The Role of Well Logging in Coal-Bed Methane Extraction

Roger Samworth

Research Director, East Leake
Weatherford UK Ltd
History of Logging For Coal

- BPB started logging for coal in the late 1960s
- World-wide operations from 1970s onward.
- BPB became “Reeves” in 1995
- Now owned by Weatherford
- Still have significant dedicated coal operations, especially in Australia
- Significant number (hundreds) of CBM wells also logged annually, again especially in Australia
History of Logging For Coal

- High Resolution data (1cm)
- Standard tool was dual density / caliper / gamma ray
- Often dual neutron
- Occasionally resistivity
- Large amount of legacy data
Coal-Bed Methane from Logs

• As with all logging for coal, the primary questions are:
  – Where is the coal?
  – How thick is it?
  – What partings has it got?
  – What is its quality?

• The primary log for answering these questions remains the density log.
  – Density logs generally have much better statistical precision and vertical resolution than any other radioactivity based log.
Measurement Precision

• All radioactivity-based logs are subject to a measurement precision governed by “counting statistics”

• Radioactive decay is a random process in time governed by “Poissonian” statistics.

• This means that the standard deviation of a measurement is proportional to the square root of the number of detected events. (count rate)

• For example, to double the precision of a measurement the count rate has to be quadrupled.

• Logs with a short source - detector spacing have higher count rates and much better precision than logs from a long - spaced one.

  – There are, of course, considerations other than precision!

• Spectral – type tools usually have poor statistical precision
Basic Density Tool

- Does not measure density!
  - Measures count rates at a detector spaced from a gamma-ray source.
  - Get density by characterization and calibration.

- Count rate at detector affected by:
  - Source activity
  - Source-detector spacing
  - Formation density
  - Borehole fluid density
  - Borehole diameter
CALLISTO – a world-standard calibration facility at East Leake
"Density Logs don’t Measure Density - -"

• Vital to understand the various log densities, especially in coal, and in particular with respect to “Z/A corrections”.

• Well logs measure *Electron density* – NOT bulk density and various relationships such as ash – density should be preferably established in this regime.
“Density Logs don’t Measure Density - -”

• The *electron* density measured by nuclear well logs is only directly related to bulk density if the number of protons and neutrons in the nuclei of the atoms of the formation are equal.

  – Gamma rays interact with atomic *electrons*, but the nucleus is where all the mass is.
  
  – Z is the atomic number, which is the number of protons in the atomic nucleus, and is equal to the number of atomic electrons.
  
  – A is the atomic mass number, that is the total number of protons plus neutrons in the nucleus.

• So electron density = bulk density only if $Z/A = 0.5$. (ie the number of protons and neutrons is equal.)

• Although this is generally true for most rock-forming elements there are a few significant exceptions, notably hydrogen whose nucleus comprises a single proton.

  – Therefore in water (H$_2$O) there are 10 protons and 8 neutrons giving $Z/A = 8/18 = 0.555$, and an electron density of 1.11.
Electron Density to Bulk Density

• With nuclear density logs, it is usual to correct logs for the anomalous electron density of water by assuming that rocks are approximated to fresh-water filled porous limestone.

• A correction of -0.11 is therefore applied when the electron density is 1.11, progressively reducing to zero at an electron density of 2.71.

• There are 2 areas where this process is inappropriate:
  – At electron densities greater than 2.71, and
  – In coal, where the above correction is generally too great
Electron Density to Bulk Density

- Compact, therefore (and all ex-Reeves density logs) limits the correction to -0.065 at low densities, which from long experience gives good bulk density values in bituminous coal, and clamps the correction at zero above 2.71 where there is no justification for its application.

- This has no effect on the correction between 1.752 and 2.71 gm/cc.

- Although better, even this might be inappropriate for high-ash coal.

Possible coal correction?
Electron Density to Bulk Density

<table>
<thead>
<tr>
<th>Substance</th>
<th>Electron Density</th>
<th>Bulk Density</th>
<th>Compact</th>
<th>Basic Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 pu limestone</td>
<td>2.71</td>
<td>2.71</td>
<td>2.71</td>
<td>2.71</td>
</tr>
<tr>
<td>20 pu limestone</td>
<td>2.39</td>
<td>2.37</td>
<td>2.37</td>
<td>2.37</td>
</tr>
<tr>
<td>Coal</td>
<td>1.38</td>
<td>1.31</td>
<td>1.31</td>
<td>1.29</td>
</tr>
<tr>
<td>Anhydrite</td>
<td>2.97</td>
<td>2.97</td>
<td>2.97</td>
<td>2.99</td>
</tr>
</tbody>
</table>
Density Log “Compensation”

- The mudcake and/or invasion affects logs to a greater or lesser degree.
- Additionally, boreholes are seldom smooth and regular.
- To counteract these effects, logs of a similar type but having a different “measurement penetration” are combined together to compensate for the perturbations.
Density Log “Compensation”

• Compensated density logs have poor vertical resolution. (typically 15” – 45 cm)

• Short-spaced logs have good resolution (6” – 15cm) and precision, but:
  
  – They have less good accuracy.
  
  – They are susceptible to caves, particularly relevant in coals.
Coal Seam Boundary Picking

- Short-spaced Density

Caliper 6” - 16”

Density 1 – 3 gm/cc
Coal Seam Boundary Picking

- S S Density + Comp. Density

Caliper 6” - 16”

Density 1 – 3 gm/cc
Principles of VECTAR Processing

• To get the best results from density logs, we need to combine the good vertical resolution and precision of the short-spaced log with the good quantitative measurement of the compensated log.

• This is done by a mechanism known as VECTAR processing.

• VECTAR processing can be considered in two ways:
  • Imposition of the short-spacing log resolution upon the compensated, or long-spacing log.
  • Continuous dynamic calibration of the short-spacing log by the compensated, or long-spacing log.
Coal Seam Boundary Picking

- S S Density + Comp. Density

Caliper 6” - 16”

Density 1 – 3 gm/cc
Coal Seam Boundary Picking

- S S Density + Comp. Density + VECTAR Density

Caliper 6” - 16”

Density 1 – 3 gm/cc
Coal Seam Boundary Picking

- S S Density + Comp. Density + VECTAR Density + Sidewall FE
Coal Seam Boundary Picking

- S S Density + Comp. Density + VECTAR Density + Sidewall FE + Shading

Caliper 6” - 16”

Density 1 – 3 gm/cc  SFE 2 – 200 ohm-m
Compact Imaging

- Compact Micro-Imager (CMI)
  - 8 arm 176 button water based mud resistivity imager
  - Minimum 4 ½ in. hole size, Maximum 8”1/2
  - 96% coverage in 6 in. hole
Coal Seam Boundary Picking

- S S Density + Comp. Density + VECTAR Density + Sidewall FE + Shading + Image
Coal Seam Boundary Picking

• S S Density + Comp. Density + VECTAR Density + Sidewall FE

Caliper 6” - 16”

Density 1 – 3 gm/cc
Coal Seam Boundary Picking

- S S Density + Comp. Density
Coal Seam Boundary Picking

- S S Density + Comp. Density + VECTAR Density

Caliper 6” - 16”

Density 1 – 3 gm/cc
Coal Seam Boundary Picking

- S S Density + Comp. Density + VECTAR Density + Sidewall FE

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- S S Density + Comp. Density + VECTAR Density + Sidewall FE + Shading
Coal Seam Boundary Picking

- S S Density + Comp. Density + VECTAR Density + Sidewall FE
Coal-Bed Methane from Logs

**ISSUES –**

1) Get good density and neutron logs.
2) Carefully align core and log data
3) Empirically relate to CBM using client data
Core – Log Alignment

Original canister alignment

Modified canister alignment
• We have a well-established method of producing good density logs through casing for reservoir monitoring or secondary exploration in cased oil-wells.
  
  • The method utilises a down-hole calibration method that often only requires one “known” density point in the well.

• The method is also applicable for reprocessing old logs, of which there is a considerable resource from the days of intensive coal exploration.

  • There is no PE log available when logging through casing, or from old “legacy” logs
There are no known methods that are able to see methane *directly* in coal, so empirical or indirect methods have to be used. So:

- Close technical liaison between operator and logging contractor is necessary, at least initially.
- The gas data is the client’s responsibility, from:
  - Core desorption data.
  - Other estimators – Kim’s Equation etc.
- Logs measure *in-situ*. (Other bases (eg dry, ash-free or d.a.f.) need to be treated with care.
- There is no fundamental problem with empirical relationships, as long as *everyone* agrees.
Coal Bed Methane Through Casing

• We can use Density to index the Proximate analysis.

• We can seek to empirically establish some gas and/or gas productivity index from the logs.
Proximate Analysis

Indexing line

Core Density

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Kim Equations

Based on Density, Proximate analysis, and depth

\[
V, \text{cm}^3/\text{g} = \frac{(100 - \% \text{ moisture} - \% \text{ ash}) \frac{V_w}{V_d}}{100} \left[ k_0 \ P^{n_0} - b \ (1.8h/100 + 11) \right].
\]

If \( P \) is estimated from the hydrostatic head, the equation is

\[
V, \text{cm}^3/\text{g} = \frac{(100 - \% \text{ moisture} - \% \text{ ash}) \frac{V_w}{V_d}}{100} \left[ k_0 (0.096h)^{n_0} - b (1.8h/100 + 11) \right],
\]

where \( h \) is the depth, in meters.
Mullen Equation

Based on Density only

Average Gas Content = \(-542 \rho_B + 1053 \text{ ft}^3 \text{ per ton}\)
Mavor, Close, McBane Equation

Based on Density and Proximate analysis

\[ g = 601.4 - 751.8a_d \]

\[ a_d = \frac{a}{(1-w)} = \frac{V_A}{(1-V_M)} \]

\[ g = \text{gas content, SCF per ton} \]
Density / Gas Empirical Relationships
Neutron / Gas Empirical Relationships

\[ y = -0.148x + 59.705 \]

\[ y = 1.4429x - 1.1517 \]
Neutron/Complementary Function Gas Empirical Relationships

\( y = -0.0107x + 79.881 \)

Constant ratio/porosity lines
Another Empirical Relationship!

Plot is from Archie paper!
Relationships From Other Logs?

- Resistivity a prime candidate.
- Very repeatable – no counting statistics.
- “Sidewall” MFE (LL3 guard tool) has high resolution (6” – 15cm) and relatively deep penetration.
- Some work by Colorado School of Mines suggests a relationship between resistivity and gas producibility.
- Permeability? Invasion into cleats?
- Resistivity sensitive to moisture?
- Resistivity may also be sensitive to rank.
Relationships From Other Logs?

- S S Density + Comp. Density + VECTAR Density + Sidewall FE

Caliper 6” - 16”

Density 1 – 3 gm/cc  SFE 2 – 200 ohm-m
Relationships From Other Logs?

- S S Density + Comp. Density + VECTAR Density + Sidewall FE + Shading
• S S Density + Comp. Density + VECTAR Density + Sidewall FE + Shading


density 1 – 3 gm/cc  SFE 2 – 200 ohm-m

Bright Coal 2.2’
Bright Banded Coal 0.5’
Bright Coal 1.3’
Bright Banded Coal w/ some inferior bands 1.8’
Inferior 0.2’

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• Array Induction, Invasion Diameter, Resistivity Profile Image

Relationships From Other Logs?

Bright Coal 2.2'
Bright Banded Coal 0.5'
Bright Coal 1.3'
Bright Banded Coal w/ some inferior bands 1.8'
Inferior 0.2'

Array induction 20", 30", 40", 60", 85", $R_{tapp}$.
• Multilateral horizontal wells along coal seams are now frequently considered for methane extraction.

• Benefits if well logs are of little use if the logging tools cannot get down the well!
Deployment

- Compact tools can be deployed using the cable-less “Well Shuttle” system
  - Tools are protected inside the drill pipe during deployment.
  - Released at TD by a mechanical dart or a pressure-pulse sequence.
  - Drawn back to surface with the drill-pipe, logging into a down-hole memory keyed to a clock.
  - Depth is measured from the surface, also keyed to a clock.
  - Conventional depth-based logs are then reconstructed at surface by synchronising the clocks.
Compact Well Shuttle

- Conveys Compact tools in total safety inside drill pipe
- No wireline, no side-door, no wet connect
- Rotate, circulate, reciprocate drill pipe to bottom with limited tool risk
- Release and deploy tools out of pipe using dart or mud pulses
Conclusions

• Methane cannot be seen directly.

• Density log crucial in coal / CBM work.
  – Density logs have to be interpreted with care and knowledge.

• Image logs bring another dimension.

• Empirical relationships can be valuable.

• High resolution deep-penetrating resistivity logs need pursuing.

• Safe economic deployment in horizontal wells now feasible.

• Knowledge from all sides needs co-ordinating if success is to be achieved.