CBM Reservoir

Porosity and permeability

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Outline

Pore

- Gas in coals is thought to occur mainly in the adsorbed state, as a monomolecular layer 0.4 nm thick on the pore surfaces
- The adsorbed layer accounts for 90-98% of total gas content with the remaining small amount of gas (2-10%) in the gaseous state, within the open pore spaces (e.g. macro-pores, fractures) (Gray, 1987)
- Coal porosity is the void space of this naturally fractured organic rock, which has a wide spectrum of pore sizes (Seidle, 2011)
- Separation of coal void space into cleat and matrix porosities for reservoir engineering purposes is artificial but useful
- A typical of naturally fractured reservoirs has cleat or fracture porosity on the order of 1% or less (Reiss, 1980) and coal matrix porosities measured in laboratory studies are typically varying from 2.5 to 18 % (Anderson et al., 1956)

Pore

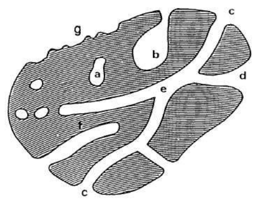
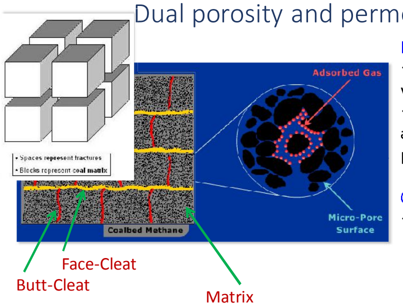


Fig.1 : Schematic cross-section of a porous solid

IUPAC, 1994

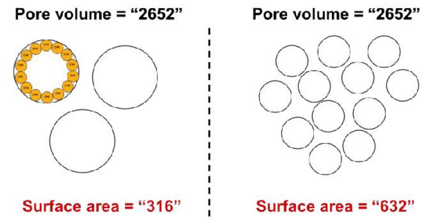
Dual porosity and permeability system

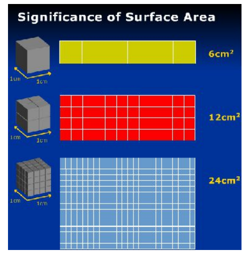


Matrix ("Primary Porosity")
✓High gas storage, low permeability via diffusion
✓Gas not "IN" pores but gas adsorbed "ON" surfaces of micro-pores

Cleat/fracture ("Secondary Porosity")
✓High permeability, low gas storage

Pore volume and surface area





1 cm^3 coal pore = 3 m^2 surface area

Fekete 2006, Moore, 2010,2014

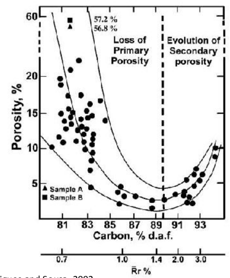
Total pore volumes

- Gan et al (1972)
  - Micro-pore: less than 1.2 nm,
  - Meso-pore: 1.2 to 30 nm
  - Macro-pore: greater than 30 nm
- IUPAC (Rouquerol et al., 1994)
  - Micro-pores: diameters less than 2 nm
  - Meso-pores: diameters between 2 to 50 nm
  - Macro-pores: diameters greater than 50 nm

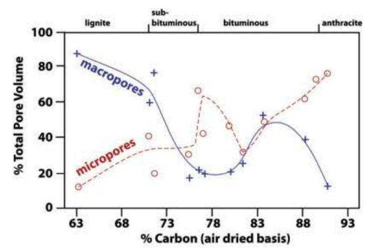
Coal porosity

- low-rank coals (< 75% fixed carbon content) is primarily due to macro-pores;
- medium-rank coals (fixed carbon between 76% and 84%) are comprised mainly of micro and meso-pores;
- high-rank coals (fixed carbon > 85%) porosity is mostly due to micro-pores (Gan et al., 1972; Seidle, 2011).
- Total porosity decreases with rank, primarily due to a decline in macro and meso-pore while micro-pore volume increased with coal rank (Clarkson and Bustin, 1999).

Coal porosity



Rodrigues and Sousa, 2002



Clarkson and Bustin, 1999; Moore, 2012

Coal density and porosity measurements

- Coal density was determined using helium (He) and Mercury (Hg).
- $V_p = \frac{1}{\rho_{Hg}} - \frac{1}{\rho_{He}}$
- $\phi = 100x\rho_{Hg}(\frac{1}{\rho_{Hg}} - \frac{1}{\rho_{He}})$
- The total pore volume accounted by Hg density is substantially less than that derived from He density.
- With respect to the difference on total pore volume accounted from He density and Hg density, respectively, rise the concept that (1) macro- and meso-pore system is accessible to Hg under pressure and (2) micro-pore system that is inaccessible to Hg but accessible to He (Speight, 2005).

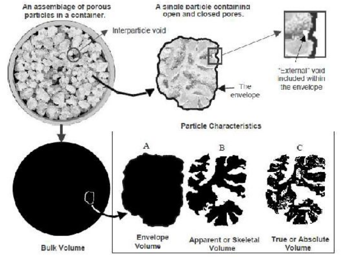


Figure 2. Illustration of various volume types. At the top left is a container of individual particles illustrating the characteristics of bulk volume in which interparticle and "external" voids are included. At the top right is a single porous particle from the bulk. The particle cross section is shown surrounded by an enveloping band. In the illustrations at the bottom, black areas shown are analogous to volume. The three illustrations at the right represent the particle. Illustration A is the volume within the envelope, B is the same volume minus the "external" volume and volume of open pores, and C is the volume within the envelope minus both open and closed pores.

True density

- *True density, apparent density, particle density, bulk density*, and *in-place density*.
- The *true density* of coal is the mass divided by the volume occupied by the actual, pore-free solid in coal
- The precise determination of true density requires complete filling of the pore structure with a fluid that has no interaction with the solid.
- No fluid meets these requirements completely.
- Helium has traditionally been considered as the best choice
- Part of the pore system may be inaccessible to the helium. Thus, when helium is used as the agent for determining coal density, the density (helium density) may differ from the true density and may actually be lower than the true density.

Speight, 2005

Apparent density

- The *apparent density* of coal is determined by immersing a weighed sample of coal in a liquid followed by accurate measurement of the liquid that is displaced (pycnometer method).
- For this procedure, the liquid should (1) wet the surface of the coal, (2) not absorb strongly to the coal surface, (3) not cause swelling, and (4) penetrate the pores of the coal.
- It is difficult (if not impossible) to satisfy all of these conditions, as evidenced by the differing experimental data obtained with solvents such as water, methanol,carbon tetrachloride, benzene, and other fluids.
- Thus, there is always the need to specify the liquid employed for the determination of density by means of this (pycnometer) method

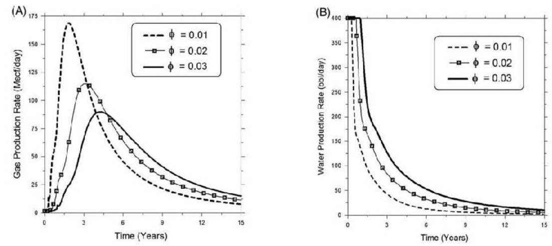
Speight, 2005

Bulk density

- The *bulk density* is the mass of an assembly of coal particles in a container divided by the volume of the container
- It depends on true density, particle size and size distribution, particle shape, surface moisture, and degree of compaction.

Speight, 2005

Effect of coal porosity (cleat) on well production



Zarrouk and Moore, 2009

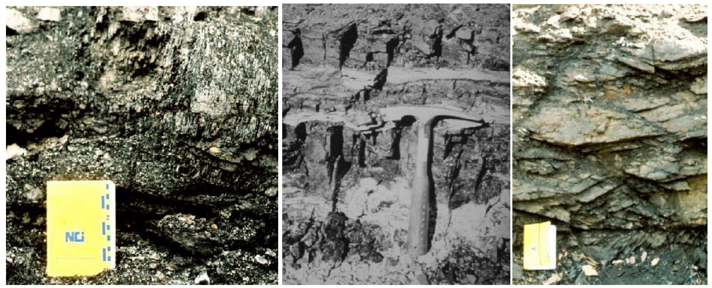
Outline

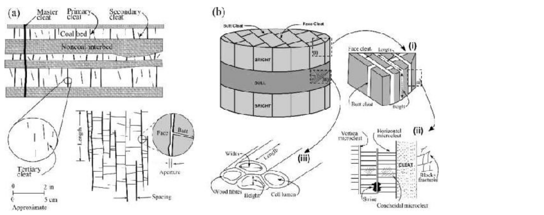
- Overview
- Adsorption (Gas content)
- Porosity
- Permeability (Cleat system)
- Gas Flow
- Reserve Analysis
- Dynamic reservoir
- Enhanced recovery

Cleat

- Systematic fracture in coal is called as cleat (Dron, 1925 vide Laubach et al., 1998)
- Cleats are fractures that usually occur in two sets that are, in most instances, mutually perpendicular and also perpendicular to bedding (Laubach et al., 1998)
- Closely spaced tension fracture normally perpendicular to bedding often in orthogonal sets
- Seams may also contain shear fractures related to regional compression these are often not perpendicular to bedding and contain obvious evidence of shearing ie fine coal and striations

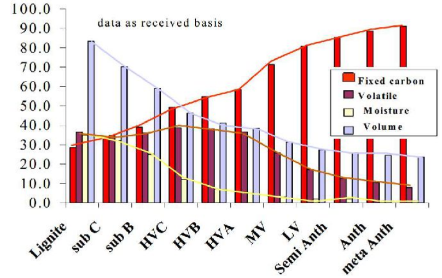
Cleats and shear fractures



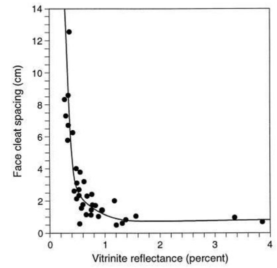


Cleat hierarchies in cross-section view and cleat-trace pattern in plan view (Laubach et al., 1998); (b) Illustration of microstructure in coal (Gamson et al., 1993); (i) cleat system in 3D view; (ii) relation between micro-cleats, striae and larger cleats; (iii) cell lumen.

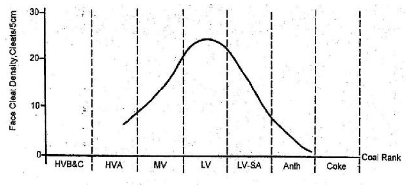
The main changes coal as rank increase



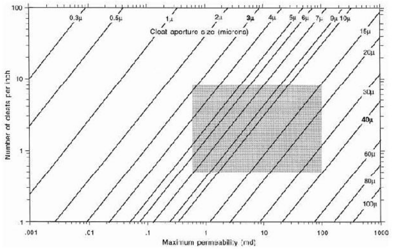
Cleat spacing decrease as rank increase



Law,1996

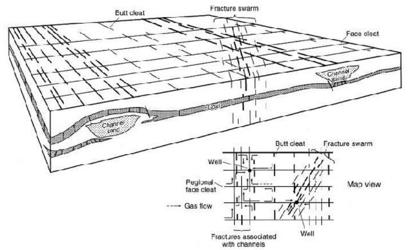


Relation among face-cleat spacing, permeability, and aperture assuming parallel-plate model



Laubach et al., 1998

Cleat patterns and potential sources of anomalous cleat attributes

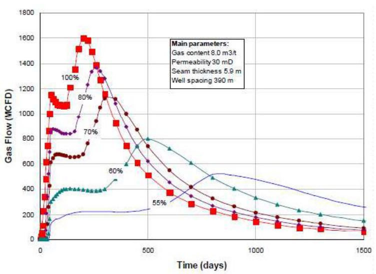


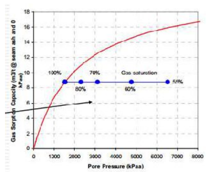
Laubach et al., 1998

Absolute permeability

- Is a function of the coal itself
- In coal, this is primarily associated with the cleat system
- Darcy's flow
- $k = \frac{2\, Q_a P_a \mu L}{A(P_1^2 - P_2^2)}$
- where, k= permeability, (mD); Q_a= volumetric rate of flow at reference pressure P_a, (cm^3/sec); P_a= reference pressure, (Pa); μ= fluid viscosity (cp); L= length of core sample, (cm); A= cross-section area of core sample, (cm^2); P_1= upstream pressure, (Pa); P_2= downstream pressure, (Pa).

Gas production from varying saturation





William, 2007

Effect of gas saturation and permeability

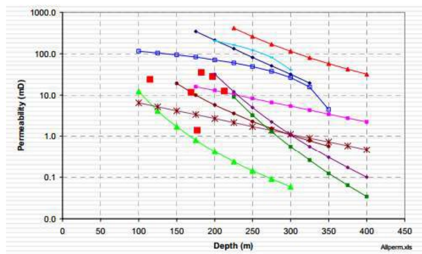
	Case A	Case B	Case C	Case D	Case E
Coal Thickness (m)	3.1	5.0	4.4	4.2	6.4
Gas Content @ 20°C (m3/t)	6	8	10	7	10
Gas Saturation%	**57%**	**71%**	**91%**	**89%**	**92%**
Permeability (mD)	10	2	3	85	5
Peak Production (MCFD)	**508**	**220**	**932**	**2965**	**1863**

Low production if lower permeability is combined with poor saturation

High production if good permeability is combined with good saturation

William, 2007

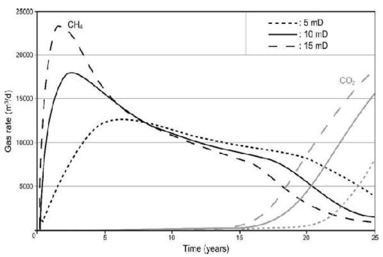
Permeability variation in Sydney/Bowen basins



There a huge variations between areas. Even in a single area where there are a lot of measurements, permeability remains the single most uncertain parameter. Inherent variability is rarely smaller than an order of magnitude

William, 2007

Effect of permeability on production curve



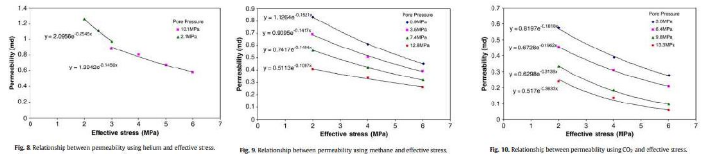
Anggara, 2014

Permeability

- When permeability is measured it is dependent upon the stress on the coal at that time
- The main reason permeability reduces with depth is the response to increasing stress
- The actual stress on the coal is called

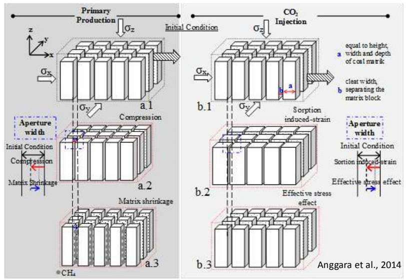
Effective Stress = Rock Stress (Formation pressure) – Reservoir Pressure

Permeability vs. effective stress



Pan al., 2010

Matchstick geometry representation of a coal seam



a. CH_4 primary production scheme: a.1 initial condition; a.2 increasing effective stress caused by drawdown pressure and it's resulting decreasing aperture width thus permeability is decreasing; a.3 CH_4 is desorbed during drawdown pressure resulting matrix shrinkage and finally permeability is rebound at certain pressure. b. ECBMR by CO_2 injection scheme: b.1 initial condition; b.2 permeability reduction caused by CO_2 sorption induced-strain; b.3 when CO_2 is injected into coal reservoir, push back phenomenon is occurred and resulting rebound permeability (model was drawn based on Seidle et al. (1992); Shi and Durucan (2005).

Permeability change due to decreasing pressure

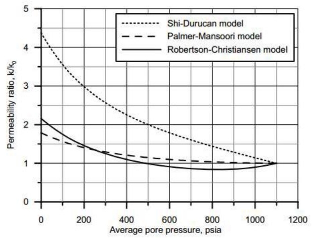
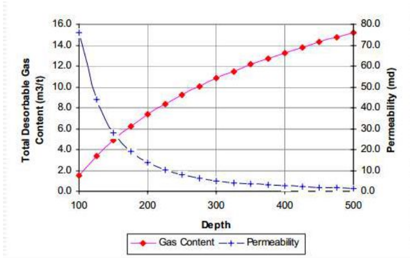


Fig. 11 – Model comparison of permeability changes for methane flowing through an "average" coal core as pore pressure is lowered.

Robertson and Christiansen, 2006

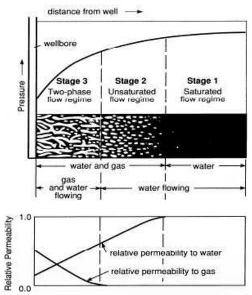
Cross over of Permeability and Gas content with depth

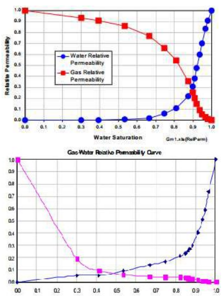


Offsetting parameters…
Gas Content Normally Increases With Depth, Permeability Normally Decreases…

William, 2007

Relative permeability





End

Pan al., 2010