CBM Geology & Well Design

5TH ANNUAL CBM & UNCONVENTIONAL GAS
WEDNESDAY 27 JUNE 2012

GEOFF BARKER, PARTNER

DECISIONS WITH CONFIDENCE

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

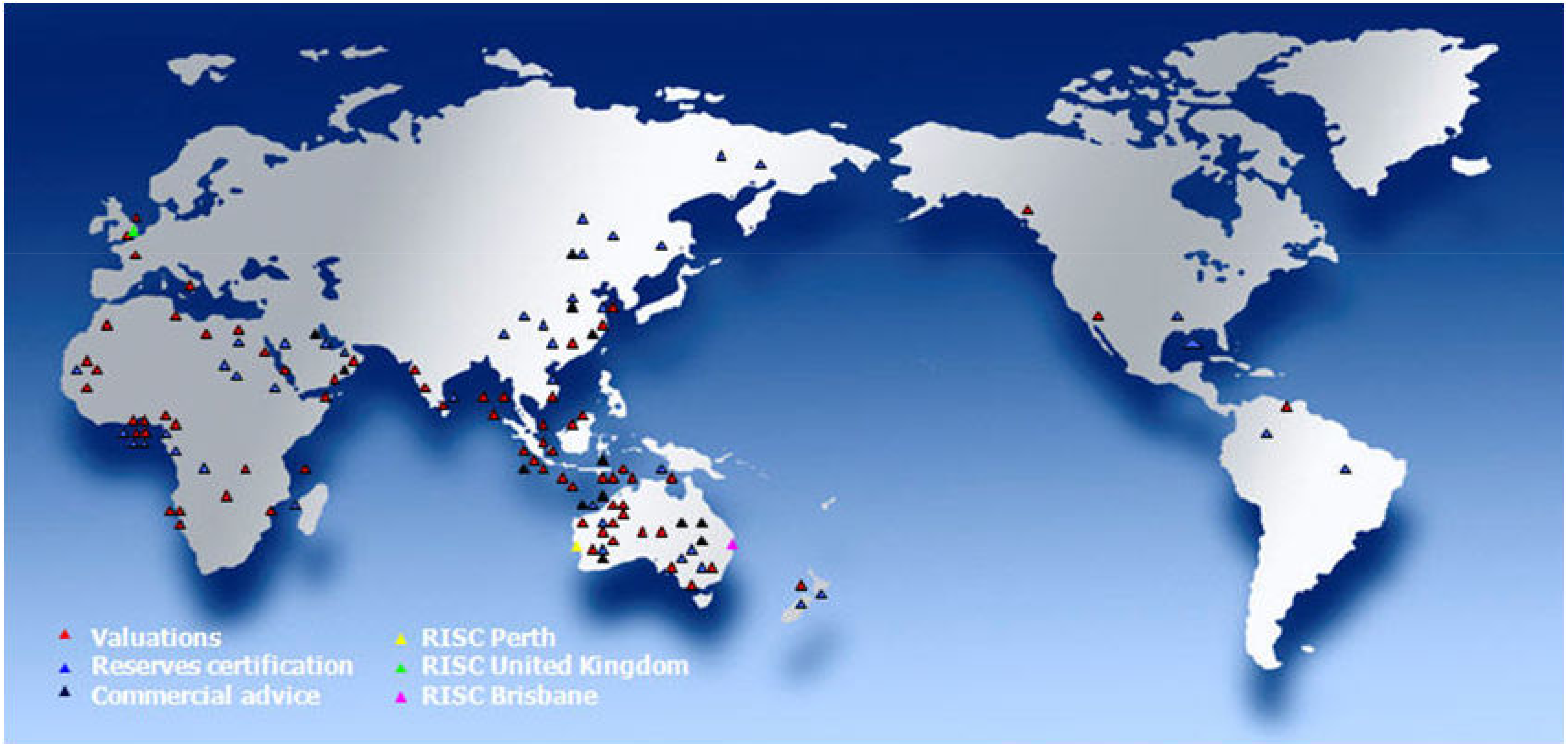
4. The Role of Geomechanics

5. Effective Well Design Options

6. Well Costs

RISC is a Leading Global Oil and Gas Advisory Firm

- Founded in 1994, RISC provides independent advice to the oil and gas sector
  - Since 2000, RISC has completed over 1,300 assignments in over 68 countries for nearly 500 clients
  - Principal technical and economic advisor on transactions valued at over US$200bn
  - Advised on all major current LNG and gas project developments in Australia
  - 40 professional staff worldwide, offices in Perth, London and Brisbane



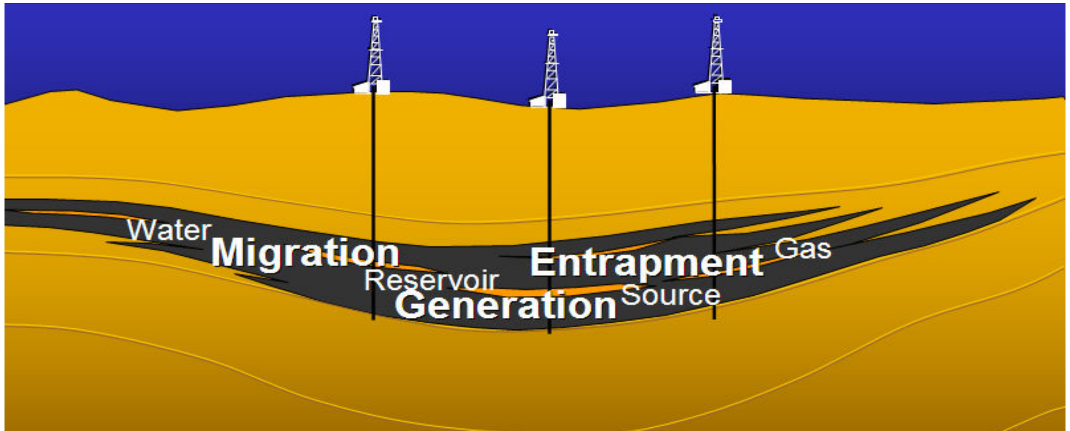
Coal as Gas Reservoir

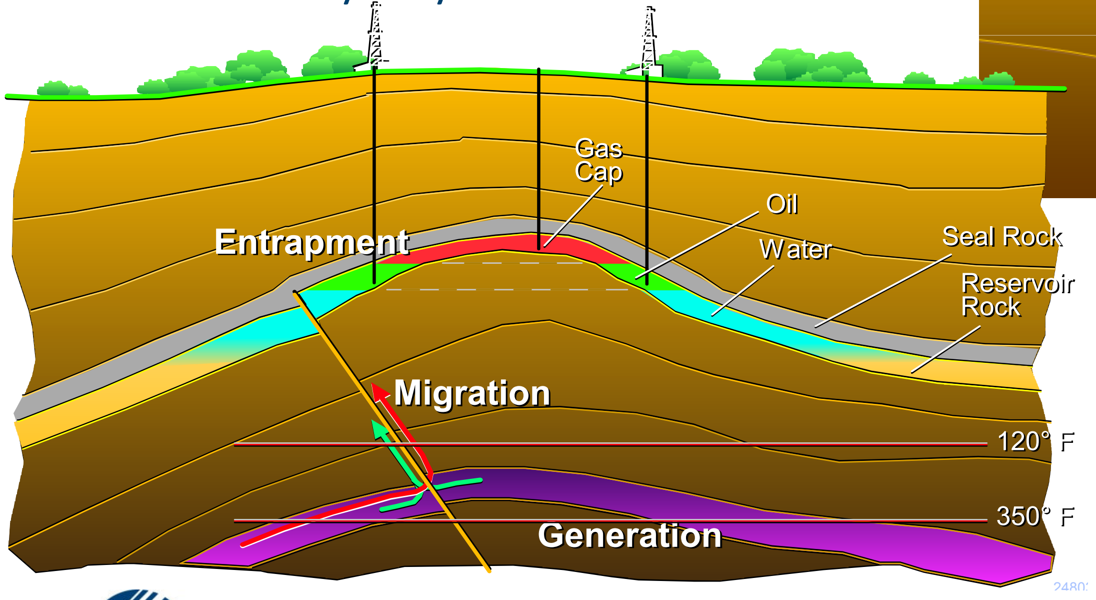
CBM Generation and Entrapment – Comparison with Conventional Hydrocarbons

Coal Reservoir vs Conventional Petroleum Traps

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

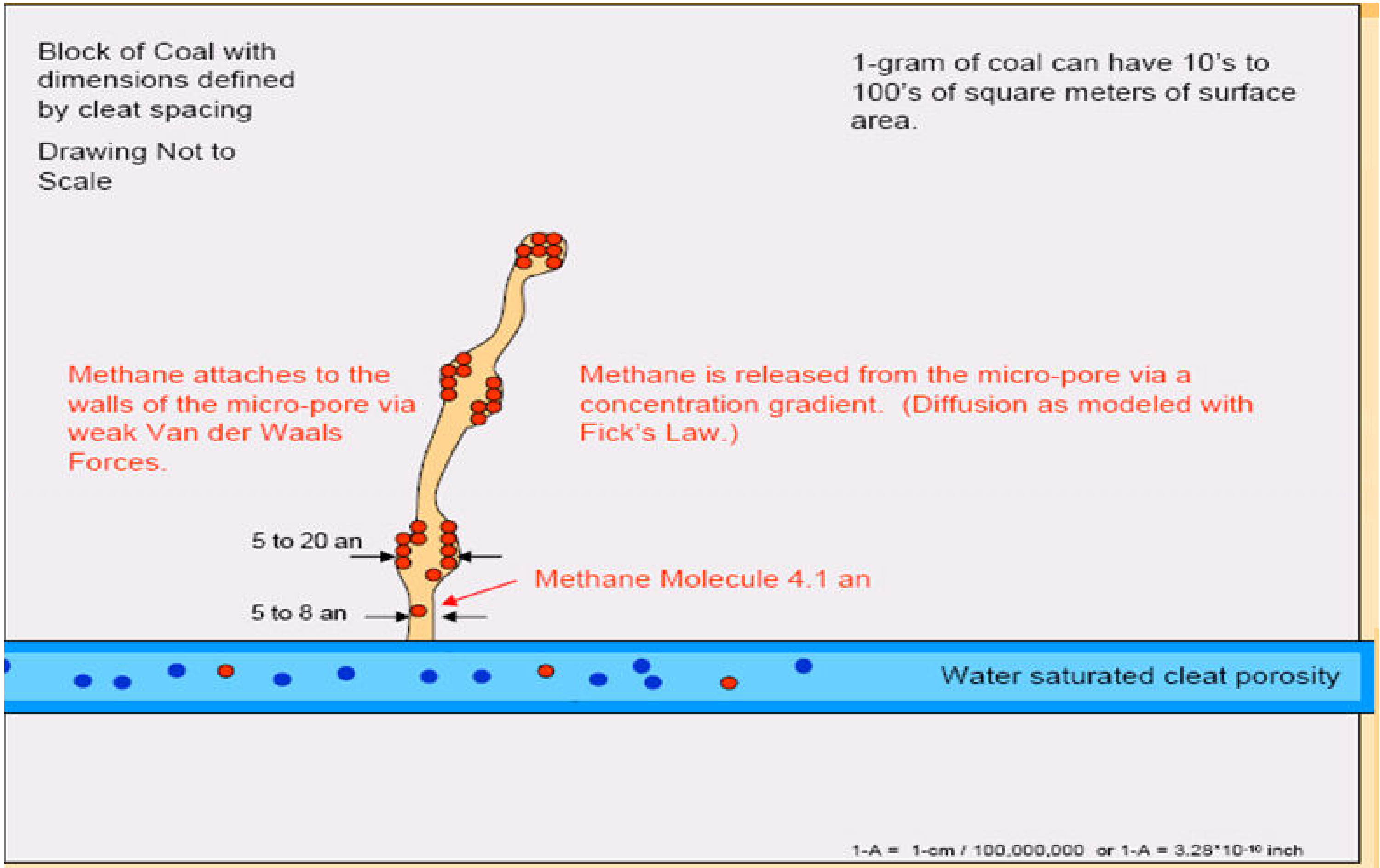




Conventional:

- 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?



Block of Coal with dimensions defined by cleat spacing

Drawing Not to Scale

1-gram of coal can have 10’s to 100’s of square meters of surface area.

Methane attaches to the walls of the micro-pore via weak Van der Waals Forces.

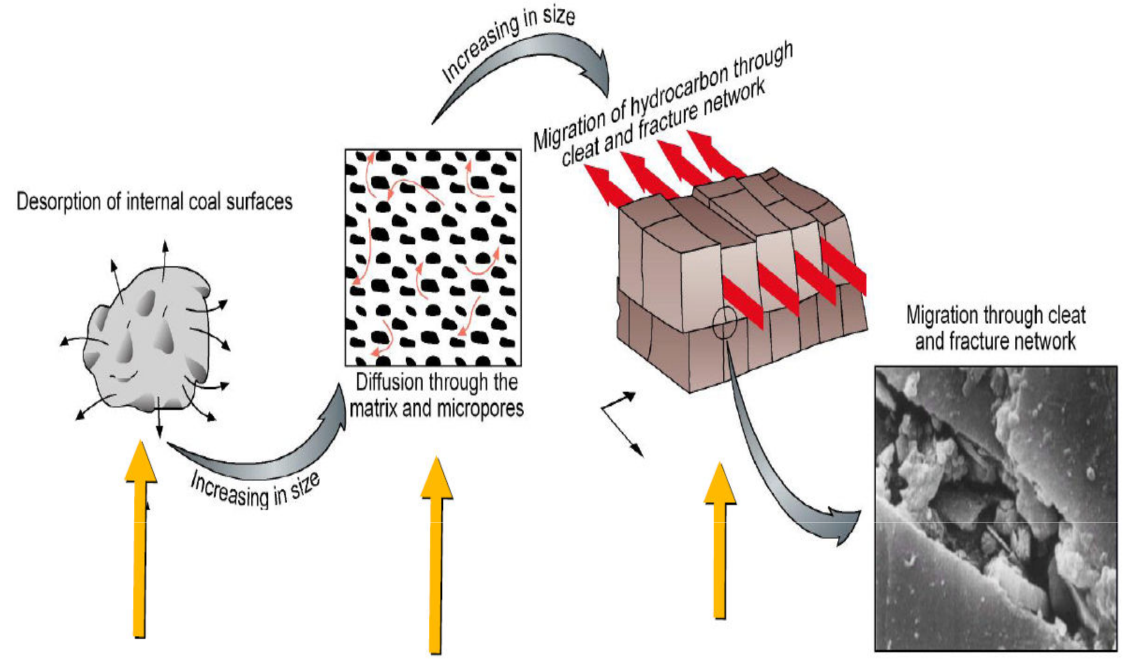
Methane is released from the micro-pore via a concentration gradient. (Diffusion as modeled with Fick’s Law.)

1-A = 1-cm / 100,000,000 or 1-A = $3.28*10^{-10}$ inch

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?



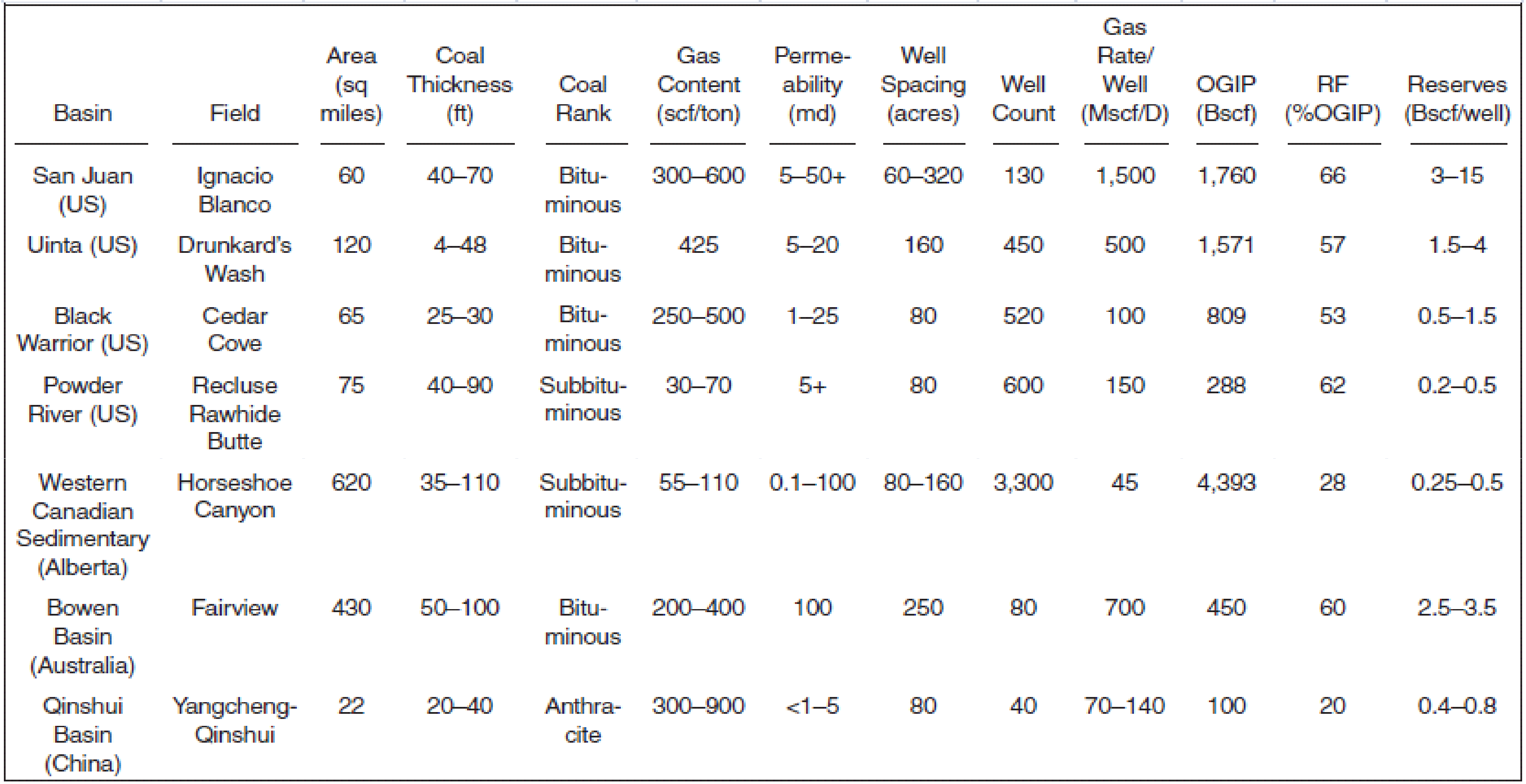
Desorption from internal coal surfaces

Diffusion through coal matrix

Flow through fracture/cleat network

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?



Basin	Field	Area (sq miles)	Coal Thickness (ft)	Coal Rank	Gas Content (scf/ton)	Permeability (md)	Well Spacing (acres)	Well Count	Gas Rate/ Well (Mscf/D)	OGIP (Bscf)	RF (%OGIP)	Reserves (Bscf/well)
San Juan (US)	Ignacio Blanco	60	40–70	Bituminous	300–600	5–50+	60–320	130	1,500	1,760	66	3–15
Uinta (US)	Drunkard's Wash	120	4–48	Bituminous	425	5–20	160	450	500	1,571	57	1.5–4
Black Warrior (US)	Cedar Cove	65	25–30	Bituminous	250–500	1–25	80	520	100	809	53	0.5–1.5
Powder River (US)	Recluse Rawhide Butte	75	40–90	Subbituminous	30–70	5+	80	600	150	288	62	0.2–0.5
Western Canadian Sedimentary (Alberta)	Horseshoe Canyon	620	35–110	Subbituminous	55–110	0.1–100	80–160	3,300	45	4,393	28	0.25–0.5
Bowen Basin (Australia)	Fairview	430	50–100	Bituminous	200–400	100	250	80	700	450	60	2.5–3.5
Qinshui Basin (China)	Yangcheng-Qinshui	22	20–40	Anthracite	300–900	<1–5	80	40	70–140	100	20	0.4–0.8

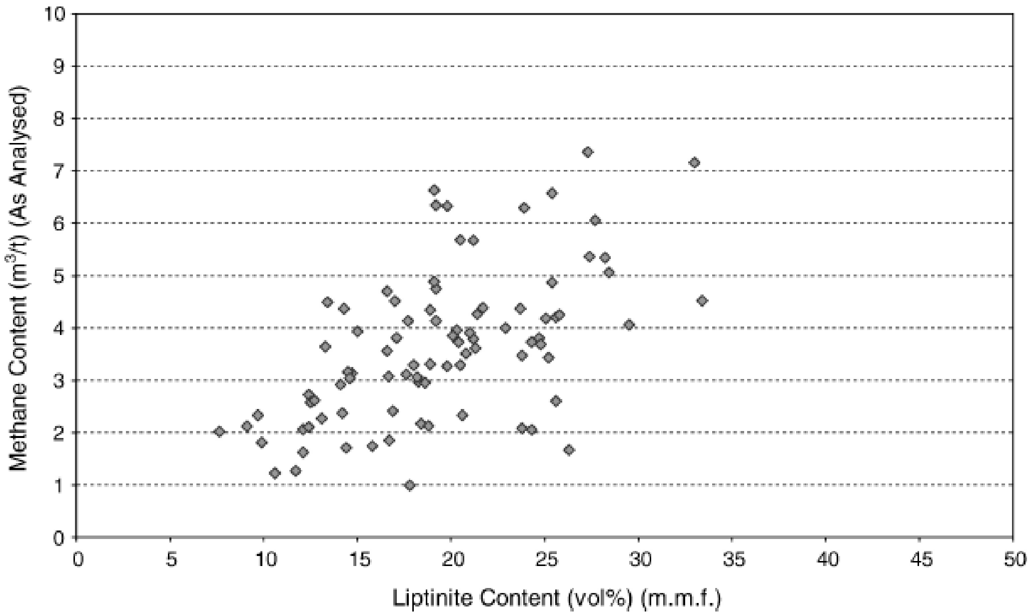
Source: Coalbed and Shale-Gas Reservoirs, Creties D. Jenkins and Charles M. Boyer II, SPE 103524 February 2008

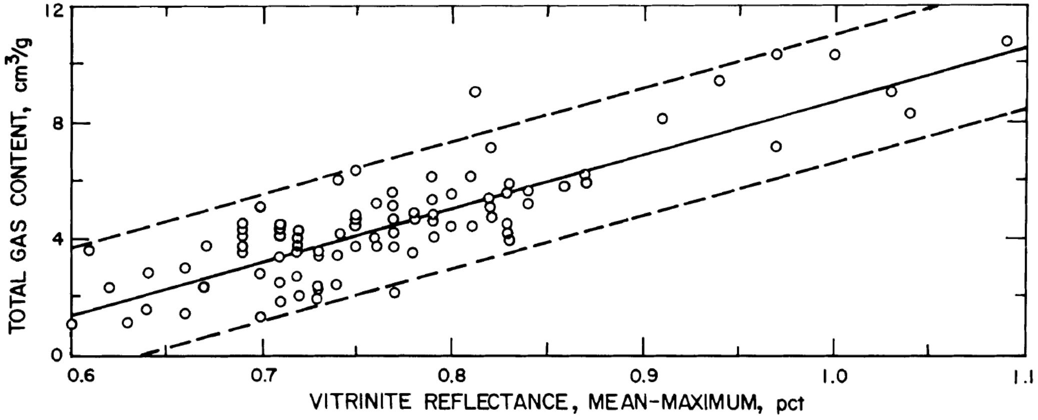
Characteristics Defining Commercial Potential of Coal as a Gas Reservoir

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

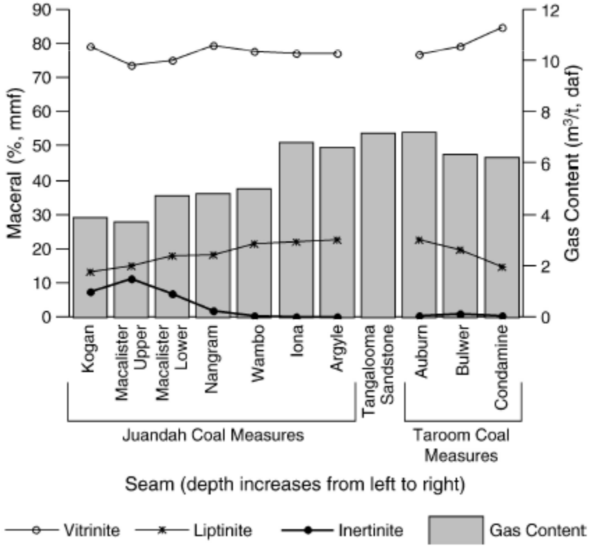
- Moisture and ash content are components that will not contribute to CBM resources and must be corrected for in the CBM resource estimate
- Volatile matter and free carbon are relevant because they can be related to gas generation and the potential for commercial CBM
- The coal composition can be related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

James P. Ulery, Report of Investigation 9196, US Department of Interior, 1988

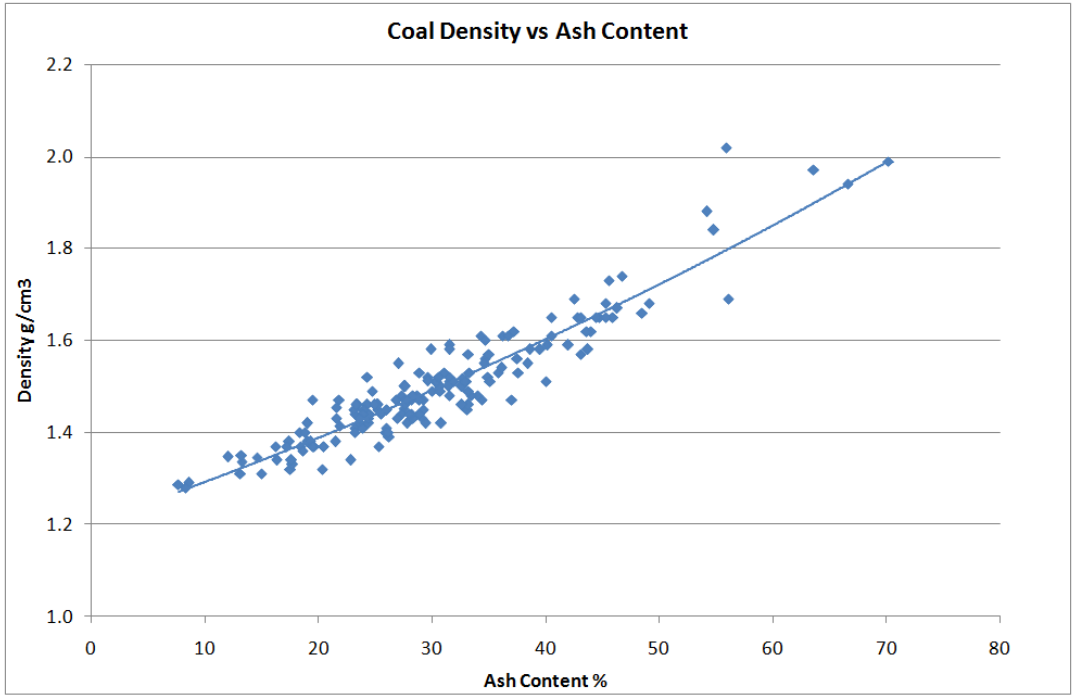


Walloon Subgroup Gas Content vs Maceral Content

Steven Scott, Bruce Anderson, Peter Crosdale, Julie Dingwall, Garry Leblang — Coal petrology and coal seam gas contents of the Walloon Subgroup — Surat Basin, Queensland, Australia. International Journal of Coal Geology 70 (2007) 209–222.

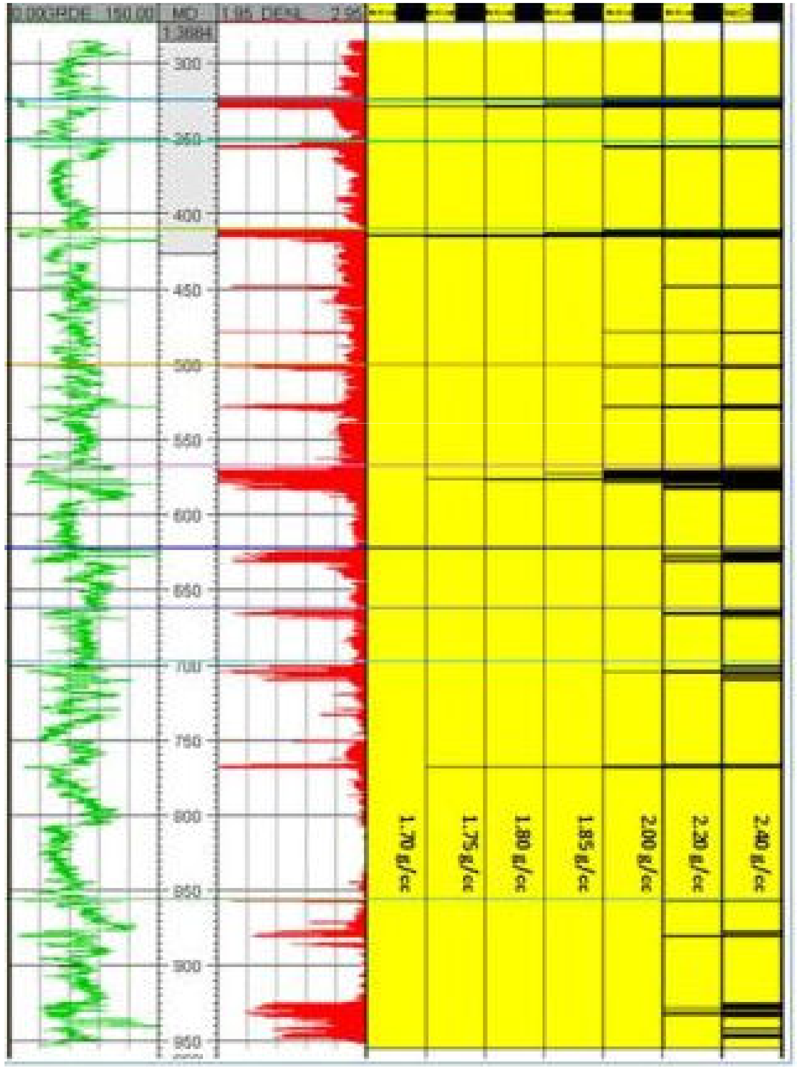
Analysis of Coal Properties – Density and Ash

- 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.



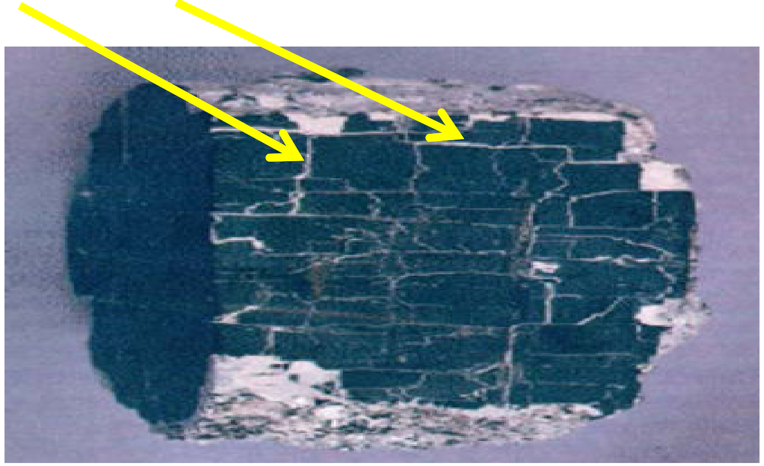
Source: RISC analysis

Density cutoff vs Net Coal

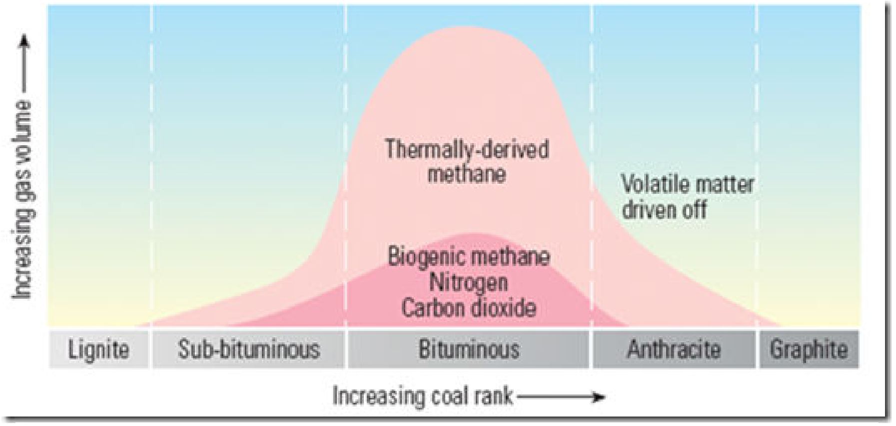


Permeability and the Coal Cleat System

Butt and face cleats create permeability anisotropy



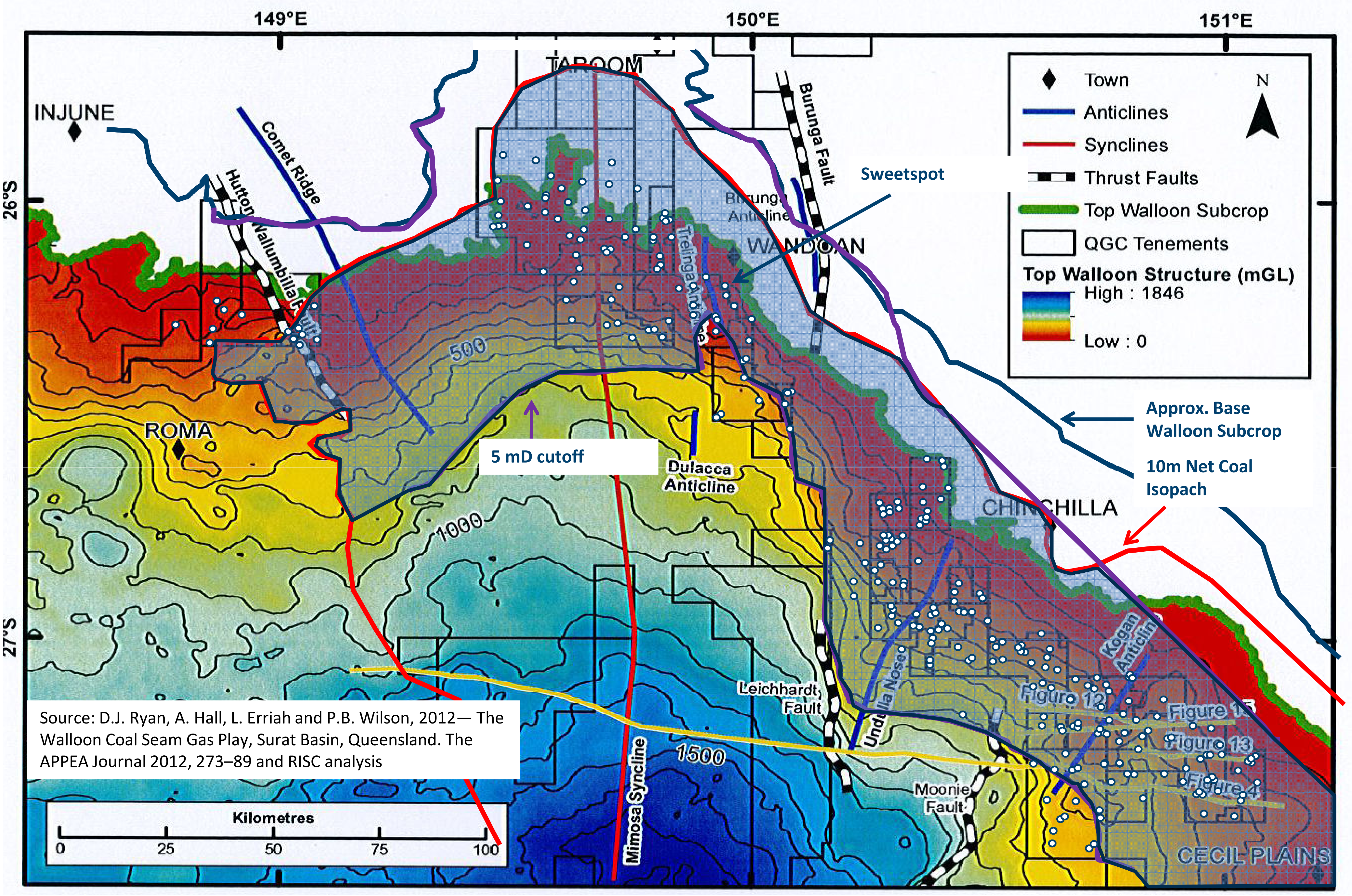
High rank coal: cleating destroyed



←Decreasing Perm→

Increasing Adsorption →

- 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)



Sweetspot

5 mD cutoff

Approx. Base Walloon Subcrop

10m Net Coal Isopach

Source: D.J. Ryan, A. Hall, L. Erriah and P.B. Wilson, 2012— The Walloon Coal Seam Gas Play, Surat Basin, Queensland. The APPEA Journal 2012, 273–89 and RISC analysis

Adsorption & Desorption Analysis

Initial Sorbed Gas Content (Desorption Analysis)

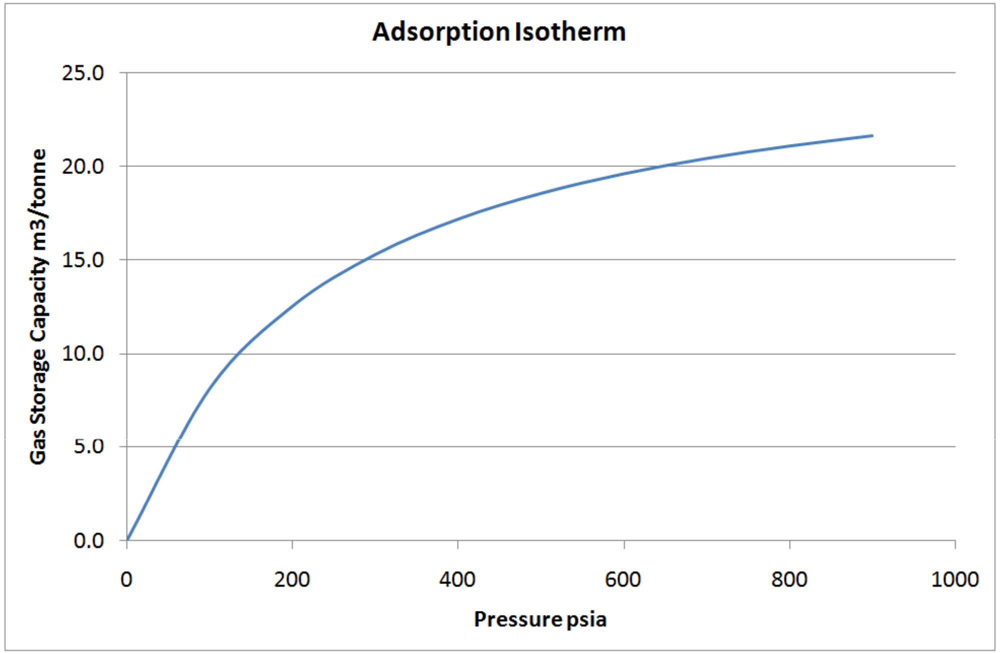
- Measured in the laboratory by measuring the amount of gas that actually is stored in a coal sample using a **desorption** process, includes:
  - Lost Gas + Gas Released + Crushed Sample Gas

- 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 ie 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 ie 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"**



Gas Storage Capacity, $G_{sL} = V_L \times p / (p + P_L) \times (1 - w_a - w_{we})$, scf/ton in situ
Where:

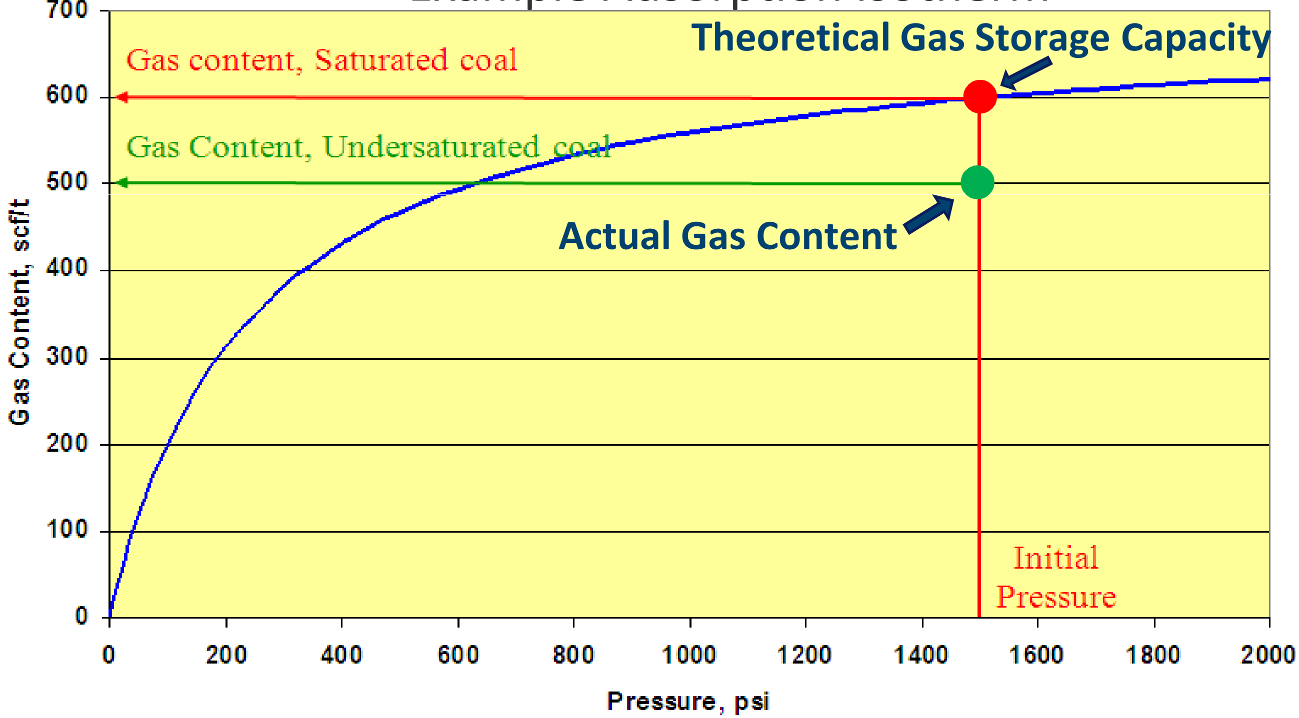
V_L = Langmuir Volume, scf/ton DAF
P_L = Langmuir pressure, psia
p = pressure, psia
w_a = ash weight content
w_{we} = equilibrium moisture content, weight fraction

Gas Saturation

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

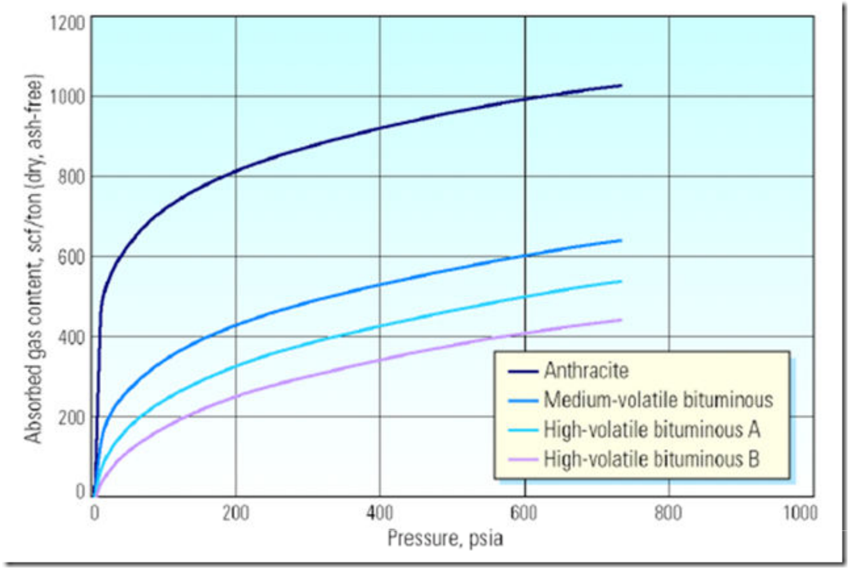
- A coal is said to be **undersaturated** when the gas content is lower than the theoretical storage capacity
- Under-saturated coal may require significant depressurisation before gas is produced

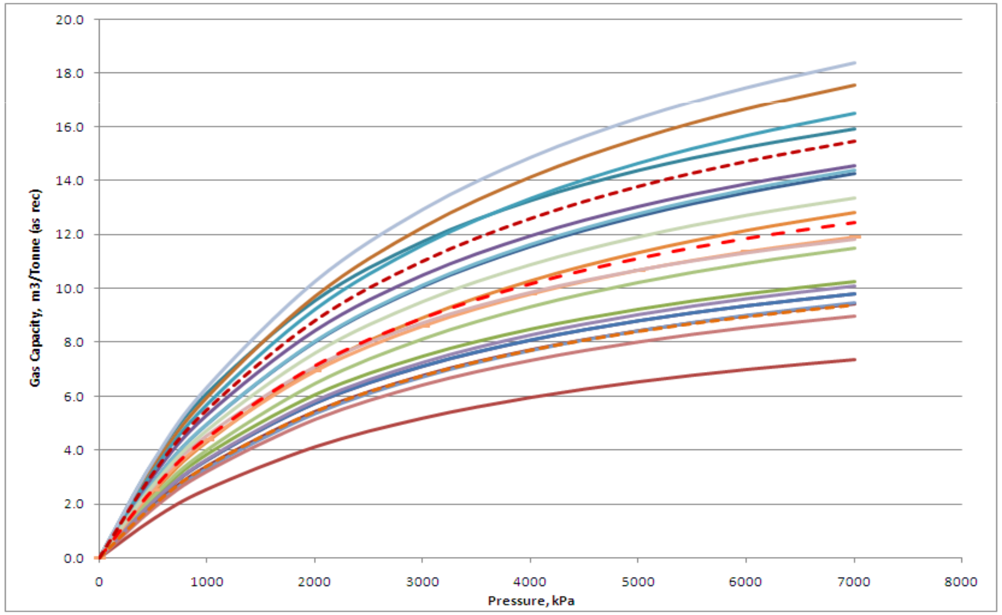
Example Adsorption Isotherm

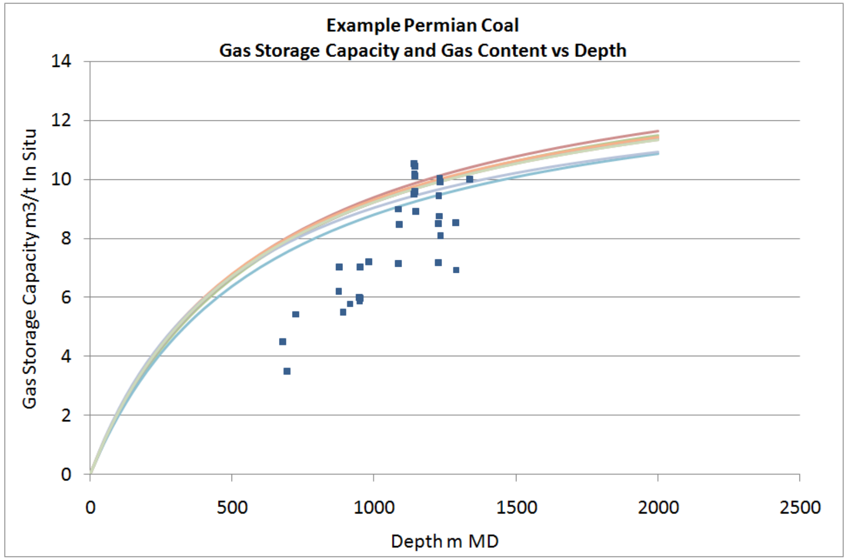


Spatial Variation of Gas Content

- 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






Example Permian Coal
Gas Storage Capacity and Gas Content vs 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: $CO_2 > CH_4 > N_2$
- The impact of the inert gases (CO_2 and 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

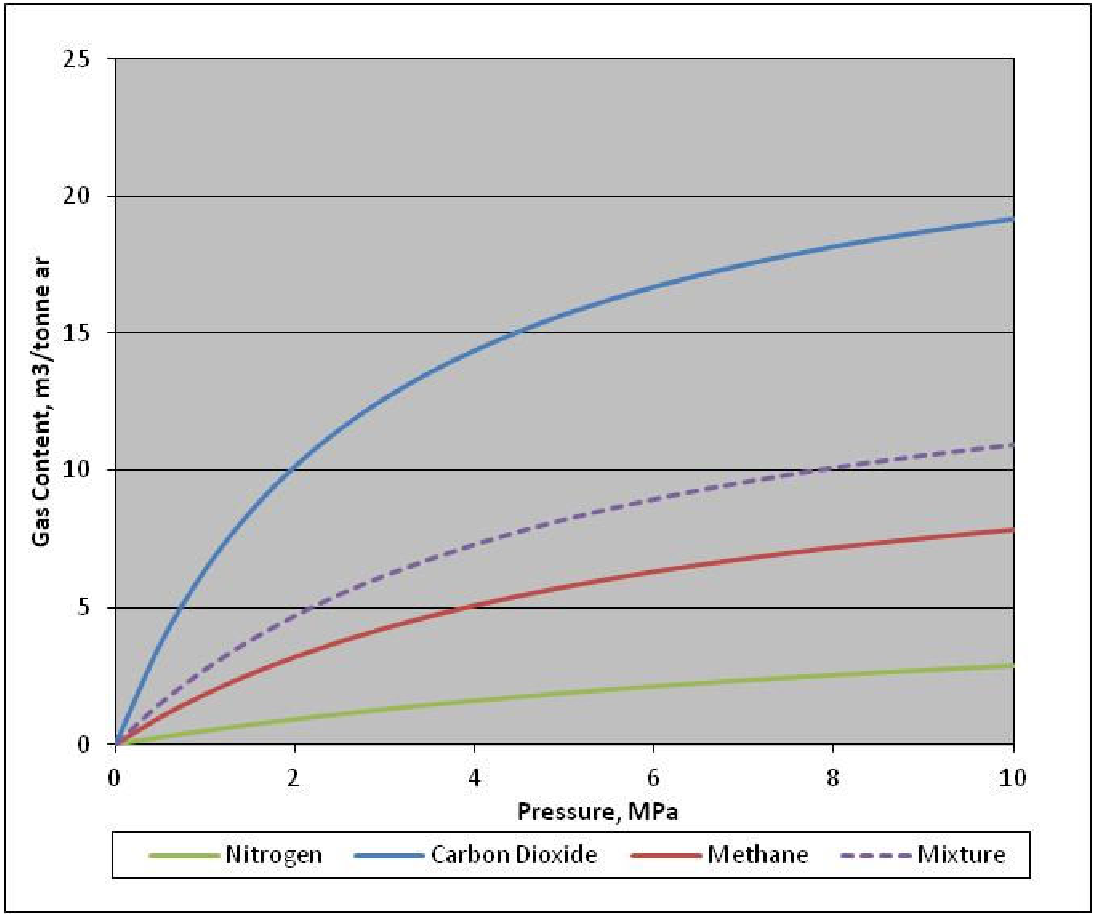
Extended Langmuir Isotherms

$$V_i = V_{L_i} \frac{b_i p_i}{1 + \sum_{j=1}^{n_c} b_j p_j}$$

Where:

V_{Li} = Langmuir Volume of component i
b_i = reciprocal of Langmuir Pressure, P_{Li}, of component i
p = pressure

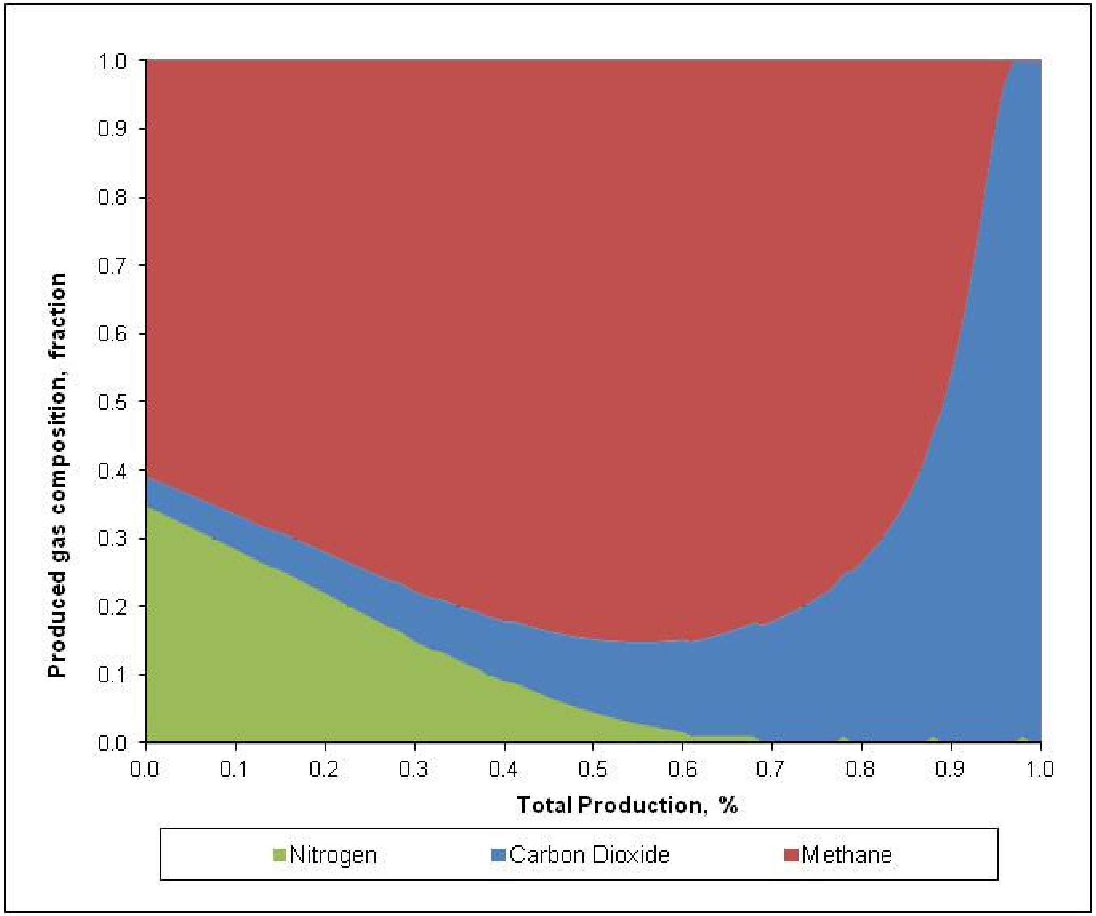
Calculate the saturation using the isotherm of the mixture



Example mixture isotherm: 20 % CO_2, 10 % 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

OGIP
Estimates

- 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

Recovery
Estimates

- Commercially viable project development plan
- Development approvals and access agreements
- Contract terms (permit terms and gas sales agreements)
- Economic analysis
- Finance

Reserve
Estimates

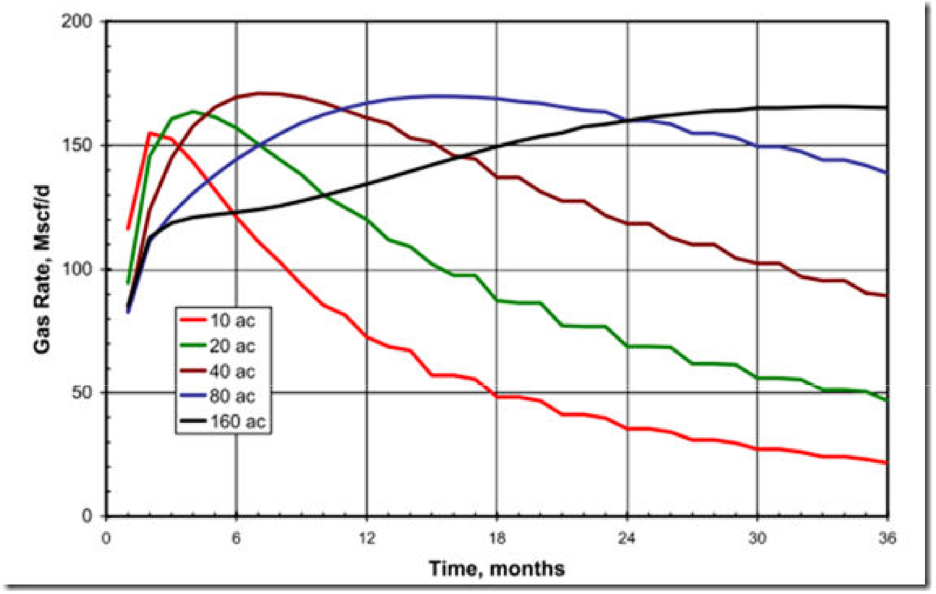
RISC

Major Parameters in CBM Evaluation – Data Sources

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

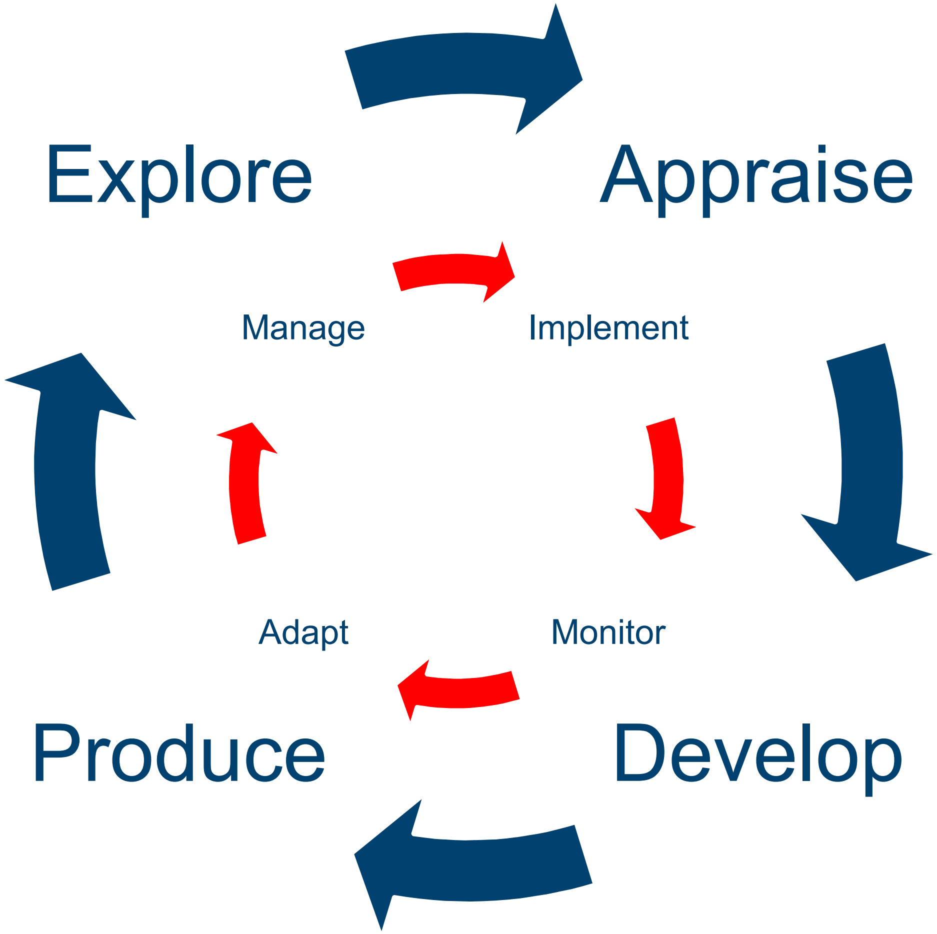
Pilot Testing

- 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

Manage

Implement

Adapt

Monitor

Produce

Develop

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 $\sigma_V > \sigma_{Hmax} > \sigma_{Hmin}$
  - Bulk (cleat) permeability decreases with depth
- Eastern Australia
  - Strike-slip ($\sigma_{Hmax} > \sigma_V > \sigma_{Hmin}$ to Reverse ($\sigma_{Hmax} > \sigma_{Hmin} > \sigma_V$)

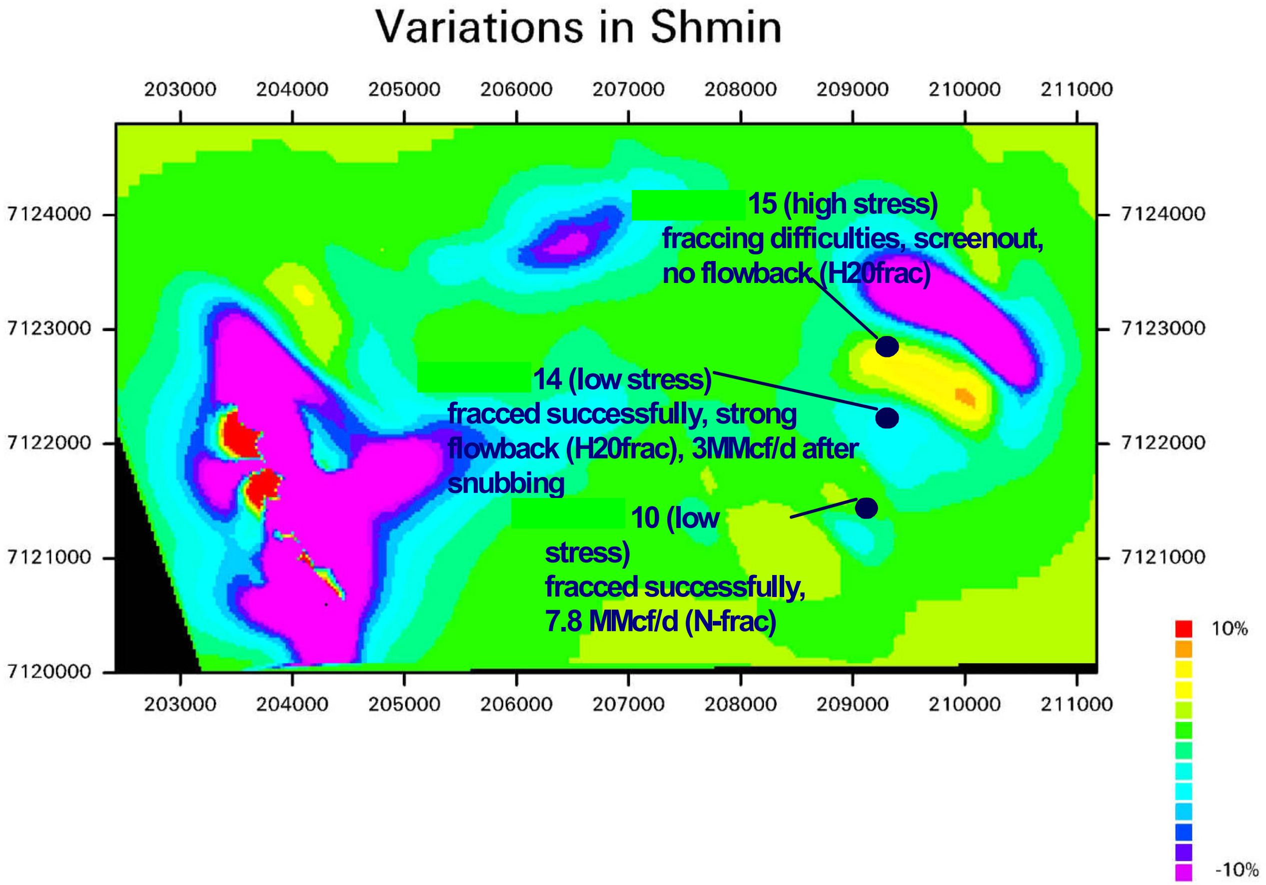
Drill Collars Bent Uni-Directionally

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



Variations in Shmin

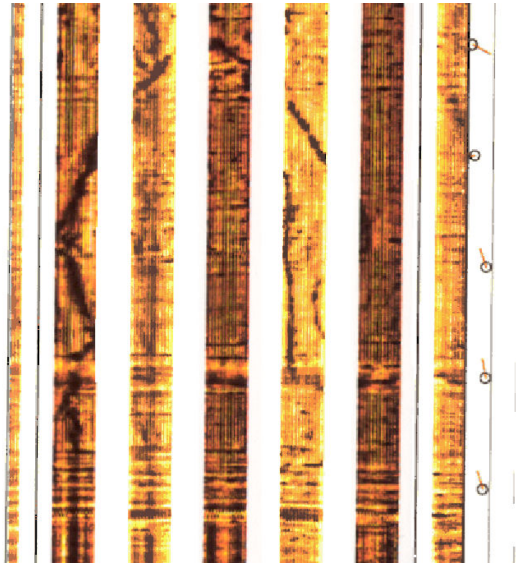
[redacted] 15 (high stress)
fraccing difficulties, screenout, no flowback (H20frac)

[redacted] 14 (low stress)
fracced successfully, strong flowback (H20frac), 3MMcf/d after snubbing

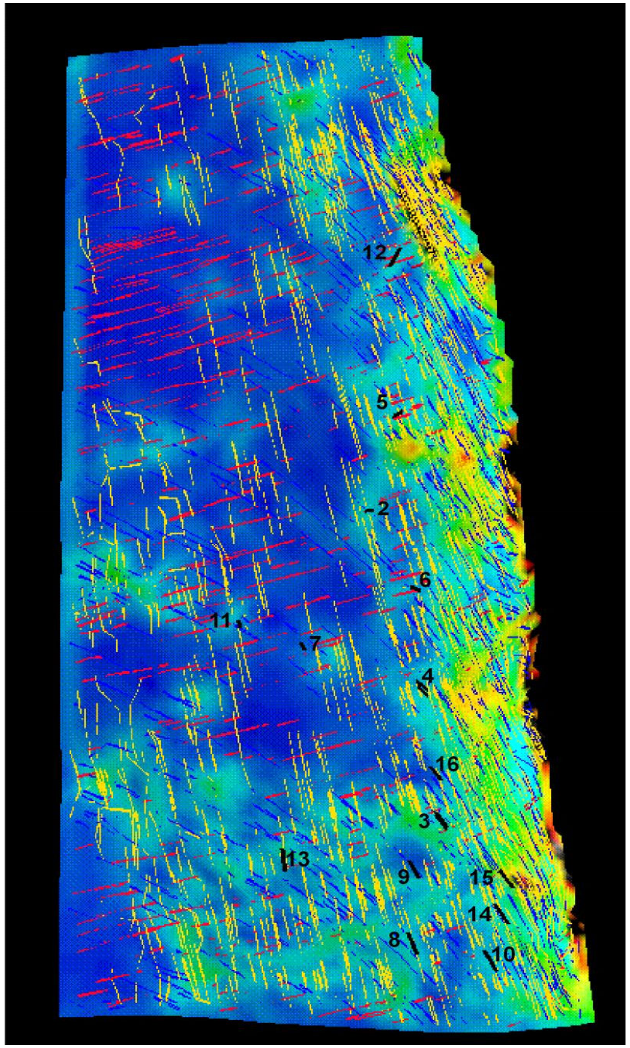
[redacted] 10 (low stress)
fracced successfully, 7.8 MMcf/d (N-frac)

Natural Fracture Modelling

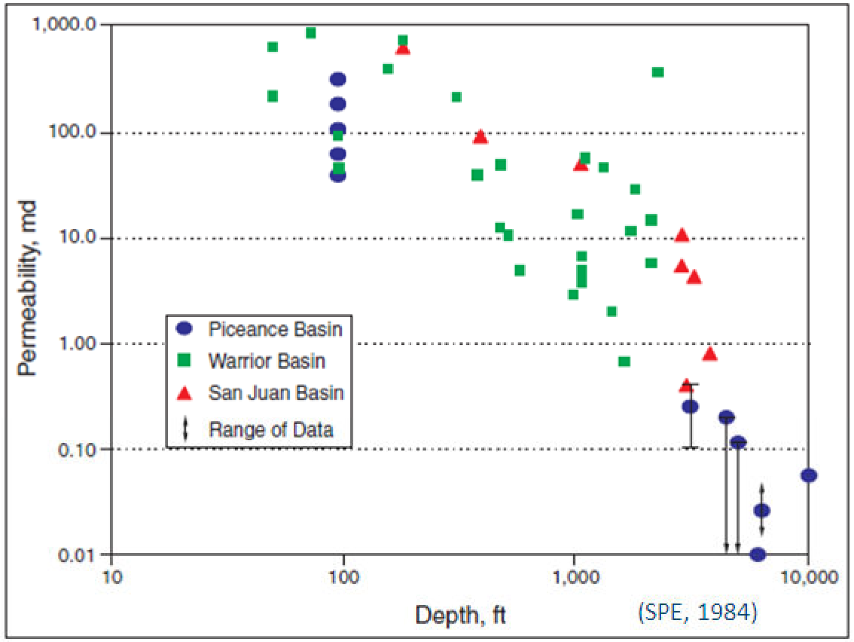
- Natural fracture system orientation identified from image logs
- Structure restored to pre-deformational geometry and forward modelled to present stress state
- Strain associated with folding captured and used to develop natural fracture distributions



Coal Seam Fractures



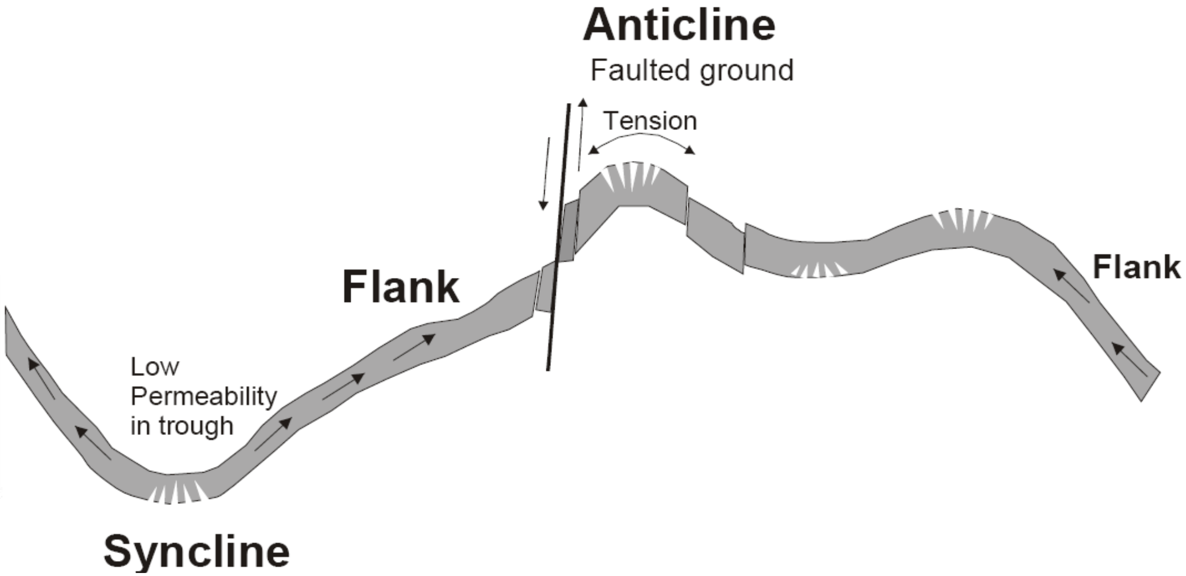
Structural & Depth Effects



(SPE, 1984)

Depth effects on Permeability

Structural effects on Permeability



Permeability changes with desorption

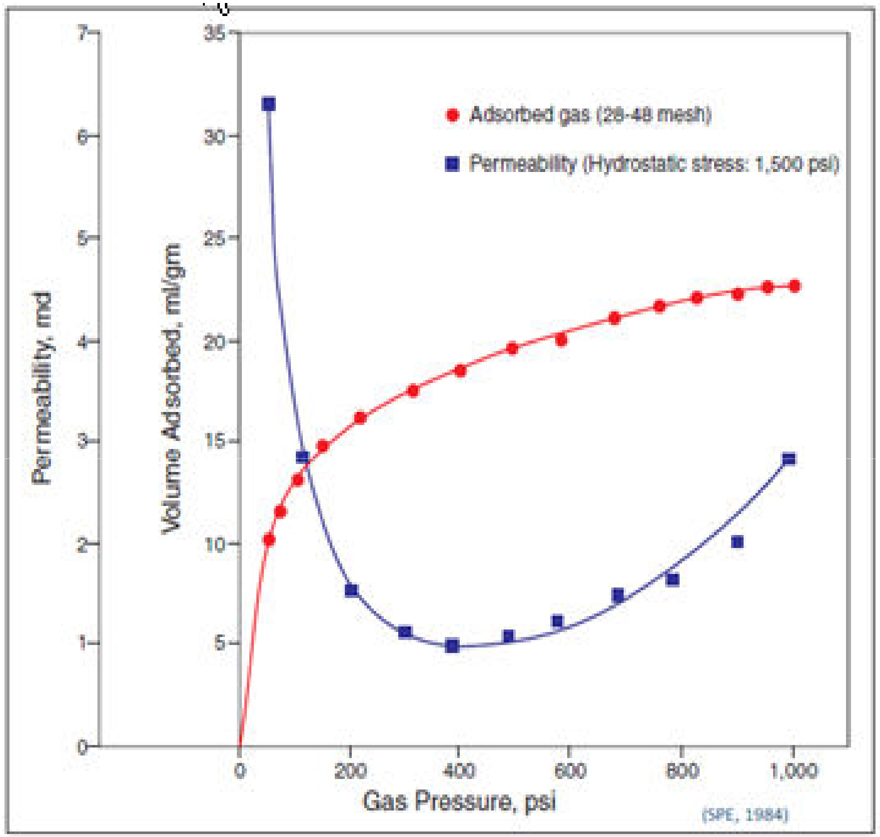
Two counteracting mechanisms are at work:

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.



(SPE, 1984)

Well Design & Recovery

Vertical Well Types

Cavitation

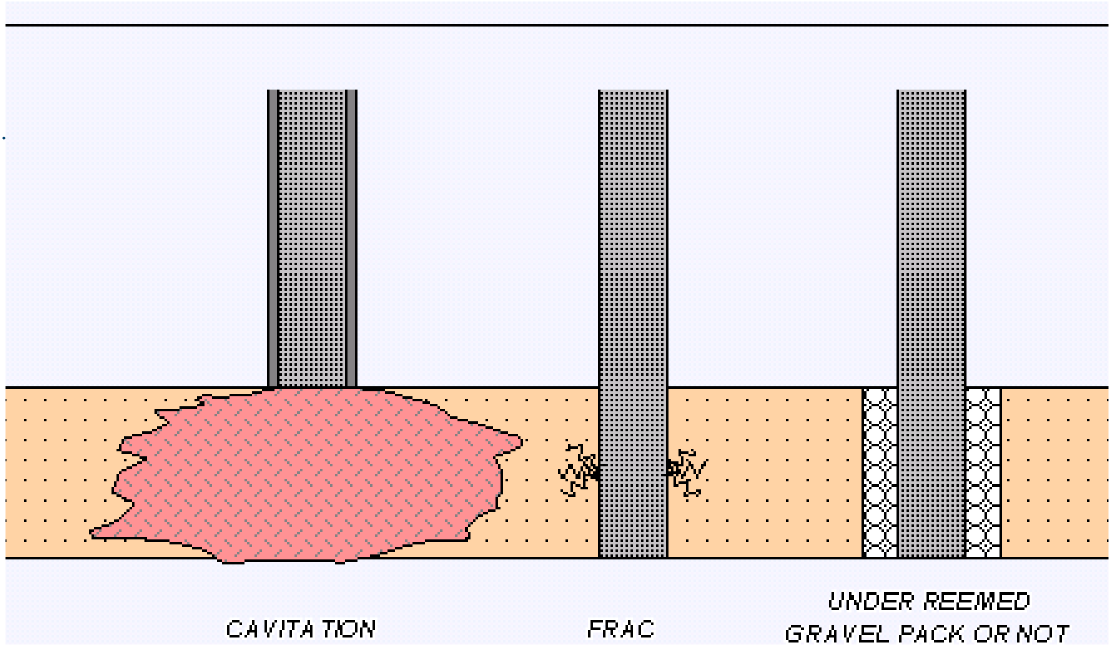
- compressed air is used to cavitate the coal seam
- increases the effective well bore radius and improves inflow efficiency
- removes coal damaged by drilling fluids

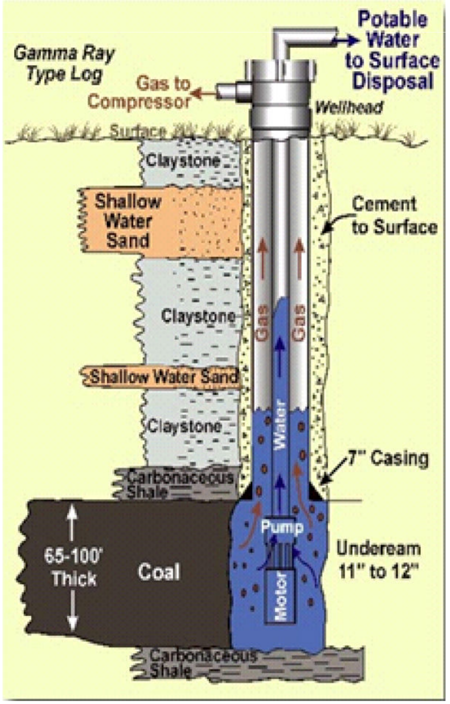
Under-reaming

- 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

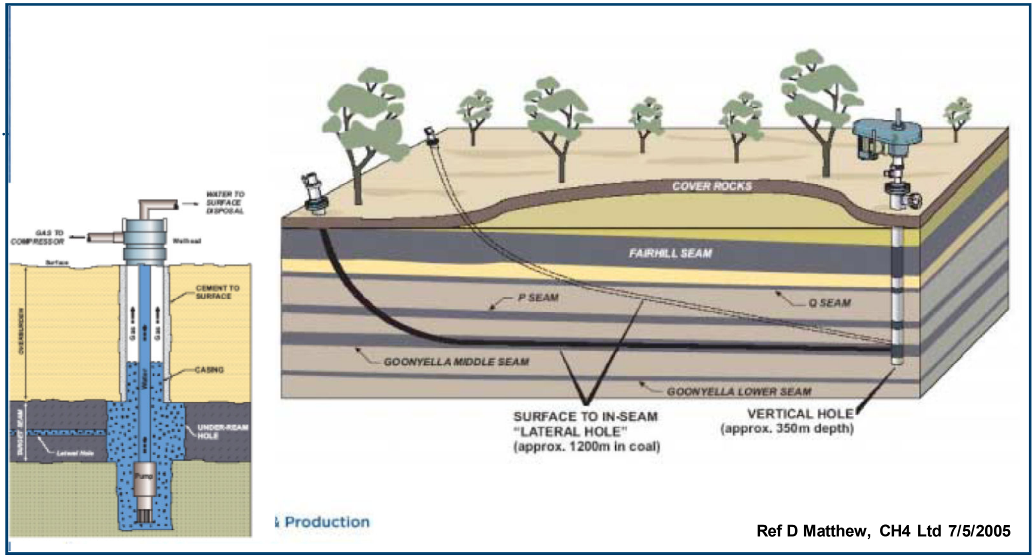
- uses high pressure water with additives to fracture the coal and proppants to keep the fracture open
- increases the effective well bore radius and improves inflow efficiency, bypasses drilling damage
- connects up cleats and natural fractures to the wellbore





Can be single seam or multi-seam

Horizontal Wells & Multi Laterals



Ref D Matthew, CH4 Ltd 7/5/2005

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

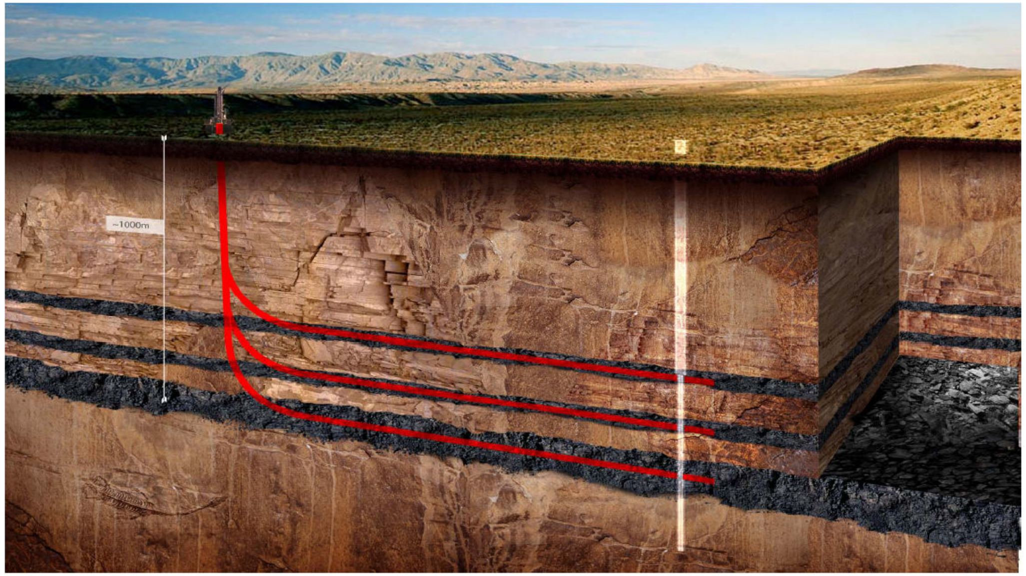
Multi-lateral

- two or more laterals in a seam

Multi-lateral stacked

- two or more laterals in separate seams

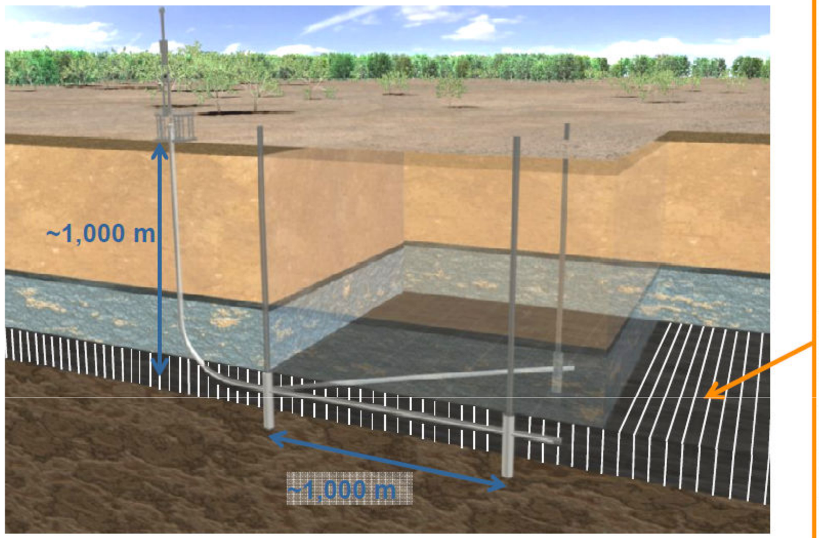
Source Eastern Star Gas



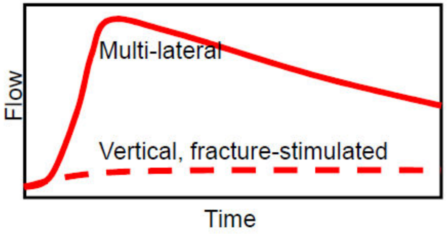
Gunnedah Basin Bohena Seam (Anisotropy Example)

- 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

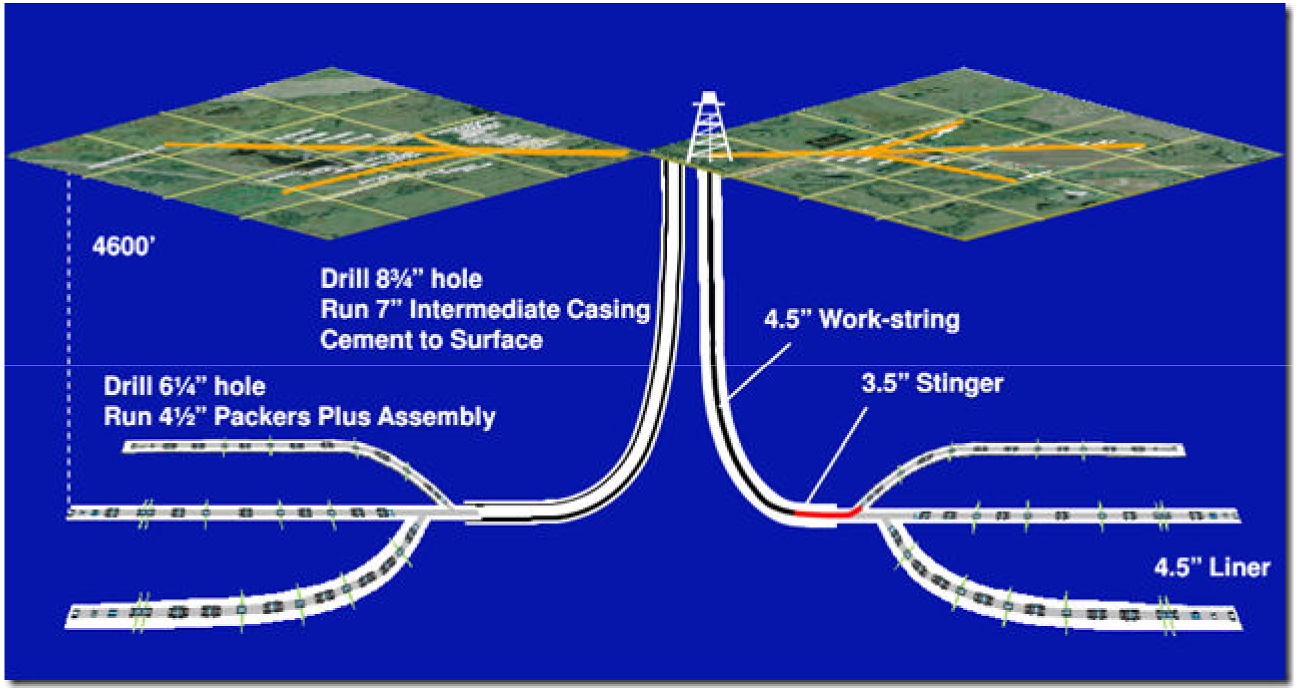


Lateral wells are drilled perpendicular to the natural fracturing system of the target coal

Source: Eastern Star Gas

Canada CBM Mannville Example

- Two Well Pad
- Stimulated Tri-Laterals



Source: Apache Canada

Comments on CBM Drilling Technology

Fracture stimulation

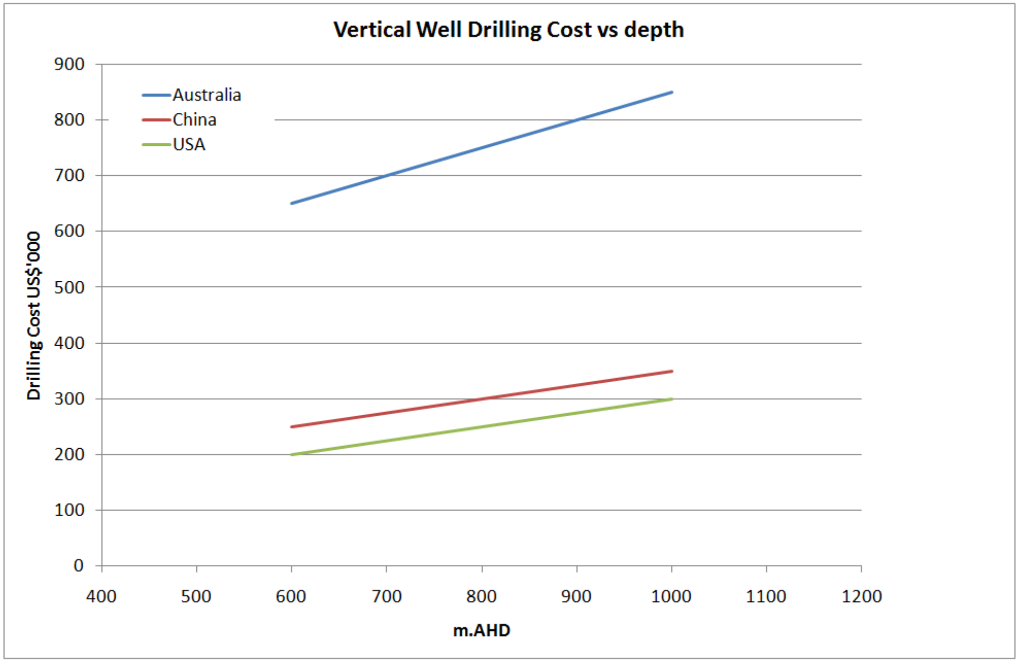
- Fracture stimulation significantly increases costs (will probably need re-fraccing?)
- Needs competent coals (soft coal fracs won’t stay open); isolation from aquifers
- Horizontal Wells
- Much higher costs; suited to lower permeability coals or where land access is an issue
- Boreholes can become 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

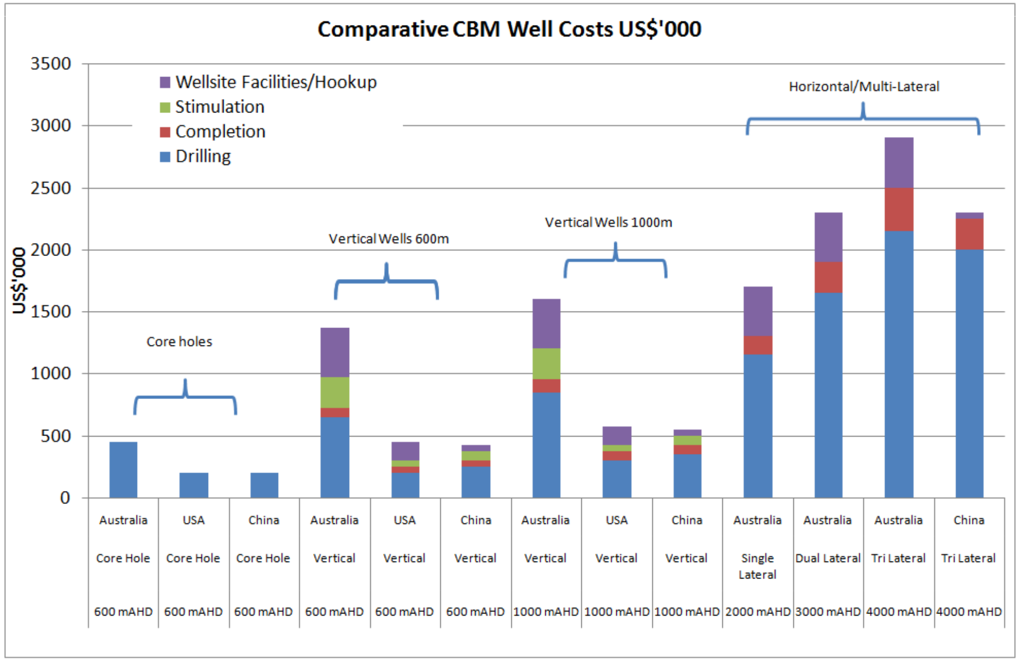
Learning Curve

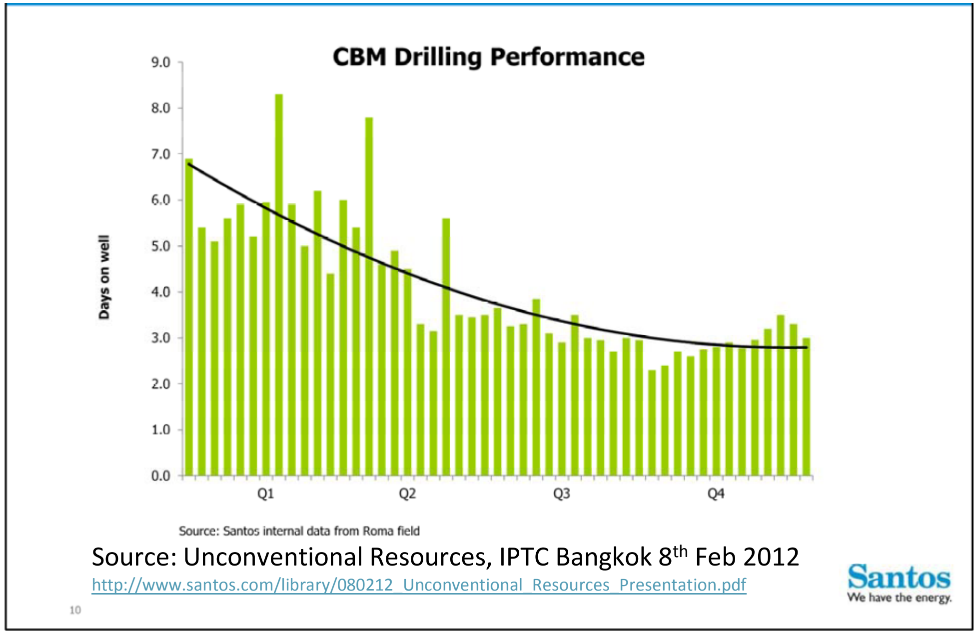
- Large well numbers in CBM developments make continuous improvement possible
- Santos Surat basin example 40% reduction in one year (see next page)

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: Santos internal data from Roma field

Source: Unconventional Resources, IPTC Bangkok 8th Feb 2012
http://www.santos.com/library/080212_Unconventional_Resources_Presentation.pdf

Source: RISC analysis

Thank You

Any Questions?

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DECISIONS WITH CONFIDENCE