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A rock mass assessment procedure based on quantitative geophysical log analysis of coal measure sequences

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Key Words: logging, coal mining, geotechnical classification

ABSTRACT

Geophysical logging is routinely undertaken as part of most coal mine exploration programs. Currently, the main application for the logs is to determine coal seam depth and to qualitatively estimate coal quality, lithology, and rock strength. However, further information can be obtained, if quantitative log interpretation is made.

To assist in the uptake of quantitative interpretation, we discuss log responses in terms of the mineralogy of the clastic sedimentary rocks frequently found in the Australian black coal mining areas of the Sydney and Bowen Basins. We find that the log responses can be tied to the mineralogy with reasonable confidence. Ambiguities in the interpretation will be better resolved if a full suite of logs is run. A method for checking for internal consistency, by comparing calculated and observed velocities, is also described.

A key driver for quantitative interpretation is geotechnical characterisation. We propose a classification system for clastic rocks that takes into consideration physical rock properties that can be inferred from geophysical logs.

INTRODUCTION

The role for geophysical logging in coal mining operations has been recognised by mining personnel and the geophysical community for many years. For example, Asten (1983) describes a computer method for lithological and geotechnical analysis, and in Buchanan and Jackson (1986) there is a collation of a number of early papers. However, despite this work, there has been little acceptance of quantitative geophysical log analysis within the coal mining industry. For example, the gamma log is still usually taken to be the sole indicator of shaliness; rock strength (unconfined compressive strength) is estimated from just the P-wave sonic velocity; and little use is made of density logs beyond determining coal seam boundaries and perhaps making a first estimate of the ash content of the coal.

The types of analysis undertaken in oilfield formation evaluation are rarely used in coal mining. If they were, the geological and geotechnical uses for logs could be expected to increase. This would be particularly true for geotechnical work because the behaviour of rocks in and around mine openings must be understood and carefully managed. If geophysical logs could be used to accurately estimate physical rock properties, geotechnical evaluation and mine design should be much improved.

Explanations of the methods for quantitative log analysis can be found in textbooks such as those by Hearst et al. (2000) and Rider (1996), and are not described in this paper. Within the petroleum industry, analysis is mainly driven by the need to understand the porosity and saturation of clastic sedimentary rocks. The basic model for clastic rocks assumes that they are comprised of three phases – the pore space, the clay (shale) component, and the matrix (grains). Once the proportions of these are known, the nature of the pore fluids and gases can be assessed.

In coal mining, the pores tend to be fluid saturated and hydrocarbons are not often present. This should make the job of understanding the porosity and the proportions of shale and matrix present easier. In this paper we put this to the test and investigate the use of the quantitative geophysical log interpretation methods in the context of the needs of the mining operations in the black coal mining areas of eastern Australia in the Bowen and Sydney Basins. This leads to a proposal for a rock classification method based on the quantitative analysis. Our work is more fully described in Hatherly et al. (2004).

QUANTITATIVE LOG INTERPRETATION

The basic suite of geophysical logs used for logging a typical HQ borehole (96 mm hole diameter) consists of the density, natural gamma-ray, sonic, and caliper logs. In addition, resistivity, microresistivity, acoustic scanner, full waveform sonic, spectrometric radiometric, and temperature are available and being increasingly used. In our work, we have considered data from this full range of logs, but in this paper we only make use of the natural gamma, caliper, density, neutron, and sonic logs.

Following standard practice, an early step in quantitative analysis involves the calculation of the porosity. It is assumed that the rock formations consist of a simple two-phase system containing saturated pore spaces and the rock substance (matrix plus clay). The usual coalfield assumption is that the densities of the rock substance and the water are 2.65 t/m^3 and 1.0 t/m^3 respectively. We have checked these assumptions by comparing log values and analyses against 50 laboratory density and porosity determinations on core. We found that the standard deviations in the errors for the log densities and derived porosities were 0.7% and 3.4% respectively. Attempts to improve the porosity determinations by introducing a second rock density for the clay fraction did little to improve this result. Presumably, this is due to the complexity of the mineralogy in the samples. Regardless, errors of about 3% in the porosity determination are considered acceptable for present purposes.

The shale content can be determined directly from the natural gamma log and from a combination of density (porosity) and neutron logs. If the gamma log is used, there may be errors because not all clay minerals contain radioactive isotopes (e.g., swelling clays such as montmorillonite) and conversely, some of

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the rock grains may be radioactive (e.g., potassium feldspar and mica). If the neutron and density logs are used, then errors are compounded from the porosity determinations.

Estimates of shaliness are also possible from resistivity logs. This provides a third measure of shaliness and will help resolve ambiguities in the other two. However, resistivity logs do not tend to be run as frequently as the others are, and they are not considered any further in this paper.

An approach we have also taken to help resolve overall ambiguities in the porosity and shale determinations is to calculate a velocity on the basis of the empirical formula derived from laboratory testing by Eberhart-Phillips et al. (1989) and to compare the calculated and observed velocities. To calculate the velocity we use the formula

$$v = 5.77 - 6.94\phi - 1.73\sqrt{V_{shale}} + 0.446(\sigma - e^{-16.7P_e}) , \qquad (1)$$

where v is the measured P-wave velocity (km/s), ϕ is the porosity, V_{shale} is the shale volume, and P_e is the effective pressure (kbar). The pressure is not normally known, but an appropriate value of P_e is relatively easy to establish because P_e increases gradually with depth and its overall effect is to produce an increase in baseline velocity with depth. The variations in velocity over shorter intervals tend to be due to changes in the porosity and shale content, and if there are significant errors in the estimates of these, they are easy to identify. Experimentation with the choice of matrix density and various shale end-points used in the quantitative analysis allows appropriate parameters to be determined which yield an acceptable correlation between the calculated and observed velocities.

MINERALOGICAL ANALYSIS OF CORES

To further understand the log responses, X-ray diffraction (XRD) analysis was undertaken on selected sandstone and siltstone cores from a number of holes in the Bowen Basin. Summary results for 11 of the cores are shown in Figure 1. In this figure, the cleaner sands are to the left and there are siltstones (shalier rocks) to the right. The minerals containing potassium are orthoclase feldspar, sanidine, microcline, illite, and mica. In general terms, there is correlation between the total volume of these minerals and the value of V_{shale} determined from the natural gamma-ray log. The large increase for sample QL011 is due to a marked increase in the amount of mica present. Overall, the amount of potassium-bearing minerals present is low in this sample suite.

The results shown for the non-potassium-bearing clays are for kaolinite, the mixed-layer clays, and chlorite. When these are added to the amount of illite that is present, values are obtained for the total clay. For this sample suite, the total varies between 10% and 50% and it is apparent that most of the clays are not potassium-bearing. It is for this reason that there is not a particularly good correlation between the V_{shale} determined from the gamma log and the total clay content.

In the case of the V_{shale} analysis from the neutron and density logs, while the absolute values differ, the general trend in the V_{shale} agrees with the trend in the total clay content. In Hatherly et al. (2004) there is a more detailed analysis, in which the amount of hydrogen present is determined and compared with the V_{shale} after correction for changes in matrix/shale density (especially taking into consideration the presence of carbonates). A much closer correlation is obtained.

The presence of non-potassium-bearing clays can present problems for natural gamma-ray interpretation of shaliness. From a mining point of view, it can be important if the presence of swelling (mixed layer) clays is not recognised in the rocks in the roof and floor of the coal seam, because they are non-potassium-bearing clays. In such circumstances there could well be rock degradation problems, when the roof and floor strata are exposed by mining and come into contact with water. Validation of gamma-based V_{shale} determinations by comparison with neutron density or other values, and thorough comparison of calculated and observed velocities, is therefore a recommended procedure.

The XRD analysis also indicated that in some samples there were significant amounts of carbonates (calcite, dolomite, and siderite) present. This has the potential to cause problems for density porosity and subsequent neutron-density shale estimations. Plagioclase is also sometimes present. Some other samples have relatively high concentrations of heavy minerals (again there are implications for the natural gamma interpretation).

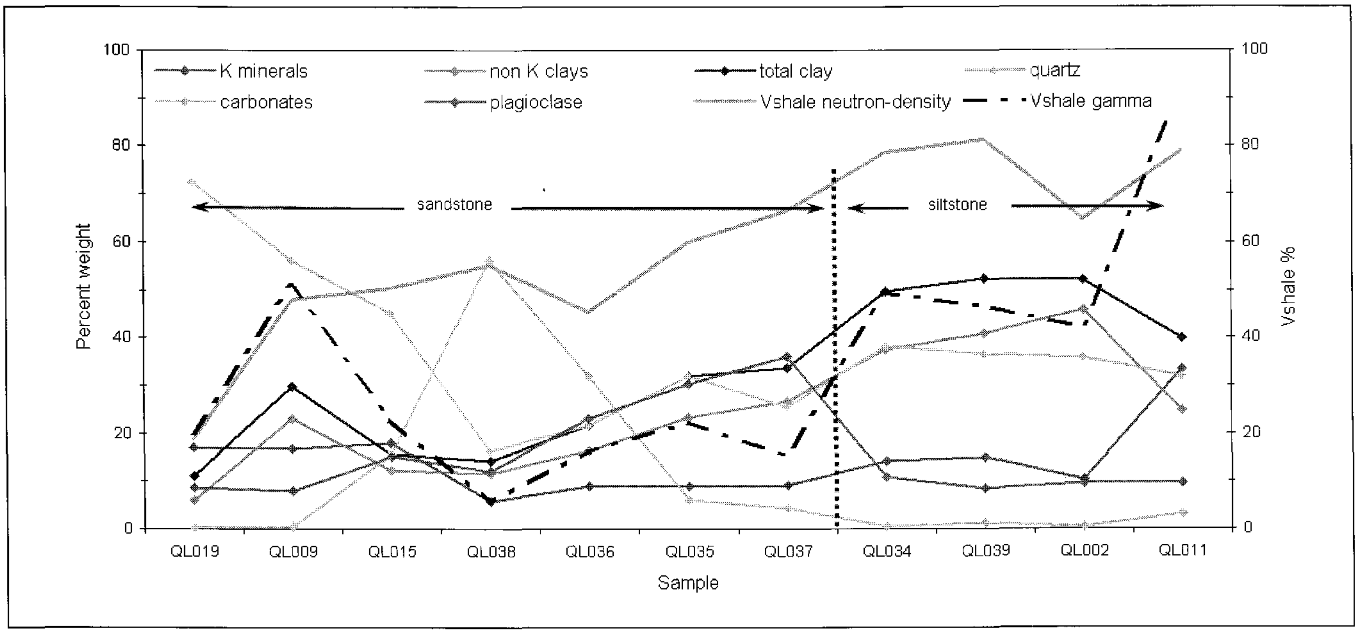

Fig. 1. XRD analyses and log responses of typical Bowen Basin sandstones and siltstones.

Strength Score (SS)	= 20 × velocity - 45	where velocity is measured in km/s
Porosity Score (PS)	= -15	where Vshale < 0.2 and porosity > 0.2
	= -5	where V_{shale} < 0.2 and porosity > 0.1
	= 0	elsewhere
Moisture Score (MS)	= -10	where V_{shale} > 0.7 and porosity > 0.075
	= -5	where V_{shale} > 0.7 and porosity > 0.05
	= 0	elsewhere
Rock Score (RS)	= SS + PS + MS	
Cohesion Score (CS)	= 25	where velocity 3.5 and Q[1] > 0.67
	= 20	where velocity > 3.25
	= 15	where velocity > 3
	= 10	elsewhere
Bed Score (BS)	= 40	where fractures/m < 2
	= 30	where fractures/m < 5
	= 20	where fractures/m < 10
	= 10	where fractures/m < 20
	= 0	where fractures/m 20
Geophysics Strata Rating	= RS + CS + BS	

Table 1. A scheme proposed for the determination of a geophysical strata rating. The total score represents a measure of rock quality in the range 0–100. [1] Quartz (Q) = $1 - V_{shale}$ - porosity

ROCK MASS CLASSIFICATION

For tunnelling and underground mining in hard rocks, the rock mass classification schemes most commonly used for design purposes are the Tunnelling Quality Index (Q-value) (Barton et al., 1974) and the Rock Mass Rating (RMR) (Beniawski, 1976). Both schemes take into consideration factors such as the strength of the intact rock, the properties of the joint systems, the groundwater, and the stress regime.

For coal mining applications, Molinda and Mark (1994) point out that these rating systems are not readily adaptable, because they do not adequately take into consideration the effects of sedimentary features, such as bedding planes and joints. Accordingly, they introduced the Coal Mine Roof Rating (CMRR), a scheme that allows these to be considered. The CMRR is designed to provide values similar to the RMR.

To apply these schemes, access to core and exposed rocks is needed. The ability to predict rock properties for underground mining is therefore limited by the amount of core drilling that is undertaken. Geophysical logging from non-cored holes has the potential to improve this situation.

One approach is to use sonic logs to estimate the unconfined compressive stress (UCS) and to use this for design purposes. The qualitative relationship between UCS and sonic transit time, t, for coal measure strata proposed by McNally (1990) is

$$UCS = 10000\, e^{-0.035t} \tag{2}$$

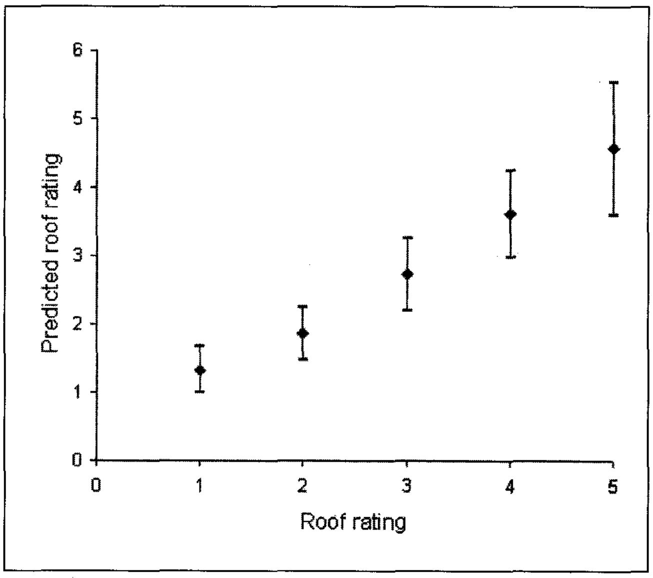

Fig. 2. Comparison of predicted roof rating and actual rating based on 185 mine roof characterisation tests. For each rating, average predicted values and values ± one standard deviation from the average are shown.

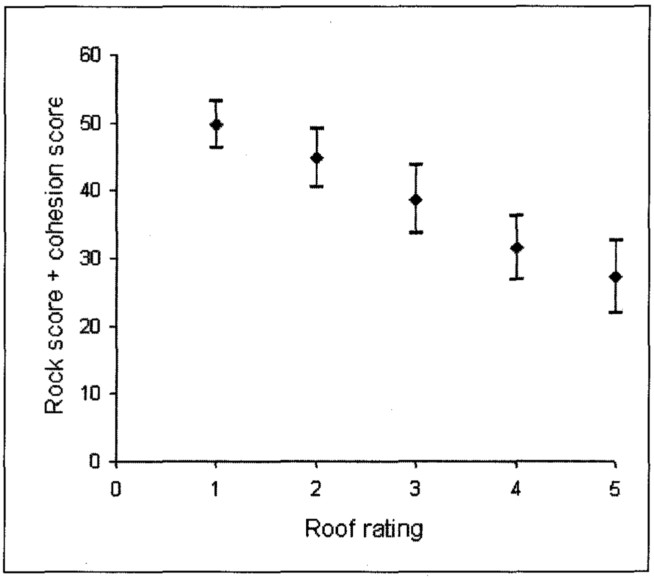

Fig. 3. Geophysical log based assessment of intact roof quality. For each class of roof rating, average values for the combined rock and cohesion scores, as well as values ± one standard deviation from the average are shown.

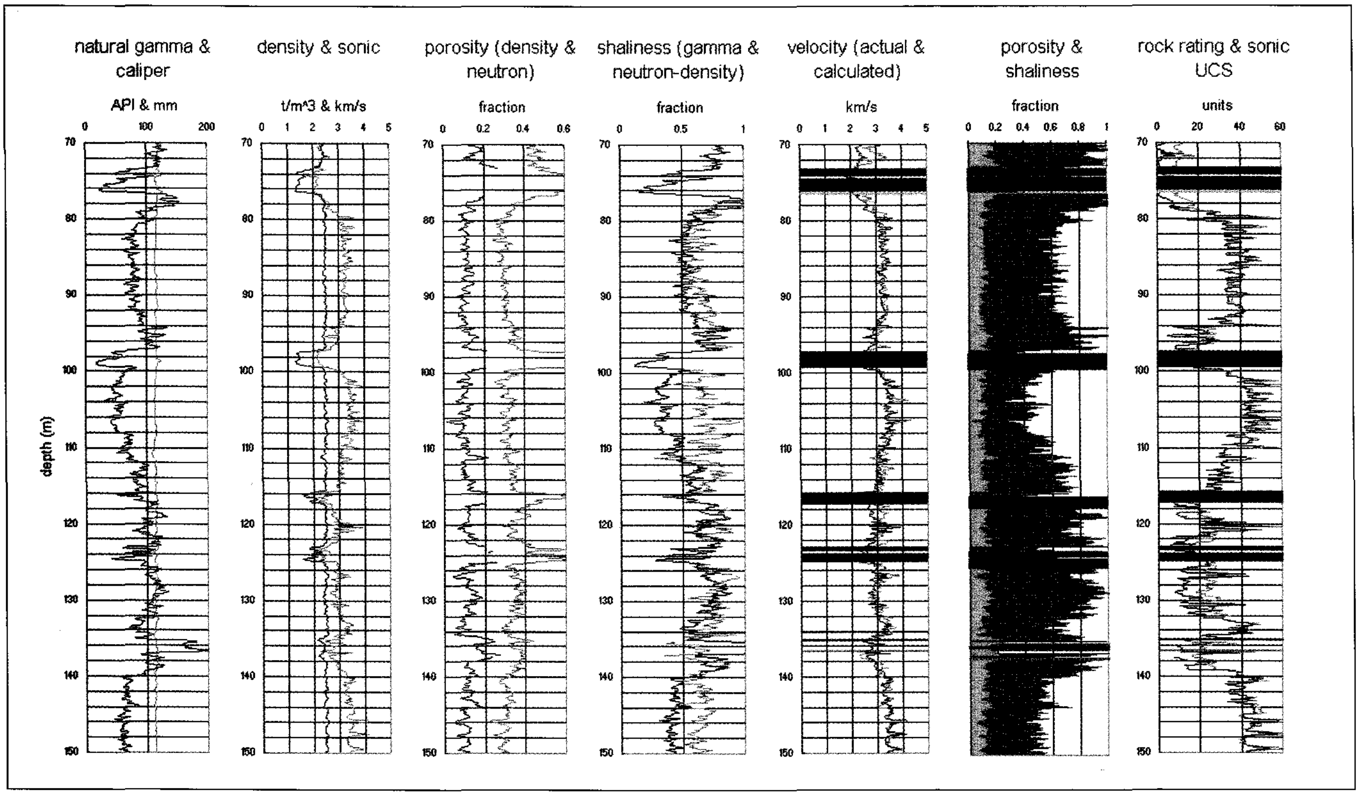

Fig. 4. Quantitative geophysical log analysis. Logs in blue and pink relate respectively to the first and second logs in the titles to each track. Non-clastic lithological units (mainly coal) have been blocked out in tracks 5, 6, and 7.

Here *t* is measured in microseconds per foot and *UCS* is measured in MPa. Numerous local mine-site schemes have been developed subsequently, and while these relationships provide good first order estimates, they lose accuracy with lower strength materials. In such materials, porosity and V_{shale} can be expected to impact on rock properties: a good relationship should also include consideration of these.

An example of using porosity, $V_{shale,}$ and velocity to predict rock conditions is shown in Figure 2. The mine in this example uses a variant of CMRR to classify their roof strata. A roof rating of 1 represents good roof requiring standard engineering support, while roof strata with a rating of 5 are in much poorer condition and require more extensive use of bolts, mesh, and straps to ensure stability. Multiple linear regression of the geophysical parameters against the mine's rating scheme shows that the actual rating can be reasonably estimated. The increase in the standard deviation for the weaker roof strata is due to a considerable bias in the data set towards results for a stronger roof (classes 1 and 2).

Another way of approaching the problem is to create a new rating scheme whereby geotechnical factors such as the intact strength, the porosity/moisture content, the cohesion and the fracture frequency are estimated from the geophysical logs. Using the same mine data set as in Figure 2, an empirical scheme was developed. Our current scheme is outlined in Table 1.

The rock score provides the basic measure of intact rock quality. Primarily based on sonic velocity, adjustments are applied via the porosity score for high-porosity, poorly consolidated sandstones, and for high water content shales using the moisture score.

The cohesion score attempts to capture the shear strength of the bedding. In general, stronger rocks in Australian coalfields have stronger bedding, hence the sonic-velocity-based rating. High quartz sandstones are assumed to have rough or cemented bedding surfaces, whereas siltier and shalier materials are assumed to have smooth, planar, and weaker bedding surfaces. A plot of rock score plus the cohesion score compared to the mine results previously discussed is shown in Figure 3. There is a clear relationship between the geophysical and mine data.

Finally, the bedding score is based on typical values of bedding and fracture frequency used in other classification systems. Bedding and fracture frequency is the most difficult parameter to estimate from geophysical logging data. Acoustic scanner and dipmeter logs are often used for this, but their analysis requires relatively laborious interactive display and interpretation. Possibly, permeability data from full-waveform sonic data could also be used, but routine analysis methods for full-waveform sonic data of the type recorded in slimline exploration holes have still to be determined. Other approaches might involve microresistivity logs, sand/shale variations, and local engineering experience.

For the purposes of this study, insufficient log data was available to provide a definitive approach to estimating bedding frequency. Notwithstanding this, it can be seen from the combined rock score and cohesion score in Figure 3 that our geophysical rating scheme provides a basis for determining the variations in the properties of the mine roof.

EXAMPLE OF LOG ANALYSIS

Results from a drillhole in the Bowen Basin are shown in Figure 4. The natural gamma, caliper, density, sonic, and neutron porosity logs are as provided by the logging contractor. The remaining logs have been derived using the quantitative analysis techniques discussed in this paper. As expected, the porosity determined from the neutron log (in pink on track 3) is greater than that determined from the density log (in blue) because the neutron porosity is affected by water bound within clay minerals. For the computations of shaliness, the values determined from the natural gamma log (in blue on track 4) and a neutron-density log analysis (pink) are roughly similar apart from in the middle and bottom sections. This is presumably due to changes in the mineralogy as discussed previously.

In tracks 5, 6, and 7, the coal seams have been blocked out in black to show logs for just the clastic sections of the hole. (There is also a tuff band at about 137 m and some issues with caving near the seams, especially at 76 m.) The calculated velocities (in pink on track 5) were determined by substituting the density porosity (in blue on track 3) and the natural gamma shale (in pink on track 4) into equation (1). The effective pressure gradient was set to 0.1 bar per metre depth of burial. The calculated velocity closely follows the broader trends in the observed velocity as well as many of the local variations. We find that such agreement is generally achievable. If the calculated velocity does not agree with the observed, then there are likely to be errors in either the porosity or shale determinations.

Track 6 presents the porosity and shaliness in a form convenient for ready assessment and comparison against the rock rating shown in track 7. Major features include the sandier sections between 100 and 110 m and below 140 m, and a shalier section between. In track 7, the log in blue is the combined rock score and cohesion score without any consideration of fracture frequency and bedding. In pink is the *UCS* (in MPa) calculated using equation (2). It is coincidental that the absolute values of these two logs are similar, but it does facilitate a comparison of the two schemes. The same general trends and local variability is to be expected because both draw on the same sonic log data. However, the rock rating scheme also explicitly considers the porosity and shaliness and there are differences in the two logs when the porosity or the shaliness changes. This is particularly evident in the weaker units, e.g., between 118 m and 132 m where the shaliness and porosity is higher. It is with such weaker units that the geophysical strata rating should provide improved discrimination.

CONCLUSIONS

Qualitative geophysical log analysis has long been used in coal mine exploration but there is scope to significantly develop applications for quantitative log interpretation. Determinations of porosity and clay content can provide insights into the lithology and geotechnical properties of the rocks present. Calculating the clay content using different methods is useful because differences in values can be used to infer aspects of the mineralogy. Validation of the porosity and various clay determinations is possible by comparing observed velocities with velocities calculated from an empirical formula relating porosity, clay content, and effective pressure to P-wave velocity (Eberhart-Phillips et al., 1989).

An important application for quantitative geophysical log interpretation in coal mining lies in developing geotechnical rock mass classification schemes that allow the properties and behaviour of rocks under mining conditions to be estimated from borehole data. The benefits from the predictive aspects of such schemes could lead to improved mining practice. We have proposed one such geophysical strata rating scheme based on sonic velocity, porosity, and shale content. The system shows reasonable agreement with one mine's approach to geotechnical logging, and the more conventional approach of estimating *UCS* values from sonic logs. The scheme takes into account intact rock mass characteristics and bedding features. However, it needs to be refined by using data from a much larger range of situations, and means of incorporating fracture frequency and bedding scores are also required.

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石炭層の定量的物理検層解析に基づく岩石の力学物性評価

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要　旨： 物理検層は炭鉱調査プログラムの一部として一般的に実施されている。現在のところ、物理検層の主な用途は、炭層深さを決定し、石炭の品質、岩質および岩石強度を定性的に評価することにある。しかし、物理検層データの定量的解釈を行うことができれば、さらに詳しい情報を得ることができる。定量的解釈を助けるため、本論文では、オーストラリアのシドニー盆地とボウエン盆地の黒炭地帯で頻出する砕屑性堆積岩中の鉱物の検層レスポンスを例に挙げて議論する。その結果、検層レスポンスと鉱物分布に強い相関性があることを確認した。解釈の任意性は多種の物理検層を併用することによって減少させることができる。本論文では、また、計算走時と観測走時の比較により、内的整合性をチェックする方法も記述する。定量的解釈の重要な目的は岩石の地質工学的分類である。本論文は、物理検層から推定できる岩石の物性を考慮した砕屑岩の分類システムを提案する。

탄층에 대한 정량적 물리검층에 기초한 암반 평가 과정

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요　약： 물리검층은 석탄광 탐사에 일상적으로 적용된다. 현재 검층의 주요 적용 목적은 탄층의 심도 탐지와 탄질, 층서 및 암반강도의 정성적 추정이다. 그러나 만약 정량적 해석이 이루어진다면 더 많은 정보가 얻어질 수 있는데, 정량적 해석의 이해를 돕기 위해, 검층 반응을 Sydney Basin 과 Bowen Basin 의 호주산 검은 석탄(black coal) 광산지역에서 흔히 발견되는 쇄설퇴적암의 광물조성에 따라 논의하였으며, 검층 반응은 충분한 신뢰도로 광물조성에 대비될 수 있음을 알았다. 해석의 모호성은 만약 모든 종류의 검층자료가 있다면 더 잘 해결될 수 있을 것이다. 음파검층에서 측정된 속도와 계산값을 비교함으로써 일관성을 검토하는 방법 또한 서술하였다. 정량해석의 중요한 목적은 지질공학적 특성화이며, 이 논문에서는 물리검층으로부터 유추될 수 있는 물리적 성질을 고려한 쇄설암의 분류 시스템을 제안하였다.

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