1. Overview - CBM basics

The fundamental difference between oilfield exploration and mineral exploration is that the former results (hopefully) in a producing well and the latter in a mine. The benefit from drilling a successful oil well is immediate whereas mine development is a long process. Generally, oilfield explorers are looking for oil or gas that can be extracted via a well whereas mineral explorers are looking for orebodies and coal seams that must be extracted from the ground by blast and shovel.

Borehole or well logging techniques describe the same parameters (density, gamma, sonic, neutron etc) but the tooling, operational scale and use of these parameters are quite different.

Where do the two disciplines meet? They meet in coalbed methane (CBM) projects.

During the study phase of a CBM prospect, there is little to differentiate the process from coal exploration. Slim stratigraphic boreholes are drilled to intersect coal measures. Drill core is taken and analysed in a laboratory. The standard coalfield wireline logs are run. During the production phase of a CBM prospect, the process takes on the characteristics of an oilfield play...drilling, casing, grouting, perforating, fraccing and pumping.

Many CBM projects, especially in the USA, employ oilfield logging technology. The measurements are generally better but they are expensive in the context of the CBM payback equation. It makes sense to employ less expensive but high quality mineral logging techniques whenever possible.

Example

The oilfield logger will deploy a dipole sonic sonde to measure compression and shear wave transit times and to indicate the orientation of the local maximum stress tensor (the anisotropy of permeability in coal caused by stress direction is a big factor in CBM operations). P and S times are used to estimate formation elasticity.

The mineral logger will run his simpler monopole sonic tool and will produce a compression wave sonic log, an incomplete shear front (see issue 2, November 2013) and no indication of stress orientation. The gaps in the shear front, seen in slower formations like coal, can be filled by an empirically-based estimation using the compression wave velocity and density logs. Stress orientation can be described by studying breakouts on an acoustic televiewer log. The oilfield data are superior but not necessarily vital. After all, the S-wave (with P-wave
and density data) is used to generate the dynamic moduli of formation elasticity but these in turn require empirical conversion in order to represent the static elastic characteristics of the formation. Yes, it is possible that the measured S-wave log will offer an empirical relationship with a sought-after parameter but that benefit could probably be duplicated using the P-wave log (check the curve shapes below). One could contend that the fracking engineer would, anyway, prefer to rely on core tests for coal seam elasticity.

The sonic log is peripheral in the CBM logging suite. The main open-hole wireline measurements, which account for 95% of the required knowledge during the study phase, are:

- Natural gamma ray
- Formation density
- Acoustic televiewer

The oilfield loggers will substitute a micro-scanner for the televiewer but, otherwise, that's it in a nutshell. Plenty of other tools are run, at great expense, but, in truth, they don't add much value unless there is a fortunate and tight empirical relationship between sonic or resistivity and permeability, for instance. The critical knowledge requirement is:

- Depth and thickness of the coal seams
- Density/quality of the coal
- Gas content the coal or adjacent formation
- Porosity and permeability of the coal
- Maximum horizontal stress orientation
- Face cleat orientation

The key parameters of gas content and permeability are not directly measured by wireline logs. There are usually site specific and coal seam specific empirical relationships between very precise wireline logs and these two important characteristics but no geologist will rely on them without well tests and drill core desorption trials.

The geologist can rely on density and televiewer logs to measure most of the other parameters.
Depth and Thickness of Coal Seams

There are plenty of books and essays that offer advice on CBM logging and coal seam thickness measurement. Whole paragraphs are written about the resolution of the induction log and how to use it to describe a coal seam. In reality, it is hard to imagine any situation where one would rely on an induction log to measure coal seam depth and thickness.

We use bed resolution density and acoustic televiewer images and we get it right within one or two centimetres.

This approach might not work so well in boreholes that are horribly caved but, in the study phase where boreholes are cored, that is an unusual scenario. If it were the case, we would juxtapose a focused resistivity log with density to reduce ambiguity. In some circumstances the natural gamma log might describe seam boundaries effectively enough. In the cretaceous coal beds of Colombia, there is a very discrete boundary between very low gamma in the coal and high gamma in the clay-rich host rocks. While we are on the subject of gamma ray...

In CBM exploration, **depth is critical**. We have to know exactly where the coal is so that we can perforate casing in the right place. The humble gamma ray log is run during both study and production phases and is a vital reference for depth matching the various open hole and cased hole logs. If the driller does not trust the logger’s depth, he should add a short casing length at a known depth near hole bottom that will be picked up by the logger’s casing collar locator when he runs the CBL tool (see section 2).

The log above illustrates the unequivocal nature of density and televiewer logs in terms of coal seam depth and thickness. The gamma log on the far left indicates very good coal at the bottom of the upper seam. The density log also indicates better coal in this zone. One would expect better coal to yield more gas but there are no cleats visible on the image. The large fractures are not cleats as they extend into partings and the roof of the seam...they are probably stress and drilling induced tensile fractures - offering some indication of predominant stress orientation. The caliper log is good throughout.
The Density of the coal

Wireline tools measure electron density which is proportional to actual bulk density. The relationship is not constant due to the organic nature of coal (non-crystalline molecular structure) and the effect of moisture content. Common hydrogen has no neutron so there is just 1 nucleon per electron not the 2 (a proton and a neutron) expected from the major rock forming elements (see issue 3, January 2014).

The best density measurements are compensated for this (Z/A) effect as well as natural gamma counts, mud cake, fluid density and borehole diameter but the density log is never perfectly accurate in coal. It can be accurate within an acceptable tolerance and certainly precise, allowing a general description of coal quality and a basis for empirical analyses of ash percentage, fixed carbon, calorific value and, perhaps, gas in place.

Any precise density data set can be adjusted to agree with laboratory data if necessary but precision must be quality assured.

The resolution of the density measurement in coal is, at best, 15 centimetres. Sharp boundaries are represented by a shoulder effect where the logged value gradually adjusts over 15 depth centimetres. This means that thin seams cannot be logged accurately and very thin seams and partings are not fully resolved by the measurement.

Generally speaking, the CBM geologist is not bothered about thin coal seams. The cost of extraction means that he is forced to concentrate on the sweet spots...thick zones of good quality coal. The wireline density log describes these very well indeed and provides an excellent overview within which the sweet spots are easily identified. Once the study phase is completed and activity switches to production, this type of flagged target seam display is pivotal. If the gamma and density log is run through steel casing and grout, it is normally easy to pick the target seams based on their shape, even if absolute density cannot be measured reliably through the casing. Gamma or neutron logs will also identify coal seams through casing but gamma does not differentiate limestone or intrusives from coal and running neutron (better penetration than density) results in duplication if density can do the job...it depends on the extent of grout-filled caving behind the casing.

CBM production results in a lot of drilling...to the extent of thousands of wells. Everything is designed to be simple, quick and repetitive (and low cost). The odd dud well becomes insignificant.

The logger must keep depth accuracy at the top of his agenda. Providing a cased test well for depth QA and CBL reference (see next section) is very prudent.
Orientation of face cleat and stress

Cleats may be identified and orientated by reference to borehole imagery. The optical (OTV) image is not usually ideal because the borehole fluid is opaque. It might be worth replacing it with fresh clean water during the study phase because OTV images have very high resolution indeed. However, dark cleat patterns do not contrast particularly well with coal whereas there is an excellent contrast in terms of electrical resistance (conductive water-filled cleat against resistive coal) if the micro-scanner is employed...some mineral loggers now offer that measurement.

This optical televiewer image describes very small openings in a coal seam due to them being in-filled with fine sediment.

It makes sense to try more than one imaging method early in the study phase. The OTV is useful to check the quality and depth of explosive perforations later on in the process.

A word or two on "cleats"...

A cleat, in the coalfield sense, is a small opening or split in coal matter caused by shrinkage of the coal during maturation. Actually, cleats are sometimes quite large events but most often just a few centimetres long and orientated perpendicular to bedding (usually sub-vertical events in horizontal coal seams). Because it may occur only in coal matter, a cleat will not extend into surrounding rocks or through partings in the coal. There are face cleats and butt cleats. Face cleats are continuous, representing the main highways through which water and gas may travel. Butt cleats are the shorter perpendicular side roads that stop at the face cleats. The representation on the right is a plan view of an area of coal with face and butt cleats annotated. When local hydrostatic pressure is reduced, by lowering the water table, methane gas that is adsorbed to micro pores in the coal is desorbed. It travels from pore to butt cleat then to face cleat and on to the point where water is drawn...the borehole/well.

That's the theory anyway. In practice, very few coal seams produce water/gas without the help of "fracking". The Powder River Basin in Montana and Wyoming, USA, where the coal is a natural aquifer, is the great, magnificent, exception.

Regardless, it is important to know the orientation of the face cleats and it is important to know the orientation of maximum horizontal stress with respect to the face cleats.

Perpendicular stress will close the face cleats and any natural or sometimes even the induced fractures that are parallel to them.
Brittle, bright, vitrinite-rich coal tends to have better developed cleat systems than dull coal. Spacing depends largely on coal rank (higher rank means higher frequency). Better quality coal with high organic content and thermal maturity has higher cleat frequency...and, usually, higher gas content. Permeability depends on both cleat frequency and cleat openness. Where cleat openings are small, the in-situ water's capillary pressure will restrict gas flow. Overburden stress/coal seam depth, as well as horizontal stress will affect permeability.

So cleat frequency, length, openness and orientation are important factors in CBM exploitation.

The acoustic televiewer provides an orientated image on which fractures and cleats can be seen quite clearly. This might require some image enhancement, but that is a routine process. The image on the right describes what appear to be face cleats orientated east - west on the amplitude image (the one on the right in this example).

A dark coal formation “enlightened” by use of a logarithmic amplitude scale with constrained end points and palette.

The left edge of the image is magnetic north and the lateral centre is south. For face cleats, one might expect a mirror effect on opposite sides of the borehole. Butt cleats would be random.

It should be clear...this type of analysis is neither easy nor perfectly reliable and, most often, requires some support from drill-core measurements.

The stress regime is orientated by the breakout effect where caving occurs, during the drilling process, perpendicular to the axis of maximum horizontal stress. This need not occur at every depth and in every borehole because it is a regional phenomenon. It need not occur in the coal, in fact it rarely does occur in plastic coal measures. A few coherent orientations of breakout in a programme of study-phase boreholes is normally sufficient. Local rotation of the stress tensor might occur near faults but, otherwise, breakout is a reliable and consistent indicator of stress orientation.
In most CBM plays, the Mineral logging option is perfectly applicable for the study phase. Its measurements are valid and cost effective. Here is a tabular review of practical applications.

### Main Measurements

<table>
<thead>
<tr>
<th>Log</th>
<th>Measurement</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gamma</td>
<td>Lithology based on clay fraction</td>
<td>Lithology and depth reference. Depth is critical in CBM.</td>
</tr>
<tr>
<td>Density</td>
<td>Coal seam depth, thickness and quality</td>
<td>Unambiguous measure of coal seam depth and thickness. some empirical conversion of density to proximate analyses possible...maybe also gas content in some coals. Porosity estimation in clay-free or low clay clastic formations, not in coal.</td>
</tr>
<tr>
<td>Full wave sonic</td>
<td>P and S wave velocities.</td>
<td>S wave not measurable in coal so no mechanical properties for fraccing engineer. Use P-wave for empirically based estimation. Can provide porosity estimation for overlying beds (compare with density porosity) but not coal.</td>
</tr>
<tr>
<td>Televiewer</td>
<td>Coal seam depth, thickness, stress and cleat orientation, fractures and faults</td>
<td>Valuable for all orientations, including drill core orientation checks. No gaps or data losses.</td>
</tr>
</tbody>
</table>

### Other measurements

<table>
<thead>
<tr>
<th>Log</th>
<th>Measurement</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual resistivity</td>
<td>Dual volume formation resistivity</td>
<td>Flags permeability by curve separation...invasion. Not a quantitative log, in terms of permeability or porosity, but offers empirical relationships with both.</td>
</tr>
<tr>
<td>Dual neutron</td>
<td>Hydrogen index, porosity</td>
<td>Porosity of overlying beds (compare with density and sonic porosities). Characterisation of coal for site-specific and coal seam specific empirical analyses.</td>
</tr>
</tbody>
</table>

The mineral full wave sonic tool has a function in cased hole logging where the production casing cement bond is important but does not require high cost orientated/segmented measurement.

### 2. Measurement Focus

A review of one wireline log measurement

**The Cement Bond Log (CBL)**

Every disaster junky knows that one major cause of the Deepwater Horizon blow-out was the failure to run a cement bond log (CBL) to check grout integrity between casing and formation.

*Deepwater Horizon blowout (from The Guardian newspaper)*

If the cement bond is poor or cement (grout) is missing, natural gas from the intersected reservoir can migrate behind the casing and reach the surface. In the oilfield scenario it can be under great pressure.
In this case, the consequences of the gas leak were extremely severe. In CBM logging, the same principle applies, we have to make sure the well is sealed, although consequences of failure are tiny in comparison to what occurred in the Gulf of Mexico.

The CBL sonde is run in cased boreholes to determine whether the cement slurry that is forced into the gap between steel casing and borehole wall has set evenly without empty zones which could allow gas or fluid leakage. It checks whether there is a good bond ... steel to cement to formation.

- **CBL** = Cement Bond Log
- **CCL** = Casing Collar Locator
- **GR** = Gamma Ray

A slug of grout, whose volume is calculated after reference to the caliper log, is pushed down the casing and forced upwards into the annulus between casing and borehole wall. The casing will normally include some centralisation.

The grouting process

It is vital that the cement is not too dry and that the driller does not push too quickly (forcing water out of the grout). Poor grout will not easily fill the annulus or bond well with the casing. A poor bond can also be caused by caving, mud cake and aquifers within the cased part of the well bore.

The logger’s job is to prove that the cement is present and has bonded with the casing. If there is a poor bond, the driller will want to know precisely where the problem is. He can then, hopefully, fix the problem by conducting a **squeeze job**; perforating the casing at the anomaly, setting a **packer** below the perforations and squeezing a second slug of cement into the perforations. Any grout left in the casing after either cementing process (as well as the packer) can be drilled through if necessary.

The mineral CBL log describes the entire annulus, making a single 360 degree measurement from a centralised position in the casing. In Oilfield logging, contractors offer a **segmented** bond log that is able to determine which side of the casing has a poor bond. This is not normally necessary in coalbed methane production logging. The important thing is to get the depth of any anomaly on the log exactly right and tie this into casing collar and coal seam depths; to within 10cm. **A good depth measurement is vital!**

If the cementation job goes well the CBM engineer can have the casing perforated at coal seam depth, taking care to miss casing collars described by the CCL log. He can then produce gas by pumping out water from the well.

The finished well is connected only to the coal seam

Reducing hydrostatic pressure causes adsorbed gas in coal to be released, hopefully into a coal seam aquifer that is washing gas into the well through the perforations. To improve lateral permeability the engineer might decide to **hydrofrac** the coal seam. That is to split the coal by injecting highly pressured water through the perforations. He will probably support the resulting permeability by pumping special sand grains (called proppant) into the newly formed fractures thus **propping** them open.

A good cement bond will ensure that both gas and pressured water do not escape upwards outside the casing. An accurate CBL log is therefore vital to the gas production process.
The logging tooling for a CBL job should comprise just one sonde. It is the CBL/CCL/Gamma ray combination tool. This allows both rapid data capture and good depth control (assuming the data capture software contains correct depth offsets, the sonde is zeroed properly and a lithology log has been run before).

**The sonde must be centralised.**

- **CBL:** Full Waveform Sonic – traditionally 3 foot and 5 foot spacing
- **CCL:** Simple magnetic device for locating casing joints
- **GR:** Important for depth matching CBL and CCL to other lithology logs

If no combination tool is available (it is common practice to employ a standard full waveform sonic tool with no gamma detector, then very careful depth matching is required).

**Correct depth and agreed zero references are vital.**

Logging winch speed is about 6 metres per minute (20ft/minute). The sonde requires a fluid-filled environment so the driller should top up the well with water before logging commences. This is straightforward since there should be no leakage.

A good log relies on the logger having a loose casing reference in at least one well. In this case, the client is responsible for making sure that the driller does not grout to surface. He would normally leave two or three casing lengths ungrouted below the fluid level. If this is forgotten or impossible, it will be up to the data processor to guess what CPS represent unbonded cement – not always easy after a good cementation job where there are no obvious ringing sections.

For added QA the client will normally ensure that a short casing joint is included in the casing string near to TD. This helps the logger’s depth control, so should be encouraged! Most clients will require a 20 metre repeat section and, since it is easy to capture, it is well worth becoming standard practice.

The logging run records two VDL images (FWS logs - the 3 feet and 5 feet waveforms) a gamma log and a CCL log. An important derivative from the shorter spaced waveform log is the peak amplitude of the first reflected P-wave arrival...usually with a mnemonic like PEAK. This amplitude depends on the grout to casing bond. If it is high, the casing is ringing (like a bell - ding)))))))))))))) so there is no bond to the casing. If it is low, close to zero, there is a perfect bond (bell full of cement - dong))).

The PEAK scale is simple...it is set between zero amplitude and the amplitude in free casing. That’s why the logger must have some free casing to log...it’s very important. The much-used alternative is to guess the maximum peak value.

In the old days, the logger would window his first arrival peak on an oscilloscope in the free casing section while running into the well. He would set the maximum (free casing) amplitude to 5 volts or 5000 millivolts. That was a universal scale.

It makes loads of sense to retain that tradition in modern data processing, which is often performed digitally in analytical software like WellCAD after the event. Where the free casing peak count rate was 572 for instance, we can normalise the PEAK log by applying:

**PEAK = (PEAK/572)*5000**

Set a scale of 0 - 5000 millivolts (mV).
CBL log interpretation

The log on the right is a typical presentation from a CBM project.

Gamma ray (GR - depth control) is plotted on the far left with density (LSD), which was requested by the client.

TR, to the right of the depth track, is the sonic transit time log.

PEAK amplitude and CCL are plotted together in the centre of the log. Casing collars are clearly seen as spikes on an otherwise straight CCL log. No bond above 440 metres.

A typical CBL log

The 3 foot and 5 foot VDLs are next and we can see a clear difference between them. Compare the 5 foot VDL (right) with the density log...we are seeing the formation beyond the casing and cement grout in the lower part of the log... a good bond.

On the far right, a high resolution three-arm caliper log is plotted, in order to offer extra casing depth alignment if necessary. It is remarkable how the fairly cheap casing used in coalbed methane production varies in internal diameter.

A poor bond between casing and cement will result in a high PEAK amplitude log. The casing is ringing.

Poor or no bond

Wiggle and gated first peak

GeoVista
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- Borehole orientation (Fibre Optic Gyro)
- Borehole Seismic (Geophone, P & S)
- Borehole Imaging (Televiewers)
- Borehole Video (Cameras)
A good bond between casing and cement is fairly easy to determine. The PEAK log will be very low and the VDL image will not describe a strong casing front...example on the right.

Because the VDL clearly describes the formation, there must be a good bond (sonic contact) between cement and formation. An interesting formation is helpful in the analysis.

This is why the 3ft- 5ft tool is popular; the 3ft VDL is used to derive the peak amplitude - casing to cement bond and the 5ft VDL, which looks further than the 3ft spacing, is used to check the cement to formation bond. A low PEAK amplitude would mean good bond casing to cement but if the formation was not then visible, there must be a poor bond cement to formation.

![Good bond, casing to cement to formation (note the CCL log to the right of the VDL and the caliper log describing casing diameter variations)](image)

Sometimes the log will exhibit both a strong casing front, with high PEAK log, but also some signs of formation on the VDL log. The inference is that a good bond exists between cement and formation but the casing is still ringing.

This might indicate a phenomenon known as a micro-annulus, especially if it is continuous over long sections of borehole pressure and more pronounced between casing joints. A micro-annulus is caused by casing swelling under well-head pressure applied during cementation and then a contraction when the pressure is released. The driller must release pressure as soon as the annulus is filled with cement, allowing wet cement to follow the contraction.

A micro-annulus is an annoying problem that impacts on log quality but it does not usually represent any significant vertical connectivity. In oil well logging there would be an option of running the CBL tool through a stuffing box and pressuring the casing string to see whether the micro-annulus effect disappeared.

The transit time log should be a straight line, since it is measuring the fixed transit time of steel at a, most often, fixed casing diameter. If casing diameter changes or there is significant corrosion then the TR log will drift. If the sonde becomes centred, the TR log will not maintain a straight line (signal stretch).

![Transit time (short to long) shown as a dashed line (left)](image)

The change in baseline at 73.5 metres is caused by T-time stretch which results from eccentricity (splurged arrival) or a change (downwards) from poor to slightly better bond (although, with no sign of the formation on the VDL the bond between cement and formation looks to be poor).

Stretch occurs because the discriminator detects the flatter low amplitude arrival later than the same event in poorly bonded high amplitude conditions.
The TR log is an important QA tool and should be displayed on all CBL logs if available.

- Centralise the sonde
- Log a section of free casing
- Use a combination sonde
- Record short and long spaced VDLs
- Check depth accuracy using the GR log

3. Guest Article

A serialisation over four issues

Towards Quantitative Use of Density Logs for Coal (Binzhong Zhou)

Part 3: Estimation of coal density and other quality parameters from geophysical logs

The discussion in issue 19 (September 2016) mainly focused on the direct comparison of the laboratory measured relative density with the geophysical logged densities. It was concluded that the geophysical density logs, especially the VECTAR processed density ADEN, are good measures for the in-situ coal densities after appropriate data editing and reconciliation.

These edited density logs can be calibrated with the laboratory RDs and used for estimation of coal quality parameters through establishing the relationships between the laboratory proximate analysis and geophysical logs by either simple regression using assumed regression functions (linear, logarithm, exponential, planar ...) or more advanced techniques such as radial basis function (RBF) and self-organising map (SOM) methods using multiple geophysical logs.

Here the RBF method will be used for estimation of the coal properties from geophysical logs.

Data description

A real data set from a mine in central Queensland is used to test the feasibility of the RBF-based coal quality parameter estimation from multiple geophysical logs and demonstrate its advantages over the conventional single-log analysis. The data set consisted of 1012 samples with laboratory coal quality proximate analysis data from 23 boreholes and corresponding geophysical logging data from the same boreholes.

The borehole distribution of coal quality and geophysical logging data from a mine site in Central Queensland.

The 23 boreholes are distributed in the NW-SE direction in an area of 12.3km x 23.58km and can be divided into two natural groups: Area-1 and Area-2, which are separated by about 9km, as shown on the right. The coal samples are from different coal seams.

The key coal quality parameters provided are air-dry basis relative density RDad, ash content ASHad, fixed carbon FCad and volatile matters VMad.

The key geophysical logging parameters include caliper (CADE), gamma ray (GRDE), bed resolution density (DENB), long-spaced density (DENL), VECTAR processed density (ADEN), compensated density (CODE), 20 cm sonic transit time (MC2F), 40 cm sonic transit time (MC4F), 60 cm sonic transit time (MC6F), Laterolog shallow resistivity (FE1) and Laterolog deep resistivity (FE2). These are Weatherford wireline logs and their unique mnemonics.
Not all boreholes from the sample have the full suite of the geophysical logs recorded. All the wireline log data are of good quality based on our examination.

**Coal quality estimations from geophysical logs – controlled training data set**

*Error! Reference source not found.* The figure below shows the cross-correlations of the coal quality parameters ash, fixed carbon and volatile matters with the geophysical density log ADEN.

![Cross-correlations of coal quality parameters with the geophysical log ADEN: (a) Ash content; (b) Fixed carbon; (c) Volatile matter.](image)

Based on the correlation relationships shown, we can use the density log ADEN to estimate the coal quality parameters as presented at the top row below.

![Curve fitting Estimation from ADEN](image)

The estimated air-dry ash, fixed carbon and volatile matter from a single geophysical log ADEN (top row) and multiple geophysical logs (bottom row).

In addition to this, we can also use multiple geophysical logs to estimate the coal quality parameters. In this case, we only have gamma ray and density logs available for the data analysis. The following logs GRDE, CODE,
DENB, DENL and ADEN are used to estimate the coal quality parameters ash, fixed carbon and volatile matters as shown at the bottom row above.

Comparing the estimations of these two approaches, it is not difficult to see that the estimations from multiple geophysical logs are more concentrated around the desirable diagonal lines than those from the single log density ADEN.

**This suggests that multi-log estimation is more accurate than the single log estimation.**

As mentioned, there are 1012 coal sample data points in the data set. These data samples have only ash content measured. To further test the advantage of multi-geophysical logging data, we used ash content as the coal quality parameter and compiled a data set of coal samples with all the geophysical logs.

The total number of samples for this reduced data set is 578. We use different combinations of the geophysical logs and the multi-logarithm RBF method to estimate the ash contents.

The table below lists the statistics of the resulting ash estimations using the conventional linear-fitting with the single geophysical density log ADEN and the multi-logarithm RBF method with the multi-geophysical logs of GRDE, DENB, DENL, CODE, ADEN, DEPO, MC2F, MC4F, FE1 and FE2.

<table>
<thead>
<tr>
<th>Geophysical logs</th>
<th>Min. Error</th>
<th>Max. Error</th>
<th>Average Error</th>
<th>Correlation R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Fitting</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADEN</td>
<td>0.02</td>
<td>43.23</td>
<td>6.67</td>
<td>0.9433</td>
</tr>
<tr>
<td>RBF</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRDE, DENB</td>
<td>0.02</td>
<td>55.91</td>
<td>8.12</td>
<td>0.9173</td>
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<tr>
<td>GRDE, DENB, DENL</td>
<td>0.05</td>
<td>47.57</td>
<td>7.83</td>
<td>0.9313</td>
</tr>
<tr>
<td>GRDE, DENB, DENL, CODE, ADEN</td>
<td>0.05</td>
<td>32.14</td>
<td>5.60</td>
<td>0.9628</td>
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<td>GRDE, DENB, DENL, CODE, ADEN, DEPO</td>
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<tr>
<td>GRDE, DENB, DENL, CODE, ADEN, DEPO, MC2F</td>
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<tr>
<td>GRDE, DENB, DENL, CODE, DEPO, MC2F, MC4F</td>
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<tr>
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<td>ADEN,</td>
<td>28.09</td>
<td>4.94</td>
<td>0.9725</td>
</tr>
</tbody>
</table>

**Statistics of the estimated ash contents from multi-geophysical logs**

This further confirms that the overall estimation errors decrease with an increasing number of geophysical logs used, while the correlations of the estimations are increased with the increasing number of geophysical logs used.

**Binzhong Zhou (CSIRO Energy)** - email: Binzhong.Zhou@csiro.au


Next (final) instalment (January 2017): Coal quality estimations from geophysical logs using an independent data set.
4. The logger on site

Never relax on safety

Logging - It can be a Dangerous Game

The author remembers attaching a heavy top pulley / depth wheel to the elevator of a large drilling rig and signalling to the driller to raise it to the top of the rig. Just as it began to rise, the pulley assembly dropped and a driller’s assistant instinctively caught it (amazing reflexes).

The pulley was held in place by a threaded bar and had gradually turned over many jobs and run out of threads. It had probably been hanging on one thread only, perhaps for several jobs. Obviously, this was not a failsafe design but the logger trusted it. Had the pulley fallen from the top of the rig, thirty feet up, the consequences could have been disastrous.

On another occasion the same logger fell asleep momentarily during a very long single-manned job and winched a dipmeter into the top pulley. The cable head tried to turn with the pulley wheel and, because of the length and weight of the sonde, snapped and the sonde fell to the floor below...narrowly missing a driller who was performing some maintenance. The heavy sonde would have killed or seriously injured the driller if he had been standing below it.

The point is, the logging/drilling environment is a dangerous place and, if you log hundreds of boreholes, the odds catch up with you sooner or later and you will be involved in a near miss, at least.

If you follow the rules, wear your PPE, hold that toolbox safety meeting, do a risk assessment and manage safety properly, you can turn the twenty year event into a one hundred year event.

Be careful out there!