CBM Geology and Well Design

1. Determining Sweet Spots
   • Coal as a Gas Reservoir
   • Gas Adsorption and Desorption principles
   • Characteristics of Commercial CBM Projects

2. Data Gathering and Types

4. The Role of Geomechanics

5. Effective Well Design Options

6. Well Costs
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  - Advised on all major current LNG and gas project developments in Australia
  - 40 professional staff worldwide, offices in Perth, London and Brisbane
Coal as Gas Reservoir
CBM Generation and Entrapment – Comparison with Conventional Hydrocarbons

CBM:
- Laterally extensive coal seams
- Gas produced in coalification process and adsorbed onto coal surfaces
- Limited communication between wells
- Water usually fills pore/fracture space
- Water production then gas
- Gas is always dry

Conventional:
- Structurally trapped by seal
- Hydrocarbon presence due to buoyancy
- Gas compressed into pore space
- 1 well may drain entire trap
- Gas then perhaps water
- Possible condensate
How is gas stored in coal?

Gas is adsorbed onto the surface of micropores within the coal. It is held in place by molecular attraction (Van Der Waal’s forces).
How is gas produced from coal?

Depressuring the coal by producing water is required to desorb gas from the coal matrix. Gas then flows into the cleat system where it can be produced by wells.
What parameters are required for a commercial CBM project?

<table>
<thead>
<tr>
<th>Basin</th>
<th>Field</th>
<th>Area (sq milos)</th>
<th>Coal Thickness (ft)</th>
<th>Coal Rank</th>
<th>Gas Content (scf/ton)</th>
<th>Permeability (md)</th>
<th>Well Spacing (acres)</th>
<th>Well Count</th>
<th>Gas Rate/Well (Mscf/D)</th>
<th>OGIP (Bscf)</th>
<th>RF (%OGIP)</th>
<th>Reserves (Bscf/well)</th>
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<tbody>
<tr>
<td>San Juan (US)</td>
<td>Ignacio Blanco</td>
<td>60</td>
<td>40–70</td>
<td>Bituminous</td>
<td>300–600</td>
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<td>1,760</td>
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<td>3–15</td>
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<td>Drunkard’s Wash</td>
<td>120</td>
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<td>Cedar Cove</td>
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<td>25–30</td>
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<td>Powder River (US)</td>
<td>Recluse Rawhide Butte</td>
<td>75</td>
<td>40–90</td>
<td>Subbituminous</td>
<td>30–70</td>
<td>5+</td>
<td>80</td>
<td>600</td>
<td>150</td>
<td>288</td>
<td>62</td>
<td>0.2–0.5</td>
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<td>Horseshoe Canyon</td>
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<td>Subbituminous</td>
<td>55–110</td>
<td>0.1–100</td>
<td>80–160</td>
<td>3,300</td>
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<td>Bowen Basin (Australia)</td>
<td>Fairview</td>
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<td>Bituminous</td>
<td>200–400</td>
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<td>Qinshui Basin (China)</td>
<td>Yangcheng-Qinshui</td>
<td>22</td>
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<td>Anthracite</td>
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<td>0.4–0.8</td>
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</tbody>
</table>

Source: Coalbed and Shale-Gas Reservoirs, Creties D. Jenkins and Charles M. Boyer II, SPE 103524 February 2008
Characteristics Defining Commercial Potential of Coal as a Gas Reservoir

1. **Coal Thickness**
   - Number, thickness and extent of coal seams
   - Typically need > 3m in aggregate

2. **Gas Content and Gas saturation**
   - Biogenic and thermogenic sourcing: understanding needed for gas content distribution
   - Coal Rank and Type: bituminous/sub-bituminous ideal, high inertinite or liptinite correlates with lower gas content
   - Gas content and composition: > 2 m³/t, 92+% CH₄
   - Sorption properties of coal: >60% saturation
   - Hydrodynamic effects can strongly influence gas content and saturation

3. **Permeability**
   - Governed by presence of cleats and natural fractures
   - Coal Rank: 0.4 < Rvmax > 1.6 to promote cleating
   - High vitrinite/inertinite (GI) ratios: promote fracturing
   - Geologic Structure: Curvature to assist cleat/fracture opening
   - Stress Setting: tension to promote cleat/fracture opening

4. **Dewatering capability**
   - Isolation from pervasive aquifers
Analysis of Coal Properties

- Moisture and ash content are components that will not contribute to CBM resources and must be corrected for in the CBM resource estimate.
- Volatile matter and free carbon are relevant because they can be related to gas generation and the potential for commercial CBM.
- The coal composition can be related to gas content and cleat mineralisation, vitrinite/inertinite ratios, inertinite or liptinite can correlate with lower gas content.
- Vitrinite reflectance ($R_v$) is a powerful indicator of coal rank/maturity and the potential for commercial CBM.

Geologic Factors Influencing the Gas Content of Coalbeds in Southwestern Pennsylvania

Walloon Subgroup Gas Content vs Maceral Content
Analysis of Coal Properties – Density and Ash

- Density is relevant because it is used for defining coal cut-offs for thickness calculations and estimating CBM volumes.
- High resolution log density is essential for differentiating between coal and carbonaceous shales or other lithologies.
- Ash content can have a significant effect on gas content and permeability: Ash cannot adsorb gas.

Source: RISC analysis
Permeability and the Coal Cleat System

Butt and face cleats create permeability anisotropy

High rank coal: cleating destroyed

- Commercial permeability in coals is created by the coal cleat or fracture system as the coal matrix permeability is very low
- The permeability of the cleat system is controlled by:
  - Coal rank
  - Mineralisation in the cleats or fractures
  - Structural factors eg anticlines can put system in tension and open cleats. Structural compression can close the cleats
- Gas generation is also a function of thermal maturity (rank)

Decreasing Perm ➔ Increasing Adsorption ➔
Adsorption & Desorption Analysis
Initial Sorbed Gas Content (Desorption Analysis)

- Measured in the laboratory by measuring the amount of gas that actually is stored in a coal sample using a desorption process, includes:
  - Lost Gas + Gas Released + Crushed Sample Gas

- Include Lost Gas Analysis (often the largest source of error in desorption tests)
  1. USBM direct method (most common method; extrapolation)
  2. Smith & Williams (suited to well cuttings)
  3. Amoco Method (numerical fitting curve)
  4. CBM Solutions

- Gas content can be expressed on an “in-situ” basis or after normalisation for ash and moisture content (DAF)
Gas Adsorption Isotherms

- **Gas adsorption isotherms** describe the maximum amount of gas that can be stored in a coal at any pressure i.e. every storage site is occupied.
- Measured in the laboratory using an **adsorption** process.
- The amount of gas (typically CH4) that can be stored in a crushed and fully degassed coal sample as a function of pressure.
- Gas storage capacity is the maximum amount of gas the coal can adsorb i.e. every storage site is occupied.
- Gas storage capacity can be expressed on an “in-situ” basis or after correction for ash and moisture content.
- The relationship between the gas storage capacity and pressure is described by an empirical relationship called the **Langmuir Isotherm**.

\[
G_{sl} = \frac{V_L \times p}{(p + P_L) \times (1 - w_a - w_{we})} \text{ scf/ton in situ}
\]

Where:
- \(V_L\) = Langmuir Volume, scf/ton DAF
- \(P_L\) = Langmuir pressure, psia
- \(p\) = pressure, psia
- \(w_a\) = ash weight content
- \(w_{we}\) = equilibrium moisture content, weight fraction
Gas Saturation

- The ratio between the theoretical storage capacity and the actual gas content is termed the **gas saturation**

- A coal is said to be **undersaturated** when the gas content is lower than the theoretical storage capacity

- Under-saturated coal may require significant depressurisation before gas is produced
Spatial Variation of Gas Content

- Gas isotherms and gas content can vary significantly depending on the coal type, from one seam to another and within seams.
- Gas content tends to increase with depth (but permeability tends to decrease).
- Gas saturation can also change with depth.
Gas composition effects
Gas Composition Effects

• CBM is (generally) predominantly methane.
• Other gases frequently encountered are
  – Carbon dioxide;
  – Nitrogen; and
  – Ethane and other h/c.
• Coal has a different affinity for different gases
  – Affinity for: \( \text{CO}_2 > \text{CH}_4 > \text{N}_2 \)
• The impact of the inert gases (\( \text{CO}_2 \) and \( \text{N}_2 \)) is:
  – Static
    – Reduction in the heating value of the gas (dilution)
  – Dynamic
    – Mixture isotherms
    – Saturations
    – Composition of the produced gas
    – Recovery factors
Dynamic compositional effects

Extended Langmuir Isotherms

\[ V_i = V_{Li} \frac{b_i p_i}{1 + \sum_{j=1}^{n_c} b_j p_j} \]

Where:
- \( V_{Li} \) = Langmuir Volume of component \( i \)
- \( b_i \) = reciprocal of Langmuir Pressure, \( P_{Li} \), of component \( i \)
- \( p \) = pressure

Calculate the saturation using the isotherm of the mixture

Example mixture isotherm: 20% \( \text{CO}_2 \), 10% \( \text{N}_2 \)
(The Extended Langmuir Isotherm is one model, other models exist)
Dynamic compositional effects

- Preferential production of less strongly bound components leads to changes in the composition of the produced gas with time.
Data Gathering & Data Types
Major Parameters in CBM Resource Evaluation

- Geological model of coals and adjacent strata
- Formation pressure and temperature
- Coal Volume (Area, Net Thickness)
- Coal Rank
- Coal Density, Ash, Moisture
- Gas Content and Composition
- Tectonic regimes and prevailing stress
- Cleat frequency and direction
- Permeability of coal
- Gas storage capacity and gas saturation
- Pilot Test Results
- Well drainage area (coal continuity)
- Viable well completion technology
- Development area and land access

- OGIP Estimates
- Recovery Estimates
- Reserve Estimates

- Commercially viable project development plan
- Development approvals and access agreements
- Contract terms (permit terms and gas sales agreements)
- Economic analysis
- Finance
## Major Parameters in CBM Evaluation – Data Sources

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Data Source</th>
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<tbody>
<tr>
<td><strong>OGIP Estimates</strong></td>
<td></td>
</tr>
<tr>
<td>Geological model of coals and adjacent strata</td>
<td>Structure maps, cross sections, geological description, seismic, well and outcrop data</td>
</tr>
<tr>
<td>Formation pressure and temperature</td>
<td>Hydrological data, well formation pressure and temperature measurements, pilot testing</td>
</tr>
<tr>
<td>Tectonic regime and prevailing stress</td>
<td>Seismic, borehole breakout, regional geology, fracture stimulation data</td>
</tr>
<tr>
<td>Cleat frequency and direction</td>
<td>Coal core, borehole imaging logs</td>
</tr>
<tr>
<td>Coal volume (Area, Net Thickness)</td>
<td>Thickness maps, well stratigraphic data, density logs</td>
</tr>
<tr>
<td>Coal rank</td>
<td>Vitrinite reflectance data, proximate analysis</td>
</tr>
<tr>
<td>Coal density, ash, moisture</td>
<td>Proximate analysis, borehole density logs</td>
</tr>
<tr>
<td>Gas content and composition</td>
<td>Desorption tests</td>
</tr>
<tr>
<td><strong>Recovery Estimates</strong></td>
<td></td>
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<tr>
<td>Permeability of coal</td>
<td>Pressure transient testing, pilot testing</td>
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<tr>
<td>Gas Storage Capacity and Gas Saturation</td>
<td>Adsorption tests</td>
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<td>Pilot test results</td>
<td>Pilot test</td>
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<tr>
<td>Well drainage area (coal continuity)</td>
<td>Pilot test, development studies</td>
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<tr>
<td>Viable well completion technology</td>
<td>Pilot test</td>
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<tr>
<td>Development area and land access</td>
<td>Development studies</td>
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</tbody>
</table>
Pilot Testing

- Pilot tests are always required in CSG developments. This is because of the nature of the coal geology, the predictive ability away from well control is poor.

- Typical objectives of a pilot test are to demonstrate commercial potential by:
  - Establishing the feasibility of dewatering the coals
  - Establishing de-watering times and gas production potential
  - Evaluating optimal well completion types, stimulation technology and stress regimes
  - Confirmation of well drainage areas and drainage pattern
  - Proving the repeated drilling and completion of wells to achieve commercial production
  - Establish a cost base for development to the required level of certainty
  - Developing the “know how” to proceed to a larger scale commercial development

Impact of Well Spacing
On Pilot Response
E&P Project Lifecycle – CSG Continuous Cycle Perspective

Explore → Appraise

Implement → Manage

Adapt → Monitor

Develop → Produce
Geomechanics
**In-situ stress - importance**

- Knowledge of regional *in-situ* stress tensor important to drilling and completion design
  - Well bore stability
  - Fracture stimulation difficult in reverse or high stress regimes
  - Low mean stress regimes support open and conductive natural fracture
  - Stress intensity affects production
- CSG wells should be targeted in areas of low mean stress with fracture systems that are conductive in the *in-situ* stress regime
- North America
  - Normal stress regime $\sigma_V > \sigma_{H_{max}} > \sigma_{H_{min}}$
  - Bulk (cleat) permeability decreases with depth
- Eastern Australia
  - Strike-slip ($\sigma_{H_{max}} > \sigma_V > \sigma_{H_{min}}$) to Reverse ($\sigma_{H_{max}} > \sigma_{H_{min}} > \sigma_V$)
**In-situ Stress Tensor Characterisation**

- Can vary vertically and laterally depending upon rock strength and structural history
- Vertical stress variation characterised from well bore measurements
  - Vertical stress magnitude from integration of density log to surface
  - Maximum horizontal stress:
    - magnitude from rock strength tests and calibrated mechanical logs
    - Orientation from image logs
  - Minimum horizontal stress:
    - magnitude from leak off tests, mini-frac
    - Orientation from image log
- Areal stress variation from measurements in many well bores and structural analysis (seismic)
Impact of Stress on Completions & Fracturing

- 3D stress geometry modelled using a boundary element algorithm
Natural Fracture Modelling

- Natural fracture system orientation identified from image logs
- Structure restored to pre-deformational geometry and forward modelled to present stress state
- Strain associated with folding captured and used to develop natural fracture distributions

Coal Seam Fractures
Structural & Depth Effects

Depth effects on Permeability

Structural effects on Permeability

Anticline
Faulted ground

Flank
Low Permeability in trough

Syncline

(SPE, 1984)
Permeability changes with desorption

Two counteracting mechanisms are at work:

Matrix compressibility (k decrease)
The coal matrix is compressible, as pressure is released it may swell which will contract the cleat space.

Matrix volume reduction (k increase)
Gas is held on the surface of the coal at a high density, effectively as the outer layer of the coal. The cleats on which the gas are held have a similar size to the gas molecules, therefore as the coals desorb and gas is produced the available space in the cleat increases and gas molecules may move more freely.
Well Design & Recovery
**Vertical Well Types**

**Cavitation**
- compressed air is used to cavitate the coal seam
- increases the effective well bore radius and improves inflow efficiency
- removes coal damaged by drilling fluids

**Under-reaming**
- uses specialised drilling but to open out borehole diameter in coal to 0.3m diameter or greater
- increases the effective well bore radius and improves inflow efficiency
- Can be used with gravel packed screens to eliminate fines production

**Fracture stimulation**
- uses high pressure water with additives to fracture the coal and proppants to keep the fracture open
- increases the effective well bore radius and improves inflow efficiency, bypasses drilling damage
- connects up cleats and natural fractures to the wellbore

Can be single seam or multi-seam
Horizontal Wells & Multi Laterals

Short, medium radius or surface to in-seam
- Used in lower permeability or thinner seams
- In short and medium radius wells, horizontal section achieved by using direction drilling technology from existing well bore
- In surface to in-seam wells, a “slant” rig is used to drilled from the surface to the seam, building hole angle as the well proceeds
- Horizontal sections of 1000m in-seam targeting seams with a thickness as low as 2m have been achieved at depths of 1000m.

Single lateral
- one horizontal borehole

Multi-lateral
- two or more laterals in a seam

Multi-lateral stacked
- two or more laterals in separate seams
Gunnedah Basin Bohena Seam (Anisotropy Example)

- Face cleats are well developed & preferentially oriented normal to the prevailing tensional stress regime
- No butt cleats

Tailored Lateral Well Design

- Permeability of Bohena coal can be in excess of 100mD at depths of ~1000m (3280ft)
- Fracture permeability highly directional
- Minimises environmental footprint
- Maximises return on investment

Lateral wells are drilled perpendicular to the natural fracturing system of the target coal

Source: Eastern Star Gas
Canada CBM Mannville Example

- Two Well Pad
- Stimulated Tri-Laterals

Source: Apache Canada
Comments on CBM Drilling Technology

**Fracture stimulation**
- Fracture stimulation significantly increases costs (will probably need re-fracking?)
- Needs competent coals (soft coal fracs won’t stay open); isolation from aquifers

**Horizontal Wells**
- Much higher costs; suited to lower permeability coals or where land access is an issue
- Boreholes can become blocked with fines and / or borehole collapse increasing costs for clean out or reducing efficiency
- Multi-lateral wells create a reservoir management issue – you may not know where the gas is coming from therefore may not know where the remaining gas is if you need to drill infill wells.
- Geosteering technology no means that targeting seams +/-2m thick with 1000m laterals now feasible

**Learning Curve**
- Large well numbers in CBM developments make continuous improvement possible
- Santos Surat basin example 40% reduction in one year (see next page)
CBM Well Costs

- Drilling and completion cost differentials are quite marked
- Australian costs relatively high driven by:
  - regulatory compliance
  - Well integrity, land access, environmental issues
  - relatively little competition from service providers compared to USA, higher cost base than China
- Despite this operators are having significant success in driving costs down

Source: Unconventional Resources, IPTC Bangkok 8th Feb 2012

Source: RISC analysis
Thank You

Any Questions?