WHAT MAKES A GOOD COAL SEAM RESERVOIR?

**Resource**
Gas content – high gas but thin coal, or low gas but thick coal?
Gas composition – methane >98% (preferably)
  - Thermogenic vs biogenic
Coal net thickness – as much as possible
Coal seam lateral continuity – predictable
  - thickness, splitting, quality, faulting, intrusives

**Deliverability**
Saturation – high
Permeability – yes please
  - Cleat density and orientation, mineralisation, stress
  - Depth and stress
COAL SEAM GEOMETRY and CHARACTER

Goonyella Mine, Bowen Basin, Qld

- Sandstone proximal to seam
- Water ingress
- Tighter but stable
- Permeable but weak
- Thrust
COAL FORMATION STAGES

Ingredients

Compost pile

Earth oven

Schematic diagram of the burial process (source: http://smtc.uwyo.edu/coal/swamp/anatomy.asp)
INGREDIENTS MATTER
Climate: need conditions of high rainfall or humidity to support luxuriant plant growth (can be tropical, temperate or cold)

Slowly subsiding basin: to allow thick accumulation of peat and burial under continuous shallow water

No clastic sediment: little or no influx of normal clastic sediment into peat mires from surrounding water courses

Reducing conditions: Stagnant or nearly stagnant water so that available oxygen is used up and plant material is not oxidised
MODERN ENVIRONMENTS FOR PEAT ACCUMULATION

Low lying areas like alluvial floodplains, deltas, and coastlines accommodate peats

Moreso- want to preserve them in the subsurface

Peat mires adjacent to the Copper River Delta, Alaska

http://www.wadih-ghsoubi.com/Nature/1/
MODERN GLOBAL PEAT BELTS

RESPONSE TO MOST RECENT SEA LEVEL HIGH STAND
END OF THE LAST BIG ICE AGE
6000 – 10,000 Y.B.P.

Global occurrence of peat accumulating mires
(source: http://www.peatlandsni.gov.uk/formation/global.htm#globalmap)
Regional Bio-Climatic Peat Belts

Overlain by Bowen Basin (upside down)

Climate and water table will control the ingredients and success of the compost pile.

Source: Wladimir Bleuten; http://www.geog.uu.nl/fg/casus/noframes.htm
LOCAL BIO-CLIMATIC PEAT BELTS

Source: Wladimir Bleuten; http://www.geog.uu.nl/fg/casus/noframes.htm
Modern Peats- Vertical And Lateral Plant Succession

Primary peat woodland

Oligotrophic bog lake

If water table is raised or lowered, then these different vegetation zones will succeed one another

Photos courtesy Elena Lapshina Tomsk University
PEAT STRATIGRAPHY

ice/permafrost
Reconstruction of plant communities and conditions affecting peat accumulation and subsequent types of coal for a Permian age deposit (source: Diessel, 1980).
ANCIENT GLOBAL PEAT BELTS

Too arid in Euramerica At this time

Permian Cool Temperate belts

Upper Carboniferous Tropical belt

can (black dots) and thereby known paleomires (modified from Scotese, 2001). AU = Australia, CH = China, EU = Europe, NA= North America, SA = South America, SI = Siberia.

Greb et al, 2006 modified from Scotese, 2001
http://www.scotese.com/
ANCIENT GLOBAL PEAT BELTS

ANCIENT GLOBAL PEAT BELTS

coal (black dots) and thereby known paleomires (modified from Scotese, 2001). AU = Australia, CH = China, EU = Europe, NA= North America, SA = South America, SI = Siberia.

Greb et al, 2006 modified from Scotese, 2001
http://www.scotese.com/
WORLD DISTRIBUTION OF COAL BASINS

(source: Landis and Weaver, 1993)
AGE DISTRIBUTION OF MAJOR COAL DEPOSITS

Evolution of Land plants

Flowering plants

modified after Walker, 2000 and Thomas, 2002
COAL CHARACTERISATION

TYPE = organic composition

RANK = thermal maturity

GRADE = mineral matter impurities
COAL LITHOTYPE CLASSIFICATION

First coined by Marie Stopes 1919- “On the Four Visible Ingredients of Banded Bituminous* Coal”

*there’s another one for brown coal

DULL
- DULL
  - <1% bright
- DULL w/MINOR
  - 1-10% bright
- BANDED DULL
  - 10-40% bright
- BANDED
  - 40-60% bright
- BANDED BRIGHT
  - 60-90% bright
- BRIGHT
  - >90% bright

SA
- DULL
  - <1% bright
- DULL w/MINOR
  - 1-10% bright
- BANDED DULL
  - 10-40% bright
- BANDED
  - 40-60% bright
- BANDED BRIGHT
  - 60-90% bright
- BRIGHT
  - >90% bright

ICCP
- DURAIN
- DURO-CLARAIN
- CLARAIN
- VITRO CLARAIN
- VITRAIN

ASTM
- DURAIN
- DULL CLARAIN
- CLARAIN
- BRIGHT CLARAIN
- VITRAIN

Others:
- fibrous coal = fusain = charcoal = mother coal
- shaley coal = bone
- coaly shale = carbonaceous mudstone
- cannel coal

Non-banded ——→ Well banded
• Multiple stacked plant successions and flooding cycles

• Coal seams subdivided into different plies or benches

• Plies often have different coal type and grade that will impact upon:
  • gas holding capacity
  • permeability
COAL TYPE-SCALES OF CHARACTERISATION

MEGASCOPIC

MACROSCOPIC

MICROSCOPIC

BRIGHT BANDED

DULL

telovitrinite

dv

id

sf

250 microns

50 mm

5 cm
MICROSCOPIC CHARACTERISATION- “THE MACERAL”

Composition will control source of hydrocarbons
Texture will control storage and permeability
All things being equal…

van Krevelen, 1993
Coal Grade or Mineral Matter Abundance

**Occurrence**

**Bands and lenses** (partings) that result from the *influx of minerals* in sediments washed into the peat mire during deposition or fallen in from air due to volcanic activity (i.e. volcanic ash falls=tuffs, tuffaceous sediments). These are “easy” to separate from the coal during mechanical processing (i.e. crushing, density separation)

**Adventitious** or *dissolved minerals* that precipitate out of solution from ground water; these often occur admixed with the groundmass or matrix macerals and are small and difficult to separate from the coal during mechanical processing.

**Inherent ash** that is precipitated by the plants themselves either as minerals or organo-metallic complexes. E.g. phytoliths. These are really small, often molecular scale and nigh impossible to separate from the coal during mechanical processing.

**Others** that fill cracks or fissures (cleats) in the coal, or replace the cellular structure of the plants and phyterals in the coal. These are often epi- or diagenetic, i.e. occurring after peat accumulation and can also occur due to igneous intrusions into the coal.
COAL GRADE- MINERAL MATTER IMPURITIES

Major species
- Quartz (SiO₂)
- Clays
  - Illite (K, Al, Silicate)
  - Kaolinite ((Al₂ Si₂)₅ (OH)₁₄)
  - Mixed-layer clays (K, Al, Mg, Fe silicates)
- Carbonates
  - Calcite (CaCO₃)
  - Siderite ((Fe, Mn)CO₃)
- Pyrite (FeS₂)

Accessories
- Galena (PbS)
- Sphalerite ((Zn, Cd)S)
- Clausthalite (PbSe)
- Chalcopyrite (CuFeS₂)
- Crandallite Group (Ca, Ba, Sr)Al₃ (PO₄)₂ (OH)₅H₂O
- Monazite (REE, Th) PO₄
- Apatite (Ca₅ (PO₄)₅ (F, OH))
- Barite (BaSO₄)
- Rutile (TiO₂)
- Zircon (ZrSiO₄)
- Feldspars (Ca, Na, K, Al silicates)
- Zeolites (Ca, Na, K, Al silicates)
- Ankerite (Ca (Fe, Mg, Mn)(CO₃)₂)
- Micas (K, Fe, Mg, Ti, Al silicates)
COAL CHARACTERISATION – RANK

- Increase in thermal maturity
- Stacked sequences of lithotypes

Peat

Lignite/brown coal

Black/bituminous coal
Mineral matter includes other components lost upon combustion such as

- \( \text{CO}_2 \),
- \( \text{SO}_2 \) and
- \( \text{H}_2\text{O} \) of hydration
- Salts (e.g. Cl)
- Carbonates
- Sulphides

Reporting bases: raw, dry, dry ash free, dry mineral matter free

Why is this important?
<table>
<thead>
<tr>
<th>Rank Stage</th>
<th>% Carbon (d.a.f.)</th>
<th>% Volatile Matter (d.a.f.)</th>
<th>Specific Energy (gross in MJ/Kg)</th>
<th>% In Situ Moisture</th>
<th>% Vitrinite Reflectance upper boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>50</td>
<td>65</td>
<td>11.7</td>
<td></td>
<td>Random 0.20</td>
</tr>
<tr>
<td>Peat</td>
<td>60</td>
<td>60</td>
<td>14.7</td>
<td>75</td>
<td>Maximum 0.20</td>
</tr>
<tr>
<td>Brown Coal</td>
<td>71</td>
<td>52</td>
<td>23.0</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Sub bituminous</td>
<td>80</td>
<td>40</td>
<td>33.5</td>
<td>5</td>
<td>0.60</td>
</tr>
<tr>
<td>Hi Volatile</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>bituminous</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black Coal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium volatile</td>
<td>90</td>
<td>22</td>
<td>36.0</td>
<td>1</td>
<td>1.49</td>
</tr>
<tr>
<td>bituminous</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low volatile</td>
<td>91</td>
<td>14</td>
<td>36.4</td>
<td>1</td>
<td>1.85</td>
</tr>
<tr>
<td>Semi Anthracite</td>
<td>92</td>
<td>8</td>
<td>36.0</td>
<td>1</td>
<td>2.65</td>
</tr>
<tr>
<td>Anthracite</td>
<td>95</td>
<td>2</td>
<td>35.2</td>
<td>2</td>
<td>6.55</td>
</tr>
</tbody>
</table>
## MAJOR STAGES OF COALIFICATION FROM LEVINE (1993)

<table>
<thead>
<tr>
<th>COALIFICATION STAGE</th>
<th>APPROX ASTM RANK</th>
<th>PREDOMINANT PROCESSES</th>
<th>PHYSICO-CHEMICAL CHANGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peatification</td>
<td>Peat</td>
<td>Maceration, humification, gelification, fermentation, concentration of resistant substances (lipids, minerals)</td>
<td>Formation of humic substances, increased aromaticity</td>
</tr>
<tr>
<td>Dehydration</td>
<td>Lignite to sub-bituminous</td>
<td>Dehydration, compaction, loss of o-bearing groups, expulsion of -COOH, CO2 and H2O</td>
<td>Decreased moisture contents and O/C ration, increased heating value, cleat growth</td>
</tr>
<tr>
<td>Bituminisation</td>
<td>Upper sub-bituminous A through high volatile A bituminous</td>
<td>Generation and entrapment of hydrocarbons depolymerisation of matrix, increased hydrogen bonding</td>
<td>Increased Rvo, inc. fluorescence, increased extract yields, dec. in density and sorbate accessibility, increased strength</td>
</tr>
<tr>
<td>Debituminisation</td>
<td>Uppermost high volatile A through low volatile bituminous</td>
<td>Cracking, expulsion of low molecular weight hydrocarbons, ESP. methane</td>
<td>Still increasing Rvo, Decreased fluorescence, dec. molecular weight of extract, dec. H/C ratio, decreased strength, cleat growth</td>
</tr>
<tr>
<td>Graphitisation</td>
<td>Semi-anthracite to anthracite to meta-anthracite</td>
<td>Coalescence and ordering of pre-graphitic aromatic lamella, loss of hydrogen and loss of nitrogen</td>
<td>Dec in H/C ration, stronger XRD peaks, inc. sorbate accessibility, Rvo anisotropy, strength, ring condensation and cleat healing</td>
</tr>
</tbody>
</table>

INGREDIENT DEPENDENT
COALIFICATION PATHWAYS OF DIFFERENT INGREDIENTS

After van Krevelen, 1961

Images courtesy Encyclopedia Brittanica online
TYPE AND RANK OF AUSTRALIAN-NZ COALS

Higher hydrogen above the band, more liptinite

Lower hydrogen below the band, more inertinite

Fig. 14. Principal groups of Australian coals summarised. (A) O/C–H/C axes. (B) CV–VM axes. BA—Blair Athol; C—Callide; Co—Coorabbin; EC—Early Cretaceous; I—Ipswich; JQ—Jurassic, Queensland; LC—Leigh Creek; OG—Off-shore Gippsland (OGLV—Latrobe Valley and Upper Eastern View facies; OGL—Lower Eastern View Facies); P—Permian (excluding BA and Co); P and L—Victorian lignites (pale and light lithotypes); VL—Victorian lignites.
GAS GENERATION DURING COALIFICATION

Jurassic Walloon Coal

$R_{vo}=0.5\%$
“oil birth line”

Permian Moranbah Coal

$R_{vo}=1.2\%$
“oil death line”

Maturation pathways leading to gas generation
(after Hunt, 1996 in Dallegge and Barker, undated)
## GAS GENERATION STAGES

<table>
<thead>
<tr>
<th>Rank Stage</th>
<th>% Vitrinite Reflectance upper boundary</th>
<th>Vitrinite Reflectance Range for Gas Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Random</td>
<td>Maximum</td>
</tr>
<tr>
<td>Peat</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>Brown Coal</td>
<td>0.40</td>
<td>0.42</td>
</tr>
<tr>
<td>Sub bituminous</td>
<td>0.60</td>
<td>0.63</td>
</tr>
<tr>
<td>Hi Volatile</td>
<td>0.97</td>
<td>1.03</td>
</tr>
<tr>
<td>Medium volatile</td>
<td>1.49</td>
<td>1.58</td>
</tr>
<tr>
<td>Black Coal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low volatile</td>
<td>1.85</td>
<td>1.97</td>
</tr>
<tr>
<td>Semi Anthracite</td>
<td>2.65</td>
<td>2.83</td>
</tr>
<tr>
<td>Anthracite</td>
<td>6.55</td>
<td>7.00</td>
</tr>
</tbody>
</table>

- **Secondary biogenic gases**

- Peat: Braided and leafy material.
- Brown Coal: Peat with lignite, bituminous, and ash contents ranging from 0.20 to 0.42.
- Sub bituminous: Contains 0.60 to 0.63% vitrinite reflectance.
- Hi Volatile bituminous: Reflectance range from 0.97 to 1.03%.
- Medium volatile bituminous: Reflectance between 1.49 and 1.58%.
- Low volatile: Reflectance ranging from 1.85 to 1.97%.
- Semi Anthracite: Reflectance between 2.65 and 2.83%.
- Anthracite: Reflectance from 6.55 to 7.00%.

*Vitrinite Reflectance Range for Gas Generation:*
- Peat: Primary biogenic methane generation.
- Brown Coal: Early thermogenic methane generation.
- Sub bituminous: Maximum wet gas generation.
- Hi Volatile bituminous: Onset of main stage thermogenic methane.
- Medium volatile bituminous: Onset of secondary cracking of condensate.
- Black Coal: Maximum thermogenic gas generation.
- Low volatile: Deadline for significant wet gas generation.
- Semi Anthracite: Deadline for significant methane generation.
- Anthracite: Deadline for significant wet gas generation.
GAS RETENTION (OR NOT)

(a) UNUSUALLY HIGH GAS CONTENTS

A Secondary biogenic gas generation and hydrodynamic trapping.
B Conventional and hydrodynamic trapping of migrating coal gases

(b) UNUSUALLY LOW GAS CONTENTS

A Low gas contents due to meteoric recharge and flushing
B Low gas contents due to convergent flow without trapping
GAS STORAGE

- Physically adsorbed to coal particles (macerals) and held by molecular attraction
- within pore spaces, cleats and fractures of the coal (~10%)
- dissolved in water contained within the coal (~5%)

It doesn’t come out until pressure is released, unless flushed by water.
SECONDARY BIOGENIC GAS GENERATION

http://www.lucatechnologies.com/content/index.cfm?fuseaction=showContent&contentID=62&navID=58

Draper and Boreham, 2006
IGNEOUS INTRUSIONS AND CO2

- CO₂ often, but not always, increases with decreasing gas content
- Can be residual
- Can be secondary due to emplacement from igneous intrusions

Draper and Boreham, 2006
Exercise 3 – borehole interpretation (10 min)

1. Interpret the section. What type of fault is it?
2. Which way does it dip?
3. Does the dip change?
4. How do you plan your drilling?

Courtesy R. Sliwa, Integrated Geoscience
LATERAL VARIABILITY IN COAL SEAMS

Depositional Environments

Hintze, 1988 in Barker et al, undated
Deltas, and coastal plains, come in many shapes and sizes.

So, the areal distribution of peat/coal deposits reflect the space between the water courses.
Peats/coals occur in variety of tectonic settings from cratonic sag basins to rift and foreland basins.
Foreland basins provide:

- laterally extensive platforms
- mechanism for accumulation of thick sedimentary pile and
- heat flow

VARIABILITY IN COAL SEAMS - TECTONIC SETTING
Active growth faulting
Rapid lateral variation
Positions of tectonic plates change through time and set up regional stress patterns.
CLEAT DEVELOPMENT

• Cleats result from coalification (moisture loss) and palaeo-tectonic stresses
  - Increasing bulk density due to pore loss and development of fracture system (cleat)
  - Bright vitrain devolatilises more than dull, inertinite rich coal, therefore greater “shrinkage” and development of cleat

• Face cleats are extensional fractures that develop parallel to maximum principal stress
• Cleats generally open during exhumation
• Cleats can be overprinted
• Cleat orientation can swing due to subsequent folding
• Cleats will be open or closed depending on current stress field and degree of mineralisation

Photo courtesy C. Ward
**FAULTING**

**Normal faults**
- Extensional strain
- Moderate dips (may flatten at depth)

**Thrust faults (=reverse faults)**
- Compressional strain
- Shallow to moderate dips (flattens at depth)

**Strike-slip faults**
- Accommodate strain (eg thrust sidewalls)
- Steep dips
- Difficult to identify

Courtesy R. Sliwa, Integrated Geoscience
Normal faults – the geometry

- Moderate dips (may flatten at depth)
- Cuts out stratigraphy
- May have strike-slip component (= oblique slip fault)
- Commonly occur in swarms:

  **graben**

  **horst**

Courtesy R. Sliwa, Integrated Geoscience
Normal fault – Burton mine

Courtesy R. Sliwa, Integrated Geoscience
Normal faults – graben (Goonyella)

Expected: valley

dome

Courtesy R. Sliwa, Integrated Geoscience
Thrust faults – simplified geometry

- Moderate to shallow dips
- duplicates stratigraphy
- May have strike-slip component
- Complex geometry

Ramsay & Huber, 1987

How much throw?

Courtesy R. Sliwa, Integrated Geoscience
Sediment – thrust fault interaction (Goonyella)
Never think of thrust faults, normal faults and sedimentary units in isolation
GAS CONTENT IN AUSTRALIAN COALS