

UNICORNS IN THE GARDEN OF GOOD AND EVIL: Part 3 – Coal Bed Methane (CBM)

By E. R. (Ross) Crain, P.Eng.

Unicorns are beautiful, mythical beasts, much sought after by us mere mortals. The same is true for petrophysical models for unconventional reservoirs. This is the third in a series of review articles outlining the simple beauty of some practical methods for log analysis of the unusual.

COAL BED METHANE BASICS

Coal bed methane (CBM) is an economic source of natural gas that is generated and stored in coal beds. It is a widely occurring exploitable resource that can be easily recovered and used near the well or where gas pipeline infrastructure currently exists.

Coal acts as both source rock and reservoir rock for methane. Methane is generated by microbial (biogenic) or thermal (thermogenic) processes shortly after burial, and throughout the diagenetic cycle resulting from further burial. Much of this gas is physically sorbed on coal surfaces. Some higher ends may also be produced by coal – such as ethane and propane – but are usually only a few percent of the total gas.

Adsorption is the process of gas adhering to a microporous surface. Desorption is the process of releasing gas from such a surface.

These surfaces are called cleats and range in size from obvious macrofractures to virtually invisible nanofractures. These cleat patterns are crucial for gas production

because they allow for the release of sorbed gas within coal beds and migration to the well bore (Figures 1, 2).

One gram of coal can contain as much surface area as several football fields and therefore is capable of sorbing large quantities of methane. One short ton (2,000 pounds mass) of coal can store about 1,300 m³ of methane. Depending on reservoir pressure, not all the storage capacity is filled with gas.

Coal-bed gas content must reach near-saturation, either by biogenic or thermogenic gas-generation processes, to be economically viable. Cleats must be present to allow for connectivity between sorption sites. If the coal-bed horizons are buried deeply (>2,000 meters), cleats are closed because of overburden pressure acting on the structurally weak coal bed. Cleats can also be filled with other minerals, reducing their effective permeability.

Methane sorbed within coal beds is regulated by the hydrodynamic pressure gradient. Methane is maintained within the coal bed as long as the water table remains above the gas-saturated coal. If the water table is lowered by basin or climatic changes, then the amount of methane stored within the coal is reduced by release to the atmosphere.

Many coal beds need to be de-watered

before they can produce gas. Some coal beds have been de-watered naturally or by crossflows due to previous drilling for oil or gas in nearby wells. Poor quality cement jobs are a major cause of such crossflows.

CBM wells, unlike conventional oil and gas producers, usually show an increase in the amount of production (after initial de-watering). As a coal is de-watered, the cleat system progressively opens farther away from the well. As this process continues, gas flow increases from the expanding volume of de-watered coal. Water production decreases with time, which makes gas production from the well more economical.

SORPTION ISOTHERMS FOR COAL BED METHANE

Sorption isotherms indicate the maximum volume of methane that a coal can store under equilibrium conditions at a given pressure and temperature. The direct method of determining sorption isotherms involves drilling and cutting core that is immediately placed in canisters, followed by measurements of the volume of gas evolved from the coal over time.

The indirect method takes advantage of core or cuttings that have been stored and does not require fresh core, thus making this method more economical. Sorption isotherms are experimentally measured using

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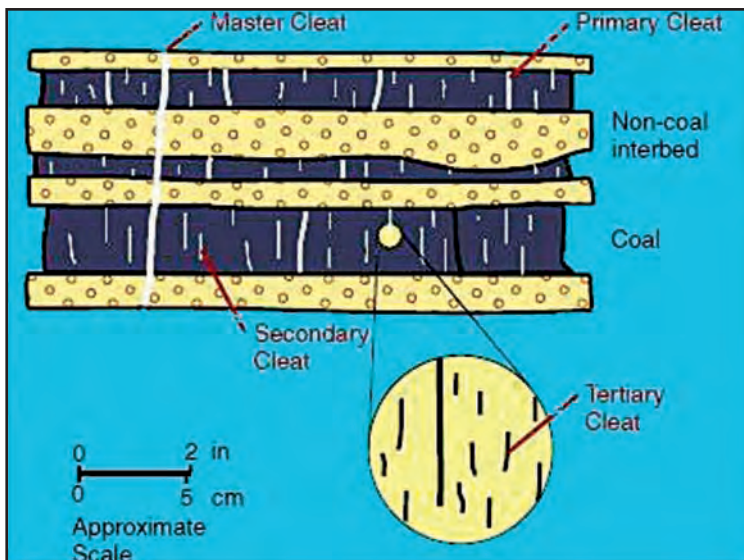


Figure 1. Illustration of cleats, large to tiny.

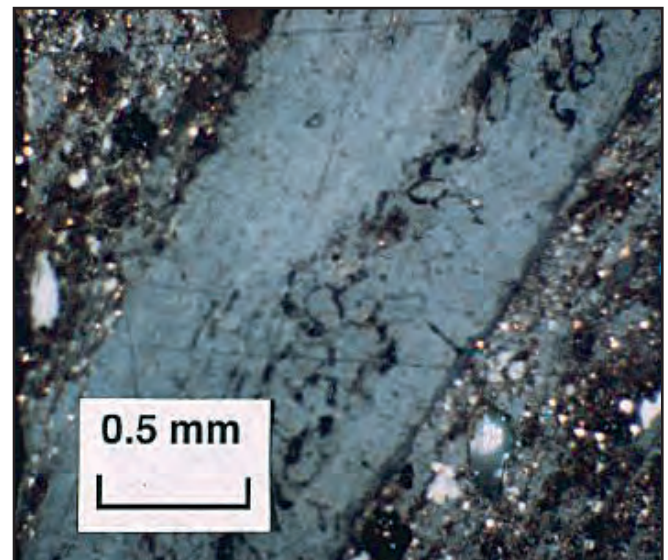


Figure 2. Microphoto shows cleats are tiny (black) but may be numerous.

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a powdered coal sample whose saturated methane content at a single temperature is measured at about six pressure points.

Moisture content in a coal decreases the sorption capacity. Because coal loses moisture at a variable rate subsequent to removal from the bore hole, a standard moisture content is used when measuring sorption isotherms.

The Langmuir equation is used to predict the maximum gas storage capacity of a reservoir and the equilibrium pressure. Most CBM reservoirs are somewhat under-saturated, so the stored gas is less than the capacity of the reservoir (Figures 3, 4). A few are reported to be hyper-saturated. The equations are:

- 1: $K1 = 0.21258 * T_f^{0.5}$
- 2: $K2 = 2.82873 - 0.00268 * T_f$
- 3: $K3 = 0.00259 * T_f + 0.50899$
- 4: $K4 = 0.00402 * T_f + 2.20342$
- 5: $G_{max} = 10^{(K1 * \log(W_{fcarb} / W_{wtr}) + K2)}$
- 6: $P_L = 10^{(K3 * \log(W_{fcarb} / W_{wtr}) + K4)}$

Where:

- G_{max} = gas volume at infinite pressure (ft³/ton)
- P_L = Langmuir pressure, at which the sample's gas content is 1/2 G_{max} (atmospheres)
- T_f = temperature (°C)
- W_{fcarb} = mass fraction of fixed carbon (fractional)
- W_{wtr} = mass fraction of moisture (fractional)

W_{fcarb} and W_{wtr} are usually measured in the lab during a Proximate Analysis. Log analysis methods for obtaining these values are described at <http://www.spec2000.net/17-speccoal.htm>.

Numerical Example:

Given:

W_{ash}	W_{fcarb}	W_{wtr}	P_r atm	T_f °C	DEPTH m
0.20	0.48	0.32	100	30	1,000

Then:

- $K1 = 1.2$
- $K2 = 2.7$
- $K3 = 0.6$
- $K4 = 2.3$
- $G_{max} = 898.2$ scf / ton
- $P_L = 267.5$ atm
(100 atm = 1,466 psi = 10,132 kPa)

GAS CONTENT FROM CORE OR SAMPLE ANALYSIS

Finding the actual gas content, G_c , in the lab can be done directly as part of the Proximate Analysis, or indirectly. Two gas content values are recorded. One is the actual gas content of the bulk coal; the second is related to the dry, ash-free state of the coal, as shown in Table 1 (see also figure 6, page 20).

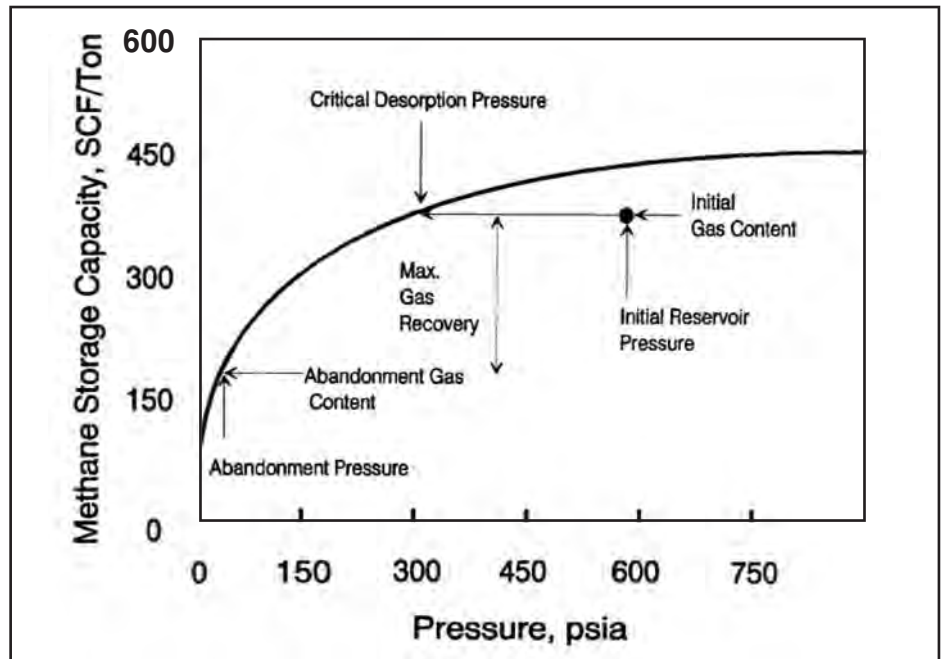


Figure 3. Comparison of conventional gas production and CBM production characteristic.

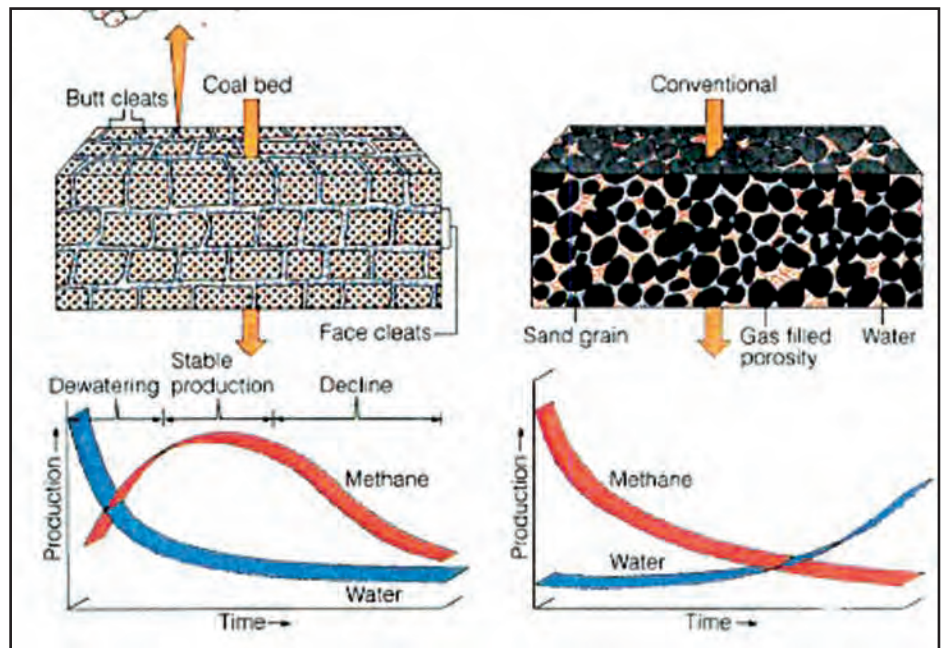


Figure 4. Typical sorption isotherm showing initial reservoir gas content vs. pressure, critical desorption pressure, and abandonment conditions Gas will not flow until reservoir pressure is less than critical pressure.

The desorption data obtained during the first several hours can be used to calculate the lost gas component. Cumulative desorbed gas is plotted against the square root of desorption time. A regression line is drawn through the first 4 to 6 hours of data points and extrapolated back to time zero. The intercept of the regression line at time zero is the lost gas, added to the actual desorbed gas volume to obtain the total actual gas. This value is further adjusted using the ash and water content from the proximate analysis to obtain the dry, ash-free value (Figure 5, page 20). Gas content (G_c) results are usually given as scf/ton or g/cc. (Multiply G_c in g/cc by 32.18 to get G_c in scf/ton).

CBM GAS IN PLACE

Gas-in-place is calculated from the isotherm curve, or from the actual gas content found in the lab, by using coal-bed thickness and coal density as measured by well logs:

$$7: GIP = KG6 * G_c * DENS * THICK * AREA$$

Where:

- GIP = gas in place (Bcf)
- G_c = sorbed gas from isotherm or coal analysis report (scf/ton)
- DENS = layer density from log or lab measurement (g/cc)
- THICK = coal seam thickness (feet)
- AREA (acres) (Continued on page 20...)

RAW DATA (AS RECEIVED FOR CORE AIR-DRIED FOR CUTTINGS)									CORRECTED DATA GAS CONTENT	
SEAM	SAMPLE TYPE	CANISTER #	DEPTH (M)		LOST GAS (SCF/TON)	MEASURED GAS (SCF/TON)	RAPID DESORB GAS (SCF/TON)	GAS CONTENT (SCF/TON)	DRY ASH FREE (SCF/TON)	CAVINGS CORRECTED (SCF/TON)
			TOP	BOTTOM						
1	COARSE AND FINE CUTTINGS	390	948.20	949.00	63.1	67.9	5.5	136.5	320.0	251.4
2	COARSE AND FINE CUTTINGS	392	962.20	963.40	75.4	71.1	5.5	151.9	353.6	265.3
3	FINE CUTTINGS	395	964.20	965.00	96.0	85.5	11.6	193.1	358.6	285.3
4U	CORE	399	980.71	981.01	19.1	116.2	38.4	173.7	351.4	N/A
4U	CORE	GG	981.01	981.09	4.0	147.5	12.9	202.4	350.3	N/A
4U	CORE	410	981.14	981.44	9.1	28.5	4.7	42.3	267.1	N/A
4U	CORE	HH	981.65	981.71	39.6	111.1	8.0	158.6	281.7	N/A
4L	CORE	442	982.01	982.31	72.4	206.3	43.1	321.8	401.2	N/A
4L	CORE	443	982.31	982.61	56.3	203.6	64.9	324.8	427.6	N/A
4L	CORE	445	982.61	982.91	51.6	193.8	61.1	306.4	395.4	N/A
4L	CORE	446	982.91	983.21	41.8	192.0	99.1	333.0	400.5	N/A
4L	CORE	447	983.21	983.51	31.9	148.0	65.5	245.4	351.8	N/A
4L	CORE	449	983.51	983.81	60.9	201.2	67.0	329.1	386.8	N/A
4L	CORE	458	984.01	984.31	47.3	209.1	93.5	349.9	408.2	N/A
4L	CORE	482	984.31	984.61	59.6	222.9	79.5	362.0	423.4	N/A
4L	CORE	483	984.61	984.91	66.8	208.3	34.8	309.9	365.8	N/A
4L	CORE	484	984.91	985.21	40.5	182.8	118.9	342.3	408.2	N/A
4L	CORE	501	985.21	985.51	29.6	140.2	109.5	279.3	379.1	N/A
5	CORE	T4	987.49	988.01	62.3	211.4	73.0	346.7	410.1	N/A
5	CORE	506	988.01	988.31	47.1	195.2	61.5	303.8	399.7	N/A
5	CORE	510/76	988.31	988.61	38.3	196.8	111.8	347.0	396.2	N/A
5	CORE	518	988.61	988.91	65.8	201.0	60.1	326.9	382.5	N/A
6	COARSE CUTTINGS	521	996.00	997.00	12.4	66.0	7.5	197.8	414.5	322.1
6	FINE CUTTINGS	523	996.00	997.00	167.5	101.2	13.5	282.3	424.3	348.4
6	COARSE CUTTINGS	531	997.00	997.50	60.9	51.1	5.7	117.7	350.0	263.5

*CLEAT SAMPLE TAKEN 983.81-984.01

Table 1. Gas content evaluation of coal beds. Notice that the dry, ash-free values are considerably higher than the actual measured values. As well, an estimate of the "lost gas" was made for each sample to account for gas evolved from the sample before the lab measurements were made.

SEAM #	LOG DEPTH		SEAM THICKNESS (M)	AVERAGE GAS CONTENT (SCF/TON)	AVERAGE GAS CONTENT (CC/G)	CI-C4 (%)	AVERAGE ASH/SEAM (%)	DENSITY (G/CC)
	TOP	BOTTOM						
1	947.2	947.6	0.4	251	7.8	99.72	15.86	1.82
2	961.8	962.2	0.4	265	8.0	99.72	21.85	1.69
3	963.8	964.2	0.4	285	8.9	99.72	14.21	1.62
4U	980.0	981.0	1.0	144	4.5	97.20	46.40	1.90
4L	981.0	985.0	4.0	316	9.9	97.20	6.92	1.29
5	987.0	988.6	1.6	331	10.3	97.94	6.90	1.29
6	997.5	998.5	1.0	311	9.7	99.15	16.32	1.68
TOTAL			8.8					

Table 2. Summary table of gas desorption analysis.

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$$KG_6 = 1.3597 \times 10^{-6}$$

If AREA = 640 acres, then GIP = Bcf/Section
(= Bcf/sq. mile).

Multiply meters by 3.281 to obtain
thickness in feet.

Multiply G_c in g/cc by 32.18 to get
 G_c in scf/ton.

Typical coal densities are in the range of 1.20 to 2.00 g/cc. Older density logs have a hard time reading less than 1.5 g/cc (FDC logs) but modern LDT logs can do it well. Some paper logs may not show the backup scale for density less than 2.0 g/cc, but this information may be included in the digital file. If density cannot be obtained from logs, use lab values or estimates.

CAUTION: If G_c is an actual measurement, the above equation gives reasonable results. If G_c is for the dry, ash-free case or a theoretical value, the GIP from equation 1 must be adjusted to represent the actual coal by multiplying GIP by $(1 - V_{ash} - V_{wtr})$.

Note that free gas in the cleats is assumed to be negligible in most coals. In computer software, coal is usually triggered and PHI_e set to zero, and conventional log analysis models used where there is no coal. Triggers are chosen based on density, neutron, sonic, or resistivity, or some combination of these. Recoverable gas can be estimated by using the sorption curve at abandonment pressure (G_a) and replacing G_c in Equation 7 with $(G_c - G_a)$.

CALCULATING GAS CONTENT FROM LOGS

These approaches are used where measured G_c values are not available and involve more detailed analysis of the coal itself. This breakdown can be derived from analysis of core data, called proximate analysis, or by analysis of log data. Some of the following methods assume a complete coal analysis is available from log or core data (See table 2 [page 19] and table 3). Note that the various authors use a variety of units of measurement, so read their original papers carefully.

Mullen equation, based on some average data in New Mexico (San Juan Basin):

$$8: G_c = 1053 - 542 * DENS_{coal}$$

Mavor, Close, McBaner equation, based on some average data in Utah:

$$9: G_c = 601.4 - 751.8 * W_{ash} / (1.0 - W_{wtr})$$

Kim Equation:

$$10: K_o = 5.6 + 0.8 * W_{carb} / W_{wtr}$$

$$11: N_o = 0.39 - 0.1 * W_{carb} / W_{wtr}$$

$$12: G_c = 75 * (1 - W_{wtr} - W_{ash}) * (K_o * P_f^{No} - 0.14 * T_f)$$

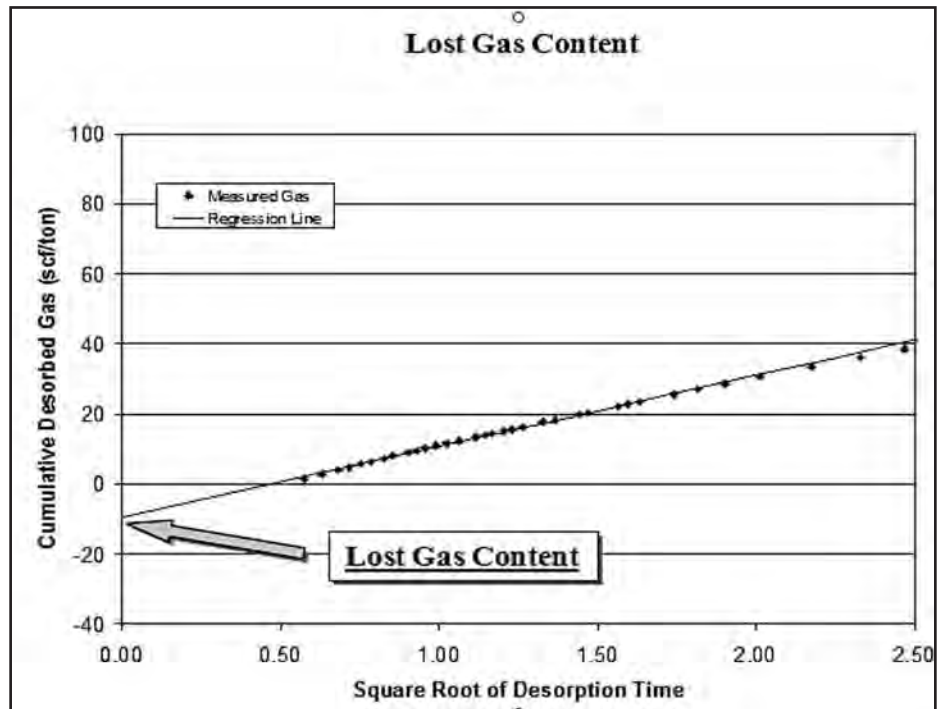


Figure 5. Example of graph for finding "lost gas".

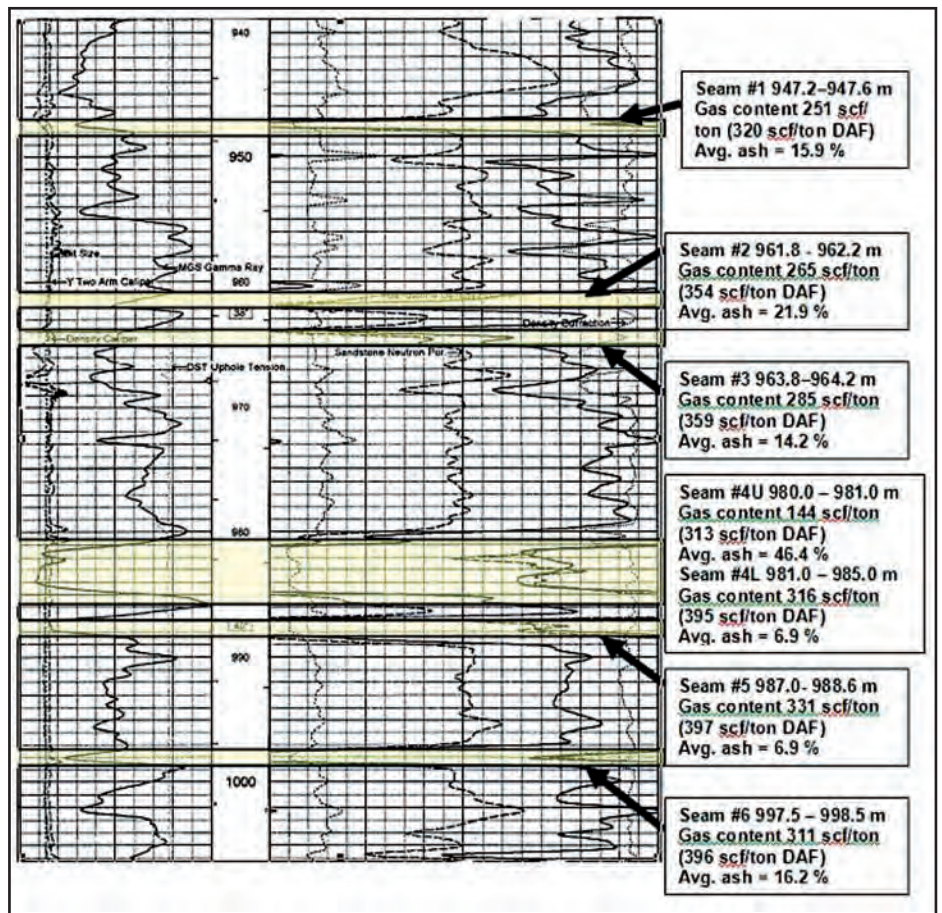


Figure 6. Well log showing location of coal layers analyzed by proximate and gas desorption analysis. Log curves are GR, CAL, PE, neutron, density, density correction.

Where:

G_c = sorbed gas estimate (scf/ton)

P_f = formation pressure (atmospheres)

T_f = formation temperature ($^{\circ}C$)

Modified Kim Equation:

$$13: G_c = 75 * (1 - W_{wtr} - W_{ash}) * (K_o * (KG_7 * DEPTH/100)^{No} - 0.14 * KG_8 * DEPTH/100 + KG_9)$$

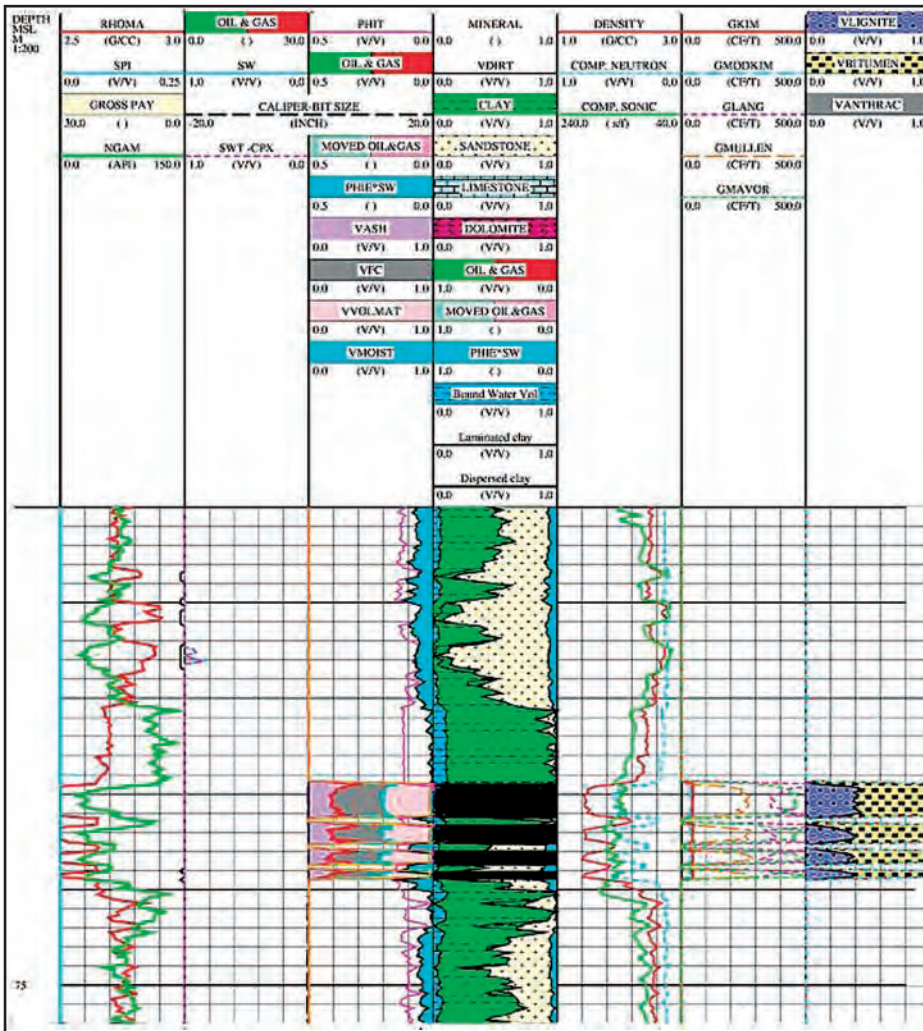


Figure 7. Example of coal-bed methane log analysis. Kim and modified Kim gas content curves are shown in 2nd track from the right. If temperature and pressure gradients matched measured values, the results should be identical to each other. The Langmuir gas curve in the same track shows the maximum storage capacity of the coal.

SEAM #	LOG DEPTH		SEAM THICKNESS (M)	RESOURCES (CC/CM2)	RESOURCES (BCF/SECTION)	RESOURCES ADJUSTED FOR C1-C4 (BCF/SECTION)
	TOP	BOTTOM				
1	947.2	947.6	0.4	571	0.52	0.52
2	961.8	962.2	0.4	560	0.51	0.51
3	963.8	964.2	0.4	577	0.53	0.53
4U	980.0	981.0	1.0	855	0.78	0.76
4L	981.0	985.0	4.0	5,092	4.66	4.53
5	987.0	988.6	1.6	2,133	1.95	1.91
6	997.5	998.5	1.0	1,632	1.49	1.48
TOTAL			8.8		10.45	10.24

Table 3. Gas in place calculation based on proximate analysis and gas desorption measurements.

Where:

- KG7 = pressure gradient (atm per 100 meters)
- KG8 = temperature gradient (°C per 100 meters)
- KG9 = surface temperature (°C)
- DEPTH = average reservoir depth (meters)
- Defaults: KG7 = 0.10, KG8 = 1.80, KG9 = 12

This equation uses local gradients relating

P_f and T_f to depth. Measured values are usually better but gradient values are useful when no measured data exists. Kim and modified Kim will give identical results if gradients match measured values.

Mullen's correlation between SP development and deliverability:

$$14: Q_g = KG10 * SP_{max} * THICK$$

Where:

- SP_{max} = absolute value of maximum SP deflection in coal (mv)
- THICK = coal bed thickness (ft)
- KG10 = 3,100
- Q_g = gas rate (mmcf/d)

The parameter KG10 should be adjusted for each project area.

Numerical Example:

Given:

W_{ash}	W_{carb}	W_{wtr}	P_f atm	T_f °C	DEPTH m
0.20	0.48	0.32	100	30	1,000

Note 100 atm = 1,466 psi = 10,132 kPa

Mullen equation (San Juan Basin)

$$G_c = 402.6 \text{ scf/ton}$$

Mavor, Close, McBaner(Utah)

$$G_c = 380.3 \text{ scf/ton}$$

Kim Equation (See Figure 7)

$$K_o = 6.8$$

$$N_o = 0.2$$

$$G_c = 588.1 \text{ scf/ton}$$

Modified Kim using default gradients

$$G_c = 586.1 \text{ scf/ton}$$



ABOUT THE AUTHOR

E. R. (Ross) Crain, P.Eng. is a Consulting Petrophysicist and a Professional Engineer with over 45 years of experience in reservoir description, petrophysical analysis, and management. He has been a specialist in the integration of well log analysis and petrophysics with geophysical, geological, engineering, and simulation phases of oil and gas exploration and exploitation, with widespread Canadian and Overseas experience.

His textbook, "Crain's Petrophysical Handbook on CD-ROM" is widely used as a reference to practical log analysis. Mr. Crain is an Honorary Member and Past President of the Canadian Well Logging Society (CWLS), a Member of Society of Petrophysicists and Well Log Analysts (SPWLA), and a Registered Professional Engineer with Alberta Professional Engineers, Geologists and Geophysicists (APEGGA).