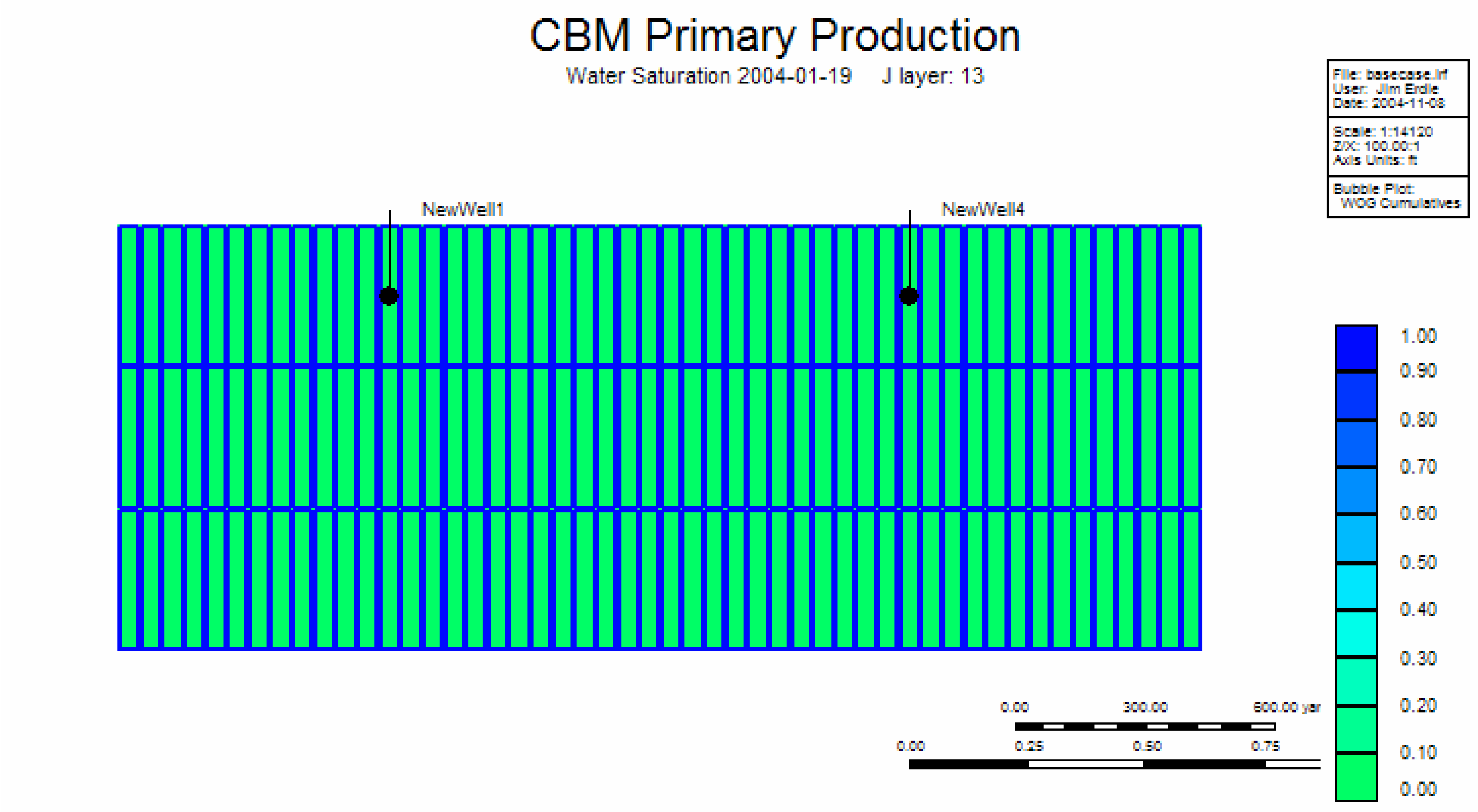
Example

- GEM for CBM has been used for both
  - Investigative modelling
  - Field studies
- Look at results from a 5-spot investigative model
  - Production with & without CO_2 or N_2 injection

3D View of 3-layer Coalbed

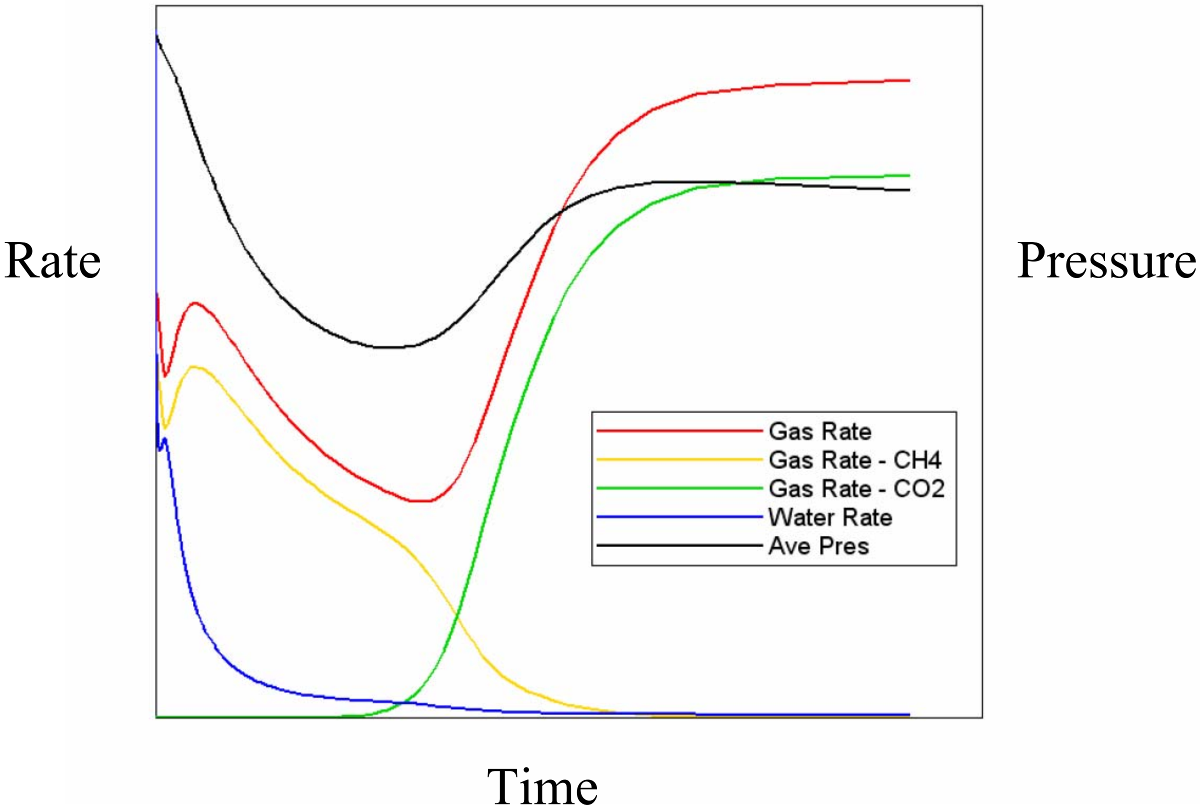


2D X-section – Dewatering Cleats



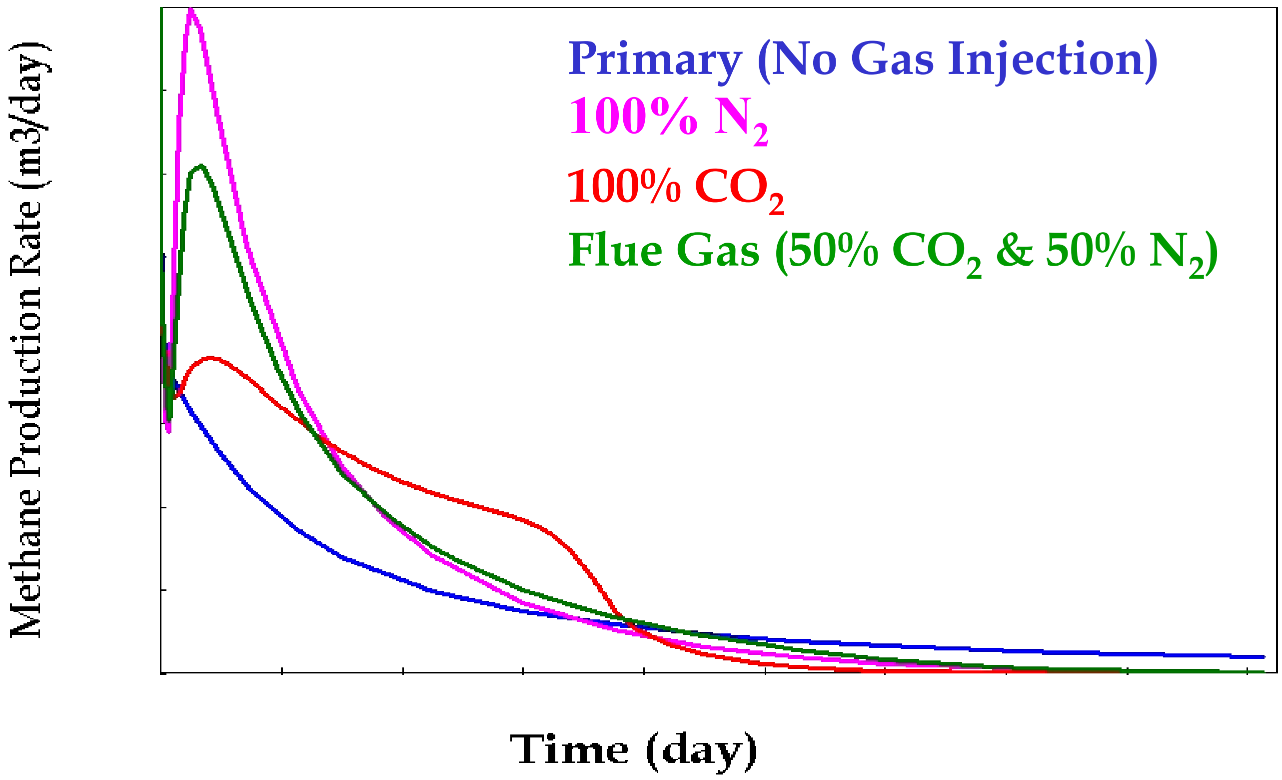
5-Spot Injection Study

- Results from a 5-spot injection model



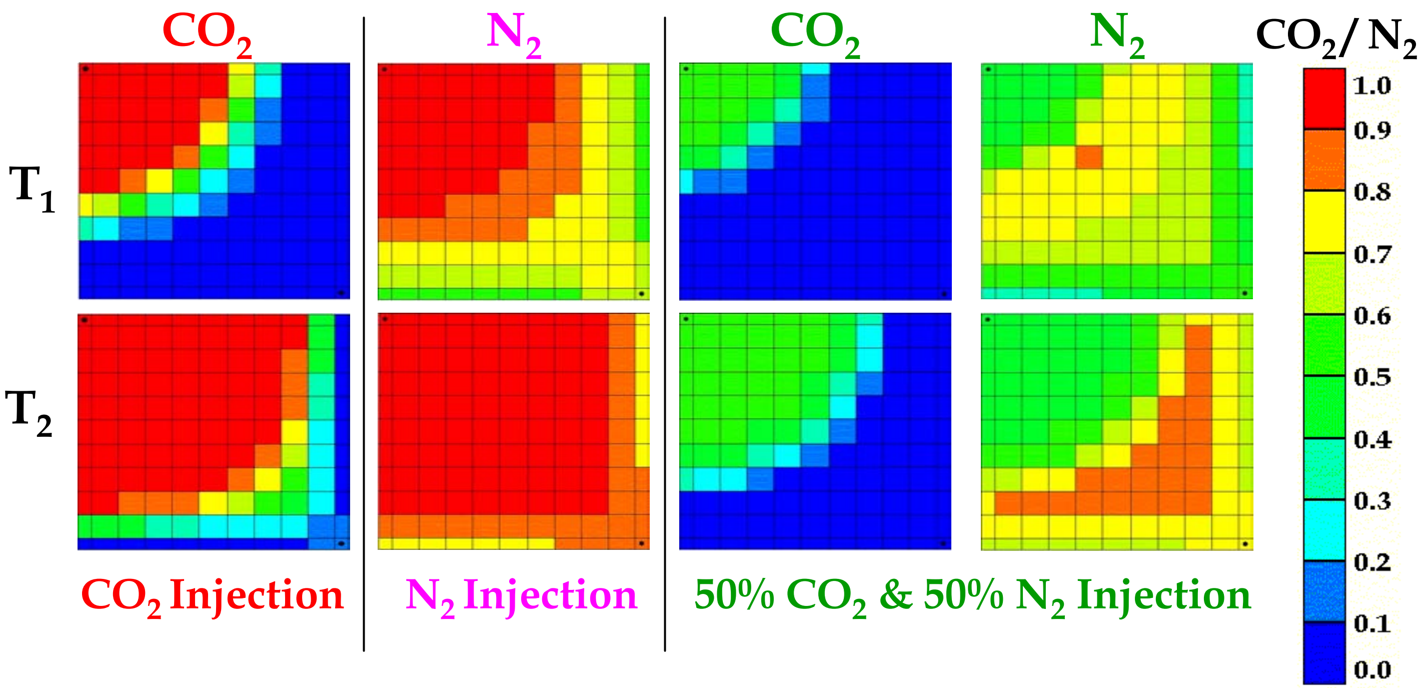
5-Spot Injection Study

- Results from a 5-spot injection model



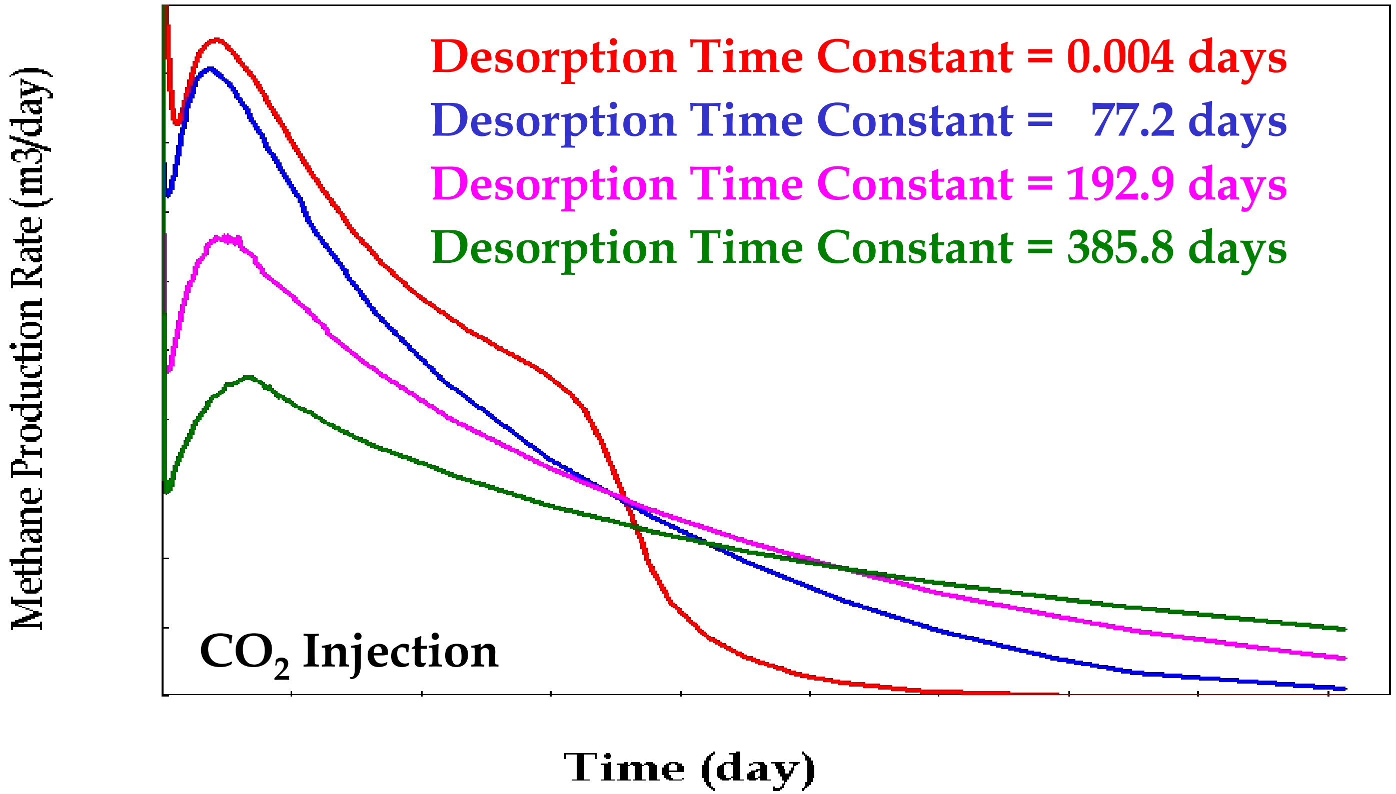
5-Spot Injection Study

❐ Injection profiles



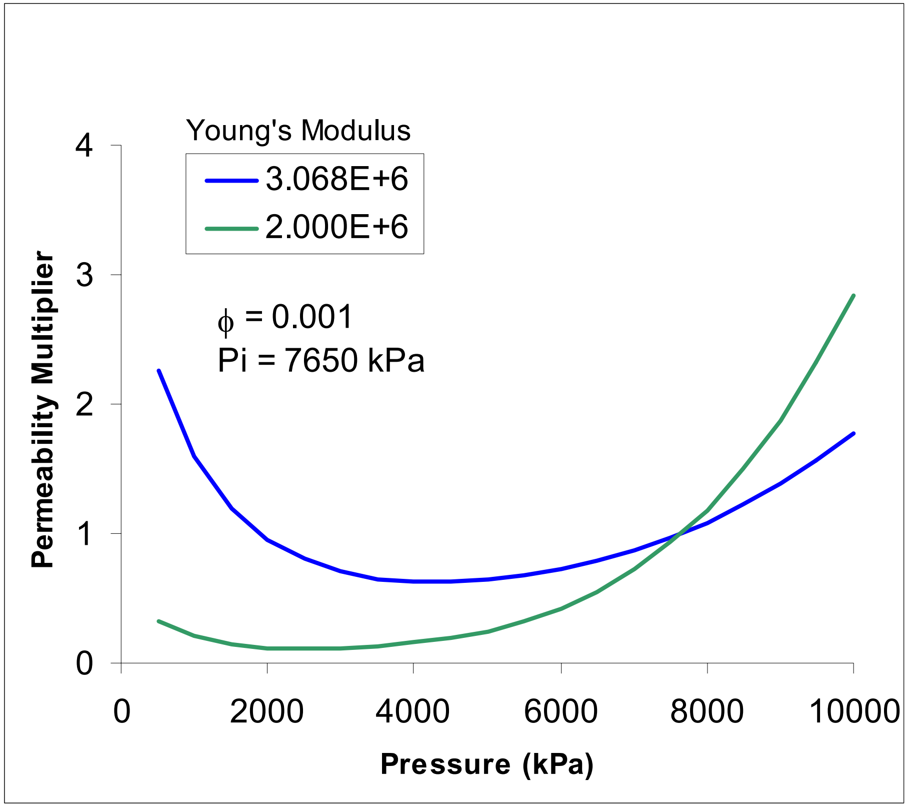
5-Spot Injection Study

- Effects of varying desorption times



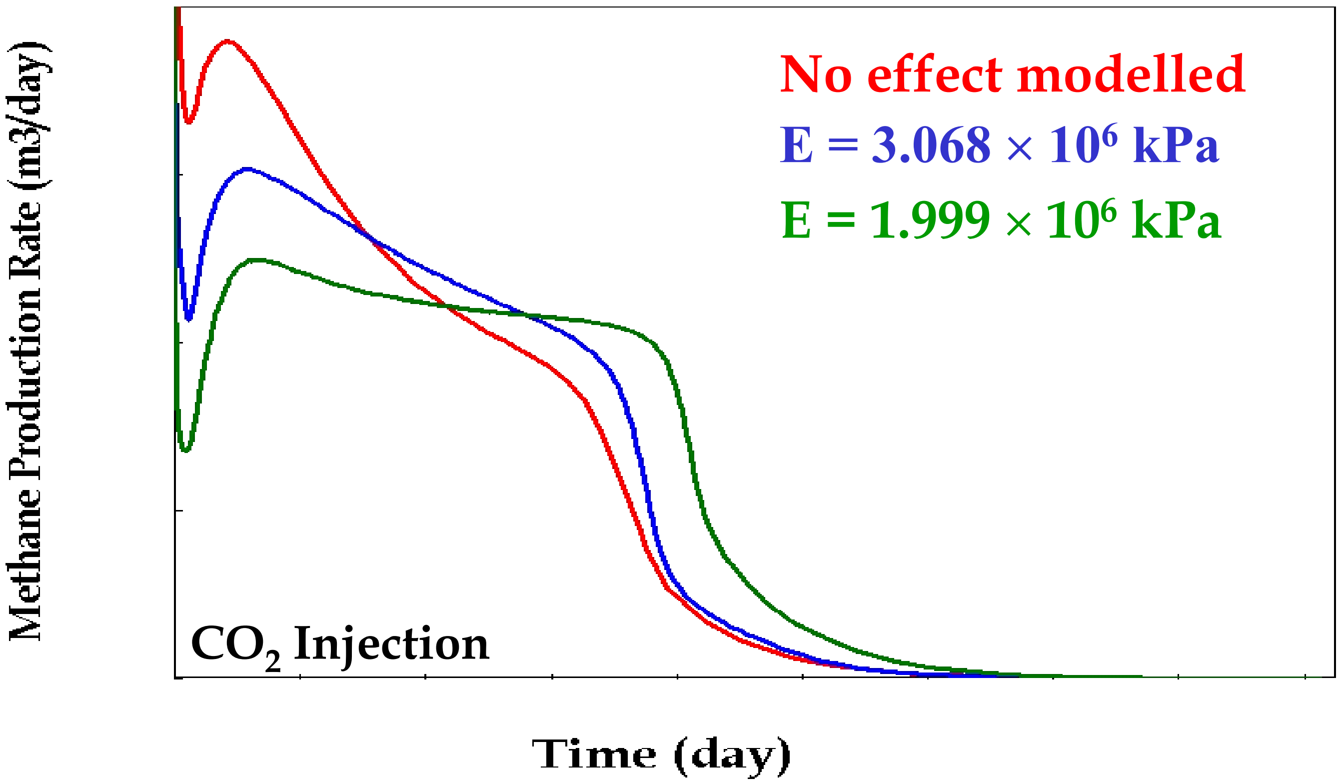
5-Spot Injection Study

- Effects of shrinkage/swelling (P&M model)



5-Spot Injection Study

- Effects of shrinkage/swelling



Conclusions (1)

- A multi-purpose compositional model (GEM) has been upgraded to include the physics for modelling CBM/ECBM recovery processes
  1. Multi-component, pressure and composition-dependent gas adsorption, desorption, and re-adsorption in the coal matrix using an extended Langmuir isotherm technique, or tables
  2. Dual porosity (i.e., coal matrix and cleat) system behavior
  3. Diffusional flow of gas between the coal matrix and the cleats
  4. Cleat permeability and porosity can be modelled as functions of effective stress (Palmer and Mansoori model)

Conclusions (2)

- A multi-purpose compositional model (GEM) has been upgraded to include the physics for modelling CBM/ECBM recovery processes

5. Coal swelling and shrinkage can be modelled as a function of gas (e.g. CO2) adsorption or gas (e.g. methane) desorption, respectively
6. General distributions of porosity and (anisotropic) permeabilities can be assigned in both the coal matrix and the cleat systems
7. Multi-phase Darcy and Non-Darcy (i.e. Klinkenberg for low pressure conditions and turbulent for high velocity conditions) flow of gas and water through the cleat system to the wells
8. Mixing of injected and in-place gases via multi-component molecular diffusion and velocity-dependent, longitudinal and transverse convective dispersion
9. Dissolution of injected and in-place gases into the aqueous (water) phase

Consultants/Universities/Labs using GEM for CBM/ECBM/CO2 Sequestration

- Tesseract (Park City) – Matt Mavor
- Mansoori & Assoc (Denver) – John Mansoori
- Sproule (Denver) – John Seidle
- Raven Ridge Resources (Grand Junction) – Ron Collings
- SI International (Denver) – George Lane
- Malkewicz Hueni Associates (Denver) – Tim Hower & Dan Simpson
- Epic Consulting (Calgary) - Richard Baker
- Ticora Geosciences (Denver) – Simon Testa
- NIOSH (Pittsburgh) - Ozgen Karacan
- KGS (Lawrence) – Tim Carr
- ARC (Edmonton) – David Law
- Penn State (State College) – Turgay Ertekin
- WVU (Morgantown) – Shahab D. Mohaghegh
- Oklahoma U (Norman) – Richard Hughes
- U of Texas (Austin) – Gary Pope
- Texas A&M (College Station) – David S. Schechter

E&P Companies using GEM for CBM/ECBM/CO2 Sequestration

- ConocoPhilips (Calgary) - Kevin Ratterman
- ChevronTexaco (Houston) – Kirk McIvor
- Shell (Houston) – Jeff Bain
- EOG Resources (Houston) – Charles Smith
- Encana (Denver) – Robert Downey & John Mansoori
- Burlington Resources (Calgary) – Chris Clarkson
- Devon (Calgary) - ?
- Talisman (Calgary) - ?
- PetroChina (China) - ?
- CUCBM (China) - ?
- Gazonor (Russia) - ?