Integration of Downhole Geophysical and Lithological Data from Coal Exploration Drill Holes

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SUMMARY

The primary variable of interest in a coal resource study is the volume of coal as estimated from the coal thicknesses in each drill hole. It is therefore essential to accurately determine, down to the centimetre level, the thickness of each seam. To attain this accuracy, each drill hole is geophysically logged as these logs provide a considerably more accurate indicator of seam boundary depths than the geologist's log. Currently, coal geologists spend a large amount of their time integrating their logs with depth information from the geophysical logs. They do this by displaying the two logs next to each other and then manually changing the depths in their logs. Most of this process is relatively routine and thus rather tedious and boring but like many seemingly simple cognitive tasks, not easily transformed into a computer algorithm. The manual method also suffers from being subjective and often non-repeatable.

Previous methods to automate this process have used multivariate statistical techniques to assign lithologies down the hole based on the geophysical values at each reading depth. However, despite these methods having been developed and publicized for over thirty years they still have not been widely adopted as they still do not integrate the information from the two types of data. Following the generation of a lithology log from the geophysics, geologists still need to manually integrate it with their log.

This current study has successfully managed to develop algorithms to automatically determine both coal/non-coal and clayey/non-clayey boundaries based on the gradients and inflection points of the geophysical logs and then integrate this information with the geologist's log.

Key words: coal exploration, downhole geophysical logs, geology geophysics integration

INTRODUCTION

When coal geologists drill a borehole, they obtain either cuttings from open holes or core from cored holes. These samples are then described in the geologist's log. They also obtain a suite of geophysical logs that measure a variety of physical characteristics of the rock. These will generally include long and short spaced density, natural gamma and caliper. Sometimes sonic may be included and occasionally neutron-neutron or resistivity is included. According to the Australian Guidelines for the Estimation and Classification of Coal Resources (Coalfields Council of New South Wales and Resource Council of Queensland, 2014), "seams covered by downhole geophysical logs in non-cored boreholes can provide Quantity Points of Observation" and that "downhole geophysical data should be used to confirm the location and nature of any core loss in coal seams".

Both the geologist's log and the geophysical logs provide information regarding both the geological characteristics of the strata and their locations down the drill hole. Even though the two types of data provide both types of information, in general:

- the geologist's log provides considerably more information on the rock characteristics than the geophysical data
- the geophysical data provides more accurate information regarding the location of the rock sample data

One of the responsibilities of the coal geologists is to merge both types of data into a single geological log. This merged log needs to account for both rock characteristic and location information from both types of data and weight the information according to its source. It should be noted though that for a cored interval with no core loss that the geologist's log is the more reliable for determining the seam thickness and the geophysics for determining its depth. The problem is to derive a computer based method to assist the geologist in this task of merging the two data types. Such a method would have the advantages of:

- making the geologist more efficient
- improving consistency between geologists
- removing some of the drudgery of merging the two data types so that the geologist can spend their limited time on the more difficult and therefore interesting parts of the merging operation

Over the last thirty years, a variety of methodologies have been developed by software houses for generating an "artificial" lithology log from the geophysics. These have generally been based on multivariate statistical methods (Fallon *et al.*, 2000; Larkin and Lay, 1995; Larkin, 1985) though one or two were based on using neural networks (Chang *et al.*, 2000; Cram *et al.*, 1995). Even though these methodologies have been available for many years they have not been widely adopted by industry. I believe that this is chiefly because after generating the "artificial" lithology log, geologists still need to manually merge this with their log. These methodologies thus do not make the geologist more efficient but merely transform the problem into a slightly different merging problem. In addition, they do not reflect the geologist's manual approach which is to chiefly use the geophysical log to identify strata boundaries from the "kicks" in the geophysical logs rather than determining a lithology for each reading depth down the borehole. One advantage of using the "kicks" in the geophysical log is that they are far less sensitive to geophysical log calibration issues than using the actual values of the readings.

This study has focused on developing methods to automatically determine lithological boundaries from the geophysics and then link these derived boundary depths to boundaries recorded in the geologist's log. Davis and Christensen (2013) successfully used wavelet theory to detect strata boundaries from geophysical logs for alluvial aquifer detection in the Gascoyne River area of Western Australia though their work did not also include matching these boundaries with those in a geologist's log. In terms of automatically matching the depths of features in different logs, the only publication that I am aware of is Kerzner, 1986, however, this only attempts to match the depths of features indicated on a set of geophysical logs that were recorded by different tool runs in the same borehole rather than matching between a geophysical log and a geologist's log. Instead of using wavelet theory and deriving a matching method based on that developed by Kerzner, I have instead tried to develop mathematically simpler methods that are relatively easy for the reader to implement. I have undertaken three case studies and these simpler methods have worked successfully. It is though quite possible that these simpler methodologies will be inadequate for some more difficult data sets.

The three case studies included:

1) A set of six boreholes each containing only one seam. This seam had sharp boundaries in all six holes.
2) One borehole containing a number of seams, most of which had gradational boundaries.
3) One borehole containing a number of seams, most of which had gradational boundaries. The seams also contained significant bands of poor quality coal with a high ash content which need to be identified.

It has always been intended that the methodologies developed in this study would not perform the entire task of merging the geologist's log and the geophysics but rather perform the majority of the task and that its results would probably require some minor adjustments by the geologist before being finally accepted.

MANUAL METHOD OF ADJUSTING THE GEOLOGIST'S LOG TO THE GEOPHYSICS

The most important geophysical variable for coal geologists is the density log which is used to find coal seam boundaries. As the density log uses a gamma radiation source and detector with a specific separation distance, the resolution of the tool is limited by this distance. Most logging contractors produce a number of density logs with different spacings and or different post-collection processing. It was decided that for the purpose of this study the Short Spaced Density (SSD) was the most appropriate. In addition to coal, the density log is also strongly affected by hole cave-outs and siderite bands and so the geologist needs to be able to distinguish between the boundaries of these and coal boundaries. Cave-outs are indicated by an increase of the hole diameter as reflected in the caliper log and siderite bands entail a sudden increase in the density log compared to the hosting sediments whereas coal entails a sudden decrease compared to the hosting sediments.

The geologist often also uses the natural gamma log in addition to the density log to determine the coal seam boundaries as generally the natural gamma value will be lower through the coal seams than in the hosting sediments. This though does depend on the lithology of the hosting sediments. The higher the clay content of the hosting sediments the higher the difference in natural gamma values between the coal and the hosting sediments. In some environments, the natural gamma log may even be a clearer indicator of seam boundaries than the density log. The natural gamma also facilitates identifying poor quality bands within the coal containing high mineral matter. The natural gamma also facilitates identifying strata with low and high clay content between the seams. Identifying these is often important for mining engineering purposes. The natural gamma radiation emitted from any point in the strata is not a constant value over time but rather has a probabilistic distribution. What the geologist requires is the average emission over time, however, generally the amount of time required to obtain an accurate average is too great to be practical and so generally averages are obtained by doing a running average over a set number of interval readings down the hole. This is known as filtering the data. The appropriate number of intervals over which to do the filtering is a function of the rate at which the sonde passes up the hole and the amount of variation in the natural gamma radiation emission at each depth. In general, without any filtering the natural gamma radiation results are of little use.

This study aimed to mathematically reproduce the processes that the geologist performs when adjusting their log to the geophysics. It became apparent that the geologist uses a two stage process for this:

1) they identify major features clearly displayed in the geophysics and adjust the geological log accordingly.
2) they then identify features in the geological log that were not identified in step 1) and then look for any expression of these in the geophysics and adjust the geological log accordingly.

It also became apparent that the geologist uses a two stage process for determining boundaries from the density log:

1) they determine a zone between two depths where a boundary exists.
2) they then determine the actual point in the zone for the boundary.

AUTOMATICALLY DETERMINING BOUNDARY ZONES

This study deemed that an appropriate measure to determine a zone in which the boundary existed was where there was a change of at least 0.15 gm/cc in the density log. However, it also determined that it needed to look for this change over both:

- a short depth interval to pick up sharp boundaries
- a longer depth interval to pick up more gradational boundaries

The two such distances used in the study were 12cms and 24cms. The zones generated by both these methods were then merged. Figure 1 shows the zones, as deemed by the above methodology, for the roof and floor of the lower of the displayed seams.

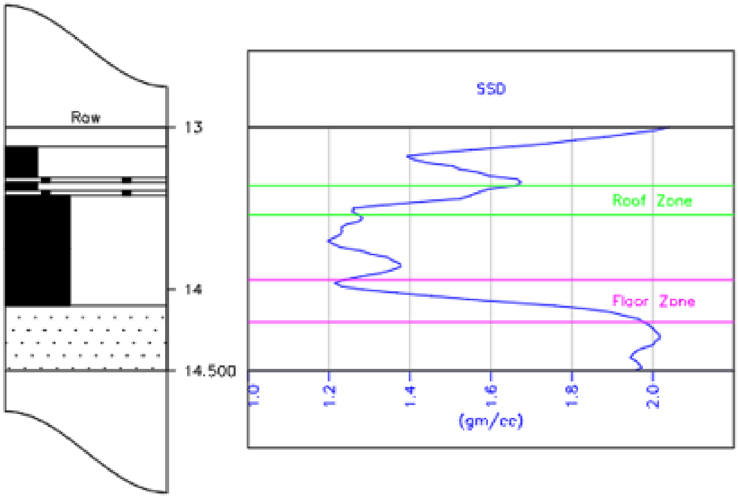

Figure 1: The geologist's log on the left and the associated short spaced density values on the right. Coal seams are shown in the geologist's log by black rectangles the width of which denotes the brightness of the coal. Also shown are roof and floor zones as deemed from the short spaced density log.

DETERMINING THE BOUNDARY POINT WITHIN A ZONE

The literature suggests a variety of ways of picking the boundary point within a zone. For example, half way or two-thirds of the way between the minimum and maximum values within the zone. This study concluded from its three case studies that the best point is where the slope of the density curve is closest to the horizontal. This will also be a point of change of curvature.

The arrows in Figure 2 indicate where the slope of the density curve is closest to the horizontal. These are also points of change of curvature. There is only one such point in the floor zone and at this point the curvature changes from concave right to concave left going down the hole. However, for the roof zone there are two such points. A criterion is required for selecting which one to use. Two possibilities are:

- the one that is the actual closest of the two to the horizontal
- going down the hole, the first one in the roof zone and the last one in the floor zone

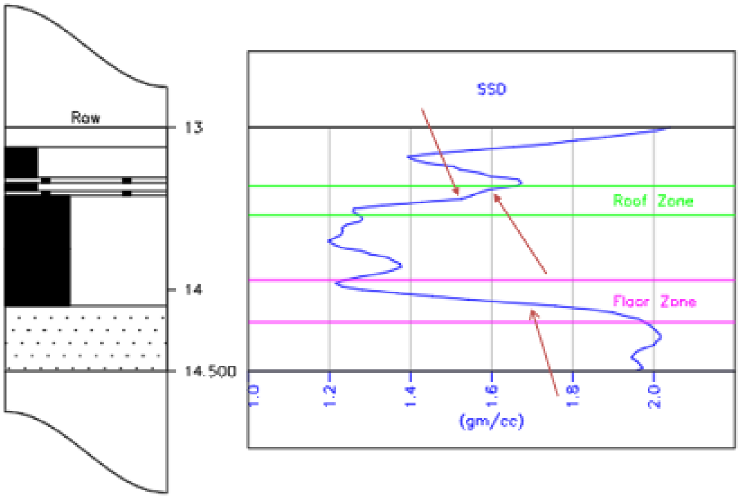

Figure 2: The geologist's log, Short Spaced Density (SSD) log and roof and floor zones as shown in Figure 1. The red arrows indicate potential boundary depths within the roof and floor zones.

In terms of matching the observations of the geologist in the three case studies, it was deemed that the second was better than the first. It is possible though that the first may be better for deriving the mining thickness rather than the geological thickness of the seam but this requires further investigation.

CASE STUDY NO. 1: SINGLE SEAM WITH SHARP BOUNDARIES

The methodologies described above were used to derive the boundaries for a single coal seam with sharp boundaries across six holes. The results of this compared to the geologist's raw log and manually adjusted log can be seen in Table 1. Notably the maximum difference in seam thickness between the geologist's manually adjusted log and the automatically derived boundaries from the density is over the six holes in the study is 13cms for a seam thickness of 5.11 metres, that is a relative error of 0.79%.

Hole		Geologist's Raw Log	Geologist's Adjusted Log	Derived Boundaries	Derived / Raw Differences	Derived / Adjusted Differences	Relative Error of Derived to Raw (%)	Relative Error of Derived to Adjusted (%)
5A	Roof	296.675	297.050	297.050	0.375	0.000	0.13%	0.00%
	Floor	301.415	301.790	301.790	0.375	0.000	0.12%	0.00%
	Thickness	4.740	4.740	4.740	0.000	0.000	0.00%	0.00%
5B	Roof	266.340	266.190	266.180	-0.160	-0.010	0.06%	0.00%
	Floor	271.555	271.405	271.400	-0.155	-0.005	0.06%	0.00%
	Thickness	5.215	5.215	5.220	0.005	0.005	0.10%	0.10%
5C	Roof	266.535	266.655	266.650	0.115	-0.005	0.04%	0.00%
	Floor	271.350	271.470	271.470	0.120	0.000	0.04%	0.00%
	Thickness	4.815	4.815	4.820	0.005	0.005	0.10%	0.10%
5D	Roof	341.825	341.825	341.840	0.015	0.015	0.00%	0.00%
	Floor	346.380	346.380	346.380	0.000	0.000	0.00%	0.00%
	Thickness	4.555	4.555	4.540	-0.015	-0.015	0.33%	0.33%
5E	Roof	342.115	342.100	342.100	-0.015	0.000	0.00%	0.00%
	Floor	347.315	347.210	347.170	-0.145	-0.040	0.04%	0.01%
	Thickness	5.200	5.110	5.070	-0.130	-0.040	2.56%	0.79%
5F	Roof	318.640	318.740	318.750	0.110	0.010	0.03%	0.00%
	Floor	323.920	323.915	323.950	0.030	0.035	0.01%	0.01%
	Thickness	5.280	5.175	5.200	-0.080	0.025	1.54%	0.48%

Table 1: Comparison of derived boundaries to the geologist's raw and adjusted logs for coal roof and floor depths and coal thicknesses.

ASSOCIATING GEOPHYSICAL FEATURES WITH THE GEOLOGY

Due to the resolution of the SSD log, I found that coal or non-coal bands less than 5cms could not be distinguished from the geophysics. To enable the matching of boundaries in the geologist's log with the derived boundaries, the geologist's log was separated into coal and non-coal zones that were greater than 5cms. Where there was a sequence of coal/non-coal bands in the geologist's log that were all less than 5cms the entire sequence of bands was allotted to being coal or non-coal depending on whether the total thickness of coal was less than or greater than the total thickness of non-coal within the sequence. Finally, each roof and floor boundary derived from the density log was matched to the nearest in depth, roof or floor boundary in the geologist's log. The results of this from the second case study of a hole with multiple seams and many gradational boundaries is shown in Figure 3. At around 13.8 metres the density log indicates a non-coal or low quality coal band that has not been logged by the geologist. As the algorithm matches the top and bottom of this with the nearest non-coal top and bottom, a crossover of links is produced. It would be easy to automatically remove the links for the band that the geologist has not logged but the crossover has not been removed so as to highlight the issue to the geologist.

ASSOCIATING GEOLOGICAL FEATURES TO THE GEOPHYSICS

After the geologist has identified important features in the geophysics which they can associate with features in the geology they then find other features in the geology that may be observable in the geophysics though are not significant features in the geophysics. Prime example of these are:

- The location of thin partings within coal seams.
- The location of thin seams within the interburden.

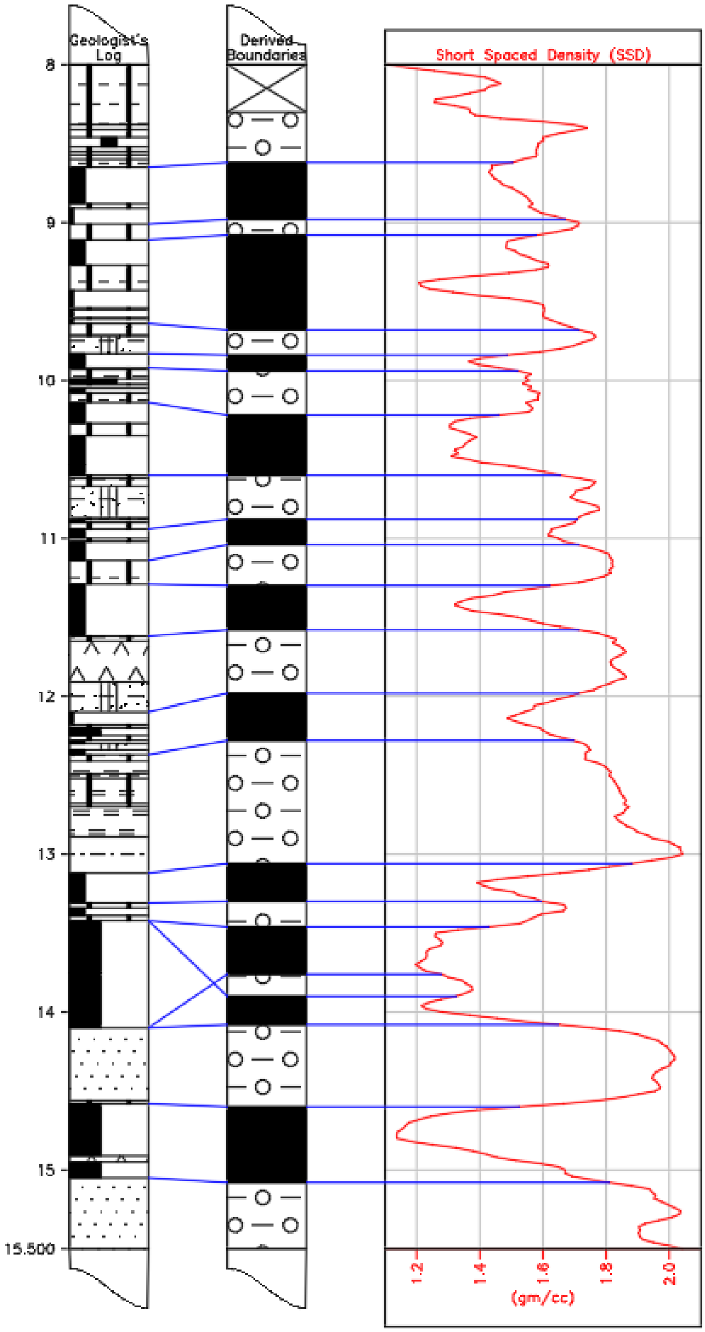

Figure 3: Geologist's log, boundaries derived from the short spaced density (SSD) log and the actual SSD log. Each derived boundary has been connected to the point in the SSD log from which it was derived and its associated depth in the geologist's log.

Associating such features in the geologist's log with depths from the SSD log was undertaken by:

1) Creating a list of the depths of each local SSD minimum within the derived interburden intervals and each maximum within the derived coal intervals.
2) Each of these depths was converted to a proportional position within its derived coal interval. For example, a local maximum just below the Coal Roof Boundary may have a proportional position of 0.02, one half way through the coal interval would be 0.50 and one just above the floor may have one of 0.98.
3) The geologist's log is divided into coal and interburden intervals as defined by those roof and floor boundaries within the geologist's log that have been associated with a derived roof or floor boundary from the density log.
4) For each of the intervals in 3), the proportional position of the mid-point of each recorded parting within coal intervals and coal band within interburden was calculated.

5) Finally, each of the mid-points in 4) is associated with the SSD minimum/maximum in its corresponding derived coal or interburden interval that has a proportional position closest to its proportional position in the geologist's log.

The associated midpoints of partings within coal seams are shown in Figure 4 and the associated midpoints of thin coal seams within the interburden are shown in Figure 5.

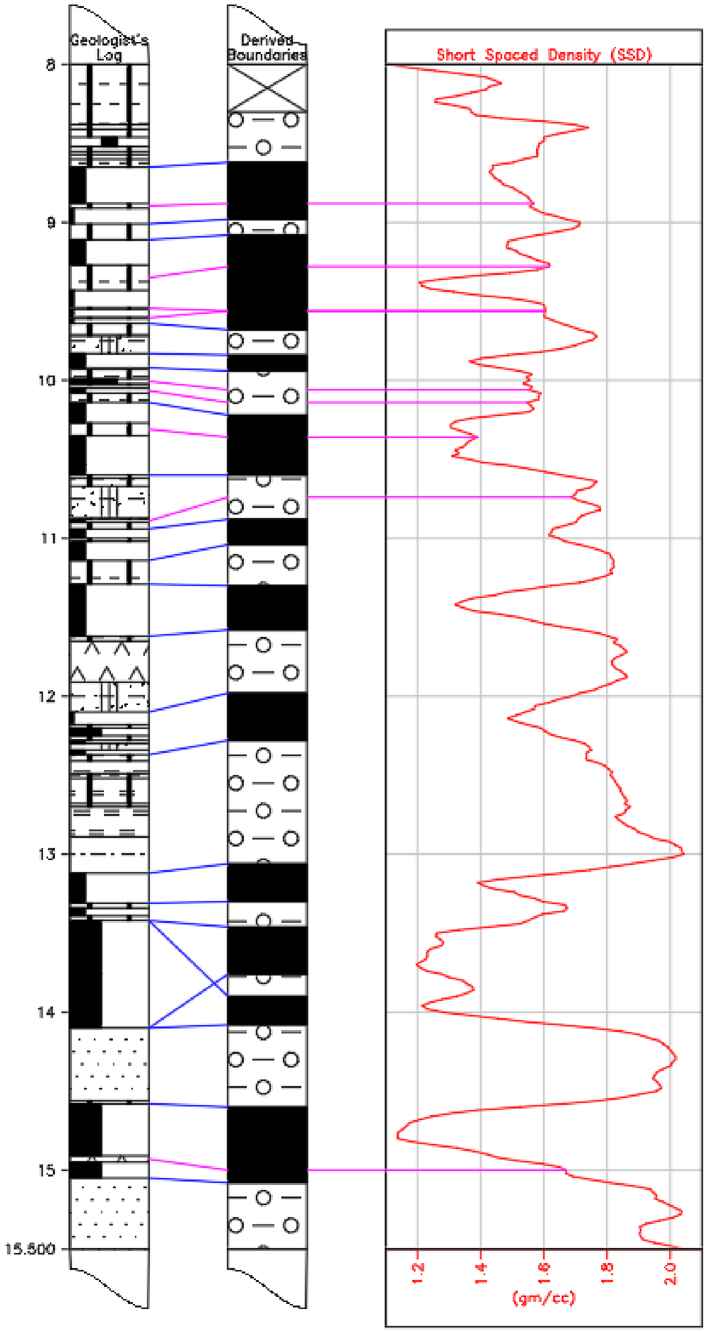

Figure 4: Geologist's log, boundaries derived from the short spaced density (SSD) Log and the actual SSD Log for the same interval as shown in Figure 3. Each derived boundary has been connected to the associated depth in the geologist's log (blue lines). Mid-points of partings within coal seams have been connected to their associated points in the SSD Log (purple lines).

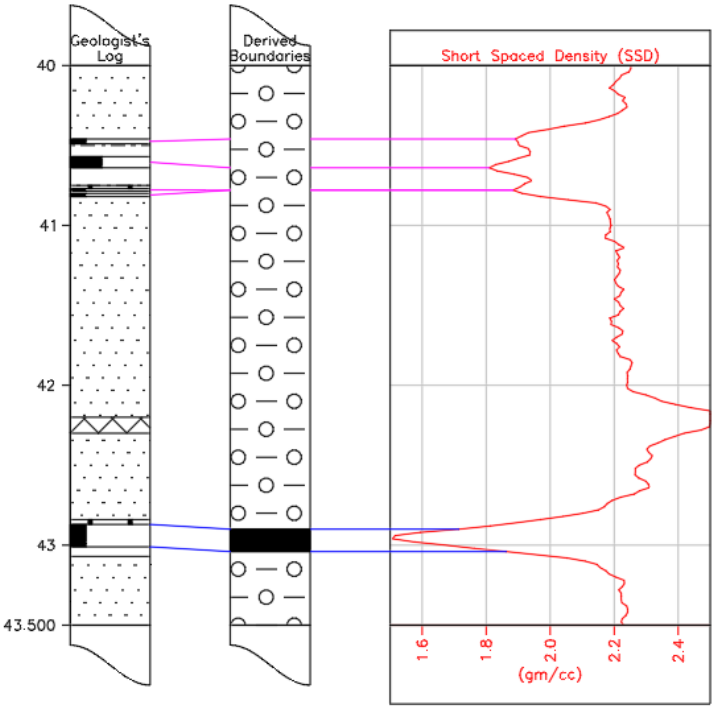

Figure 5: Geologist's log, boundaries derived from the short spaced density (SSD) Log and the actual SSD Log. Each derived boundary has been connected to the point in the SSD Log from which it was derived and its associated depth in the geologist's log (blue lines). Mid-points of thin coal seams have been connected to their associated points in the SDD Log (purple lines).

DETERMINING CLEAN/DIRTY SEDIMENTS BOUNDARIES

High natural gamma values generally indicate a high amount of clay material in the rock as most of the natural gamma radiation in coal environments is produced by potassium which mainly occurs in clays. Sediments with high amounts of clay can be referred to as dirty and those with little clay material as clean. Boundaries of clean/dirty sediments can be derived from the natural gamma log using a similar approach as described above for deriving coal roof and floor boundaries from the SSD log.

For Case Study 3, the zones in which the dirty/clean sediments boundary lay was determined as the interval where there was at least a 40 API difference in the natural gamma values 24cms apart. The actual boundary point was determined as the point within the zone with the largest slope though if no slope within the zone was greater than 500 API/m then the zone was ignored.

Finally, the derived coal boundaries and dirty/clean sediments boundaries were combined to produce a derived lithological log from the SSD and natural gamma. Table 2 describes how the derived results were ascribed to each combination.

		Derived Coal Zones	
		Non-Coal	Coal
Derived Sediment Type	Clean Sediments	Clean Sediments	Coal
	Dirty Sediments	Siltstones	Carbonaceous Mudstone

Table 2: Look-up table for combining derived coal zones and sediment types.

No attempt has yet been made to match the derived boundaries in Case Study No. 3 with those in the geologist's log.

CONCLUSIONS

This study has produced a methodology for computer assisting coal geologists in their task of adjusting geological logs to the downhole geophysics.

Implementing this methodology has the potential of:

- making the geologist more efficient
- improving consistency between geologists
- removing some of the drudgery of merging the two data types so that the geologist can spend their limited time on the more difficult and therefore interesting parts of the merging

It is unlikely though that the methodology can ever be improved sufficiently to fully replace the geologist in the task of deriving adjusted logs.

The full report for this study is available from the Australian Coal Association Research Program (Larkin, 2017).

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