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GEOTECHNICAL EVALUATION OF ROOF CONDITIONS AT CRINUM MINE BASED ON GEOPHYSICAL LOG INTERPRETATION

Peter Hatherly[1], Terry Medhurst[2], Genxi Ye[3], and Dan Payne[4]

ABSTRACT: At the underground coal operators conference held in 2008, Payne described the experiences of crinum mine in characterising the weak roof strata at the mine. To a large extent, primary and secondary roof support strategies are based on UCS values determined from sonic logs. Consideration is also made of lithological units that can be identified on natural gamma logs. At crinum, UCS values in the roof strata tend to fall in the range 3-30 MPa.

Through ACARP funded research, a new method for evaluating geotechnical conditions known as the Geophysical Strata Rating (GSR) has been developed. The GSR is based on the interpretation of sonic, density and natural gamma logs and is designed to provide a measure of strata properties on a linear scale similar to that used in the Coal Mine Roof Rating (CMRR). GSR values are largely based on sonic velocity measurements and some degree of similarity therefore exists with the UCS determinations at Crinum. A comparison between the conventional UCS results at Crinum Mine and the new GSR determinations is made. The basis for relationships between sonic velocity and UCS is also discussed. Compositional factors and the range of depths over which a relationship is applied are important. The GSR takes these factors into consideration and provides an alternative and robust approach to estimating rock properties.

INTRODUCTION

Payne (2008) describes the geotechnical experience of Crinum mine for the period 1997 to 2007 during which time 14 longwall panels were mined and 40 million tonnes of coal was extracted. In that paper, the use of sonic logs obtained from exploration boreholes to predict UCS values was described. It is based on an empirical correlation between sonic log measurements and UCS measurements on over 150 core samples. Sections and maps showing the variations in the estimated UCS are produced for the floor and roof of the working (Lilyvale) seam. Primary and secondary support decisions are made using these and they form an essential part of the mine's on-going strata management and hazard plans. Roof units with strengths less than 10 MPa represent the major roof control issue at Crinum.

Ward (2007) provides guidelines for the determination of the UCS from the geophysical logs. The main roof sequence consists of sandstones and siltstones and four main units (plus sub units) can be recognised on natural gamma logs. For each of these units, representative sonic transit times are scaled off the geophysical logs and converted to UCS. The roof sections are produced over a 12 m section along roadways and show the location of the stratigraphic units and their UCS values. Plan maps of average UCS are produced for immediate roof sections of 0.5 m and 2 m thicknesses. Crinum Mine has thus established an effective and successful method for the prediction and management of their strata conditions.

In a separate development, Medhurst and Hatherly (2005), Hatherly et al. (2007) and Hatherly et al. (2008) have introduced the Geophysical Strata Rating (GSR). The GSR is a means of empirically estimating the quality of rock masses. It is based mainly on sonic log data but unlike the usual approach of converting sonic logs to UCS through site-based relationship, the GSR is designed to work in all forms of clastic sedimentary rocks. It compensates for the variations in sonic velocity caused by factors such as changes in rock composition, changes in depth and the presence of bedding surfaces and fractures. Through this consideration of both the intact rock and the defects, the GSR has a

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geomechanical basis similar to the conventional rock mass rating schemes. The GSR rating is on a linear scale of up to 100 and can therefore be compared to the Coal Mine Roof Rating (CMRR).

One of the advantages of the GSR is the generality of the formulation. Another is the fact that it does not require manual assessment of geophysical logs. A computer based analysis is required but this process is not onerous and it provides useful geological information in its own right.

Current research into the GSR is directed towards (i) comparing the performance of the GSR with other geotechnical procedures, (ii) extending the rating to include coal, and (iii) providing a method for establishing 3D geotechnical models from borehole geophysical logs and seismic survey data (if available). Crinum Mine provides an ideal site for a comparison between GSR and a proven method involving UCS estimates. In order to provide a basis for the rationale behind the formulation of the GSR and the reasons for relationships between sonic velocity and UCS, some e fundamental issues concerning sonic velocity is discussed.

SONIC VELOCITY AND UCS

From the theory of elastic wave propagation, it is known that in homogeneous rocks, the velocity, V_p, of the P-wave that is measured by sonic logging is given by:

$$V_p = \sqrt{\frac{K + 4/3\mu}{\rho}} \quad (1)$$

Where K is the bulk modulus (incompressibility), μ is the shear modulus, and ρ is the density.

In reality, most rocks are not homogeneous on account of compositional variations and defects. Another factor in sedimentary rocks is the existence of anisotropy due to bedding - velocity depends on whether the measurements are taken across the beds or along them. The elastic parameters K and μ, and the density are therefore variable. In order to properly interpret sonic logs, it is necessary to understand the influence of the various causes of inhomogeneity and anisotropy.

In fresh igneous rocks where the porosity is low and the crystals have similar elastic properties, the main cause of inhomogeneities are fractures and joints. These have a major influence on the velocity. Barton (2006) refers to Sjøgren et al. (1979), who correlated fracture frequency and RQD with measurements of V_p from shallow seismic refraction surveys in Norwegian igneous and metamorphic rocks. This correlation is shown Figure 1. As is also reported by Barton, Deere et al. (1967) found a relationship between RQD and the square of the ratio of V_p measured in the field (which is affected by fractures) and V_p measured in the laboratory on intact samples.

In the case of sedimentary rocks compositional variations also affect the homogeneity. From petroleum exploration it is known that V_p is affected by composition, porosity and pressure. In these circumstances it is not possible to determine exact expressions for V_p, but laboratory studies have allowed development of empirical relationships. Equation 2 is an extremely useful expression obtained by Eberhart-Phillips et al. (1989), which includes terms for fractional porosity (φ), fractional shale content (V_{Shale}) and effective pressure, p_e (confining pressure minus the pore pressure).

$$V_p = 5.77 - 6.94\phi - 1.73\sqrt{V_{shale}} + 0.446\left(p_e - e^{-16.7 p_e}\right) \quad (2)$$

Velocity here is measured in km/s and the effective pressure is measured in kilobars.

When considering the sonic/UCS relationship, Equation 1, shows that there is a theoretical relationships between V_p and modulus provided inhomogeneities and anisotropy are not an issue. There is no such relationship between V_p and UCS. However, because it is generally observed that stiffer rocks with higher modulus are stronger and because velocity is related to modulus, empirical estimates of UCS can be made from V_p.

In the context of the use made of the empirical relationships between UCS and V_p in Australian coal mining, it can therefore be seen that sonic/UCS relationships need to be established for a selection of rock types where the compositional variations that affect the velocity also affect the modulus and the range of depths is limited. It would appear that this is the case at Crinum Mine because sonic logging has proved to be a very useful tool for estimating the UCS of key intervals surrounding the working seam.

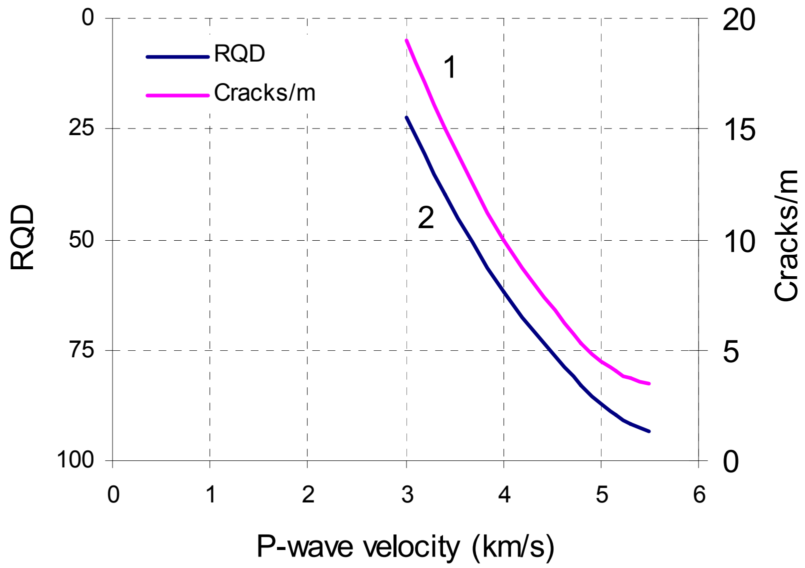

Figure 1 - Correlations of fracture frequency (1) and RQD (2) with P-wave velocity for mainly crystalline and metamorphic rocks from Scandinavia (redrawn from Sjøgren et al., 1979)

THE GEOPHYSICAL STRATA RATING

The full definition of the GSR is given in Hatherly et al (2008). In addition to sonic log values, it requires an interpretation of the geophysical logs to provide an assessment of the porosity and clay contents of the strata of interest. The log interpretation procedure follows the standard procedures described by Hatherly et al (2003). The velocity values are also corrected for the effects of depth.

For a GSR measurement, scores are provided for the following:

- rock strength (score between 0 and 55, depending on velocity)
- rock cohesion (score between 10 and 25, depending on velocity, clay content and porosity)
- porosity (score between 0 and -15, when clay content is less than 35% and depending on porosity)
- shaliness (score between 0 and -10, when clay content is greater than 65% and depending on porosity)
- presence of lithological (bed) boundaries (score between 0 and 10, with an inverse dependence on the down-hole variability of the clay measurements)
- presence of defects (score between 0 and 10, with an inverse dependence on the down-hole variability in the sum of the first 4 scores).

These terms have geomechanical significance. The first four can be added together to give an estimate of the quality of individual beds – the initial GSR (GSRi). The effects of the variability due to defects and changes in the bedding are captured by the last two terms. However, given the association between velocity and fracturing indicated in Figure 1, the score for the GSRi is also affected by defects in the form of fractures and fine bedding.

One aspect of the log interpretation procedure that is unconventional, concerns the use of Equation (2) to check the values of the porosity, clay content and velocity/depth gradient. To determine these parameters, the standard geophysical log interpretation procedures require estimation of the rock grain density, the natural gamma response in pure sandstones and the natural gamma response in pure clays. If these, so-called endpoints have been accurately estimated then substitution into Equation (2) of the calculated porosities and clay contents, together with an estimated effective pressure gradient should lead to a calculated velocity that matches that observed in the sonic log. If the calculated and observed velocities do not agree, different endpoints are needed.

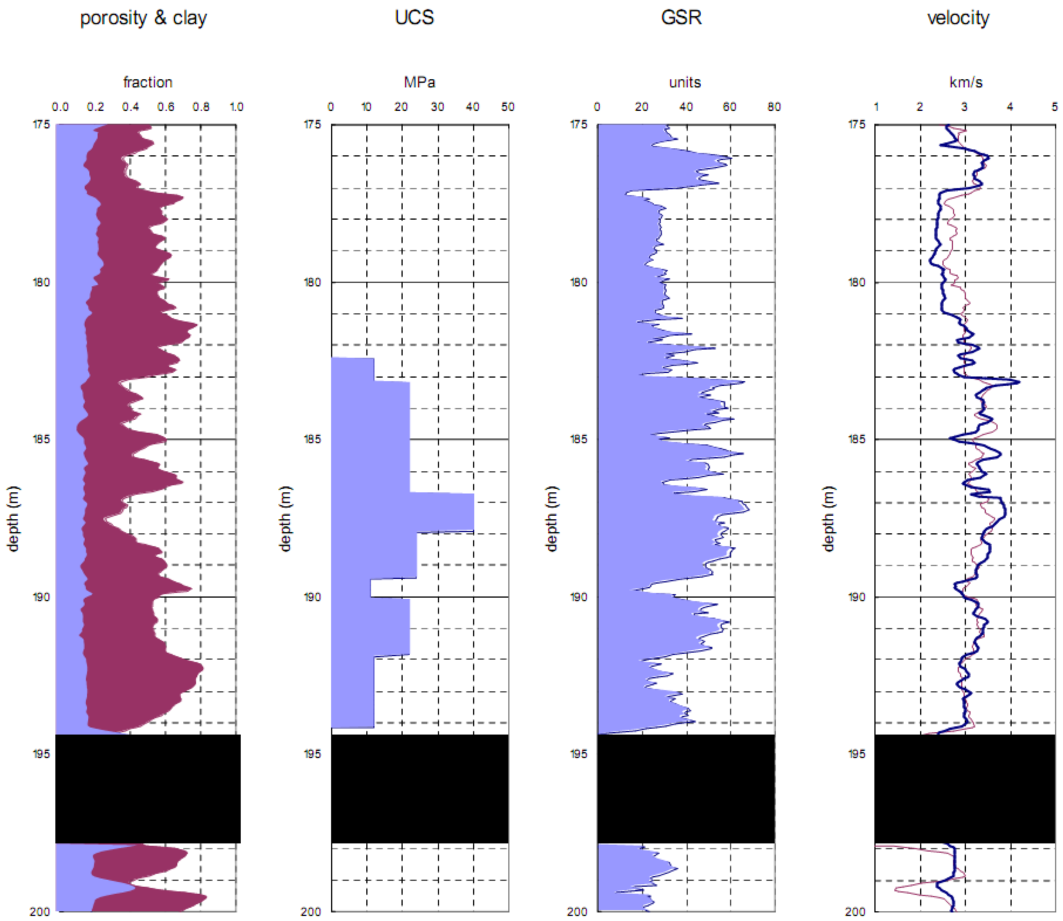

Figure 2 - Geophysical log analysis for Crinum borehole 05335. From left to right, (i) porosity (blue) and clay (maroon) values determined from density and natural gamma logs respectively, (ii) UCS values obtained using the conventional approach, (iii) GSR values and (iv) velocity logs – the thick blue line shows the measured sonic velocity. The thin maroon line is the velocity calculated using Equation 2. The higher clay values correspond to the more silty units.

If agreement is not possible, then it is possible that there are problems with the geophysical logs such as the density log being out of calibration, or the sonic log being inaccurate due to cycle skipping. Another possibility is that the geology is unusual. For example, the sandstones may have elevated natural gamma responses. If the problem is with the natural gamma logs or anomalous gamma radiation, then it may be possible to estimate the clay contents using alternative log combinations (neutron/density and resistivity/density). If the problem is with the density or sonic logs, then determination of the GSR will be unavoidably compromised. The process of calculating velocities can thus be seen as a QC step that can be used to improve the interpretation and to recognise problems in the data.

Equation (2) has another use because it allows the calculation of sonic velocities in situations where sonic logs are not available – e.g. above the standing water level in boreholes. Substitution of values for the porosity, clay content and effective pressure allows calculation of velocity and hence GSR. However caution is required because QC of the log interpretation is not possible.

As a final point, it is noted that there is a parallel between the GSR formulation and the scheme developed by Barton (2002, 2006) where it is proposed that Q-value can be estimated from seismic (sonic) velocity, after compensation for depth and porosity. The GSR is conceptually similar except that it includes the additional consideration of the effect of compositional variation as given by the clay content and required by Equation (2).

GSR ANALYSIS AT CRINUM

To illustrate the performance of the GSR, Figure 2 shows results for a single hole, 05335, over a 25 m section which embraces the Lilyvale seam. Also shown is the UCS analysis obtained by the standard Crinum procedure.

In Figure 2, the clay content has been determined from the natural gamma log and the porosity has been determined from the density log. Using these values and a suitable pressure gradient (15 MPa per km), velocities have been calculated and are shown to be in reasonable agreement with the observed sonic log. The sonic values, porosities and clay contents are therefore deemed to be suitable for calculating GSR values.

Comparing the UCS and clay results, it can be seen how the clay variations have been used to identify the lithological intervals over which the UCS values were determined. Note that in this case, the sonic velocity alone does not provide this same insight.

Examination of the GSR plot, however, conveys a clear sense of the locations of the strong and weak units within this section of the hole and their relationship to the lithologies indicated by the clay values. This illustrates that the GSR is able to respond to variations in rock type as well as the smaller discrete variations detected by the continuous sampling of the geophysical logs.

Figure 3 compares the GSR and the blocked UCS results for the takeoff roadways for longwalls 6 to 12. Lithological boundaries have been interpolated between holes and actual UCS values are given in the circled text. The colour scheme for the UCS section is lithologically based and aims to provide a guide to the geotechnical variability. In general, units coloured red, orange and yellow are weak and those coloured green and blue are strong.

In the case of the GSR results, the gridding and imaging program Surfer[1] has been used to interpolate the data between holes and a colour scheme has been chosen to convey the same meaning as in the UCS section. Red, orange and yellow correspond to low values of GSR. Green and blue are for the higher values. The similarity of the UCS and GSR sections is immediately obvious. Clearly, the GSR results over these longwall take-off roadways could have been used in the same way as the mine has utilised the UCS section.

DISCUSSION AND CONCLUSIONS

In this paper we have discussed the geological influences on seismic velocity and provided reasons for the empirical relationships between UCS and velocity. Strictly speaking, this only occurs if the elastic properties are related to strength and we therefore suggest that sonic/UCS relationships should only be applied in situations where the rock types present are not highly variable and there is no overlap in the UCS values of rocks with differing composition. The range of depths over which the relationship is applied should also be restricted.

The GSR has been designed to compensate for these limitations. The results from Crinum Mine illustrate the application of the GSR as a means of automatically assessing strata conditions. They show geotechnical variations that are similar and arguably an improvement to the UCS values that Crinum Mine has derived on the basis of sonic velocity and lithological considerations. The GSR has thus been demonstrated to be an alternative approach to obtaining geotechnical data.

Amongst the benefits of using the GSR are its objective nature and the automatic approach it provides for analysing geophysical borehole data. The method can be applied at any coal mine site and it eliminates the need to establish mine-based sonic/UCS relationships. Results can also be used in conjunction with other classification schemes. It is not difficult to include more data when they become available and to extend the range of interest if required.

[1] http://www.goldensoftware.com/products/surfer/surfer.shtml.

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REFERENCES

Barton, N., 2002. Some new Q-value correlations to assist in site characterisation and tunnel design. *Int. J. Rock. Mech. Min. Sci. 39*(2):185–216.

Barton, N., 2006. *Rock quality, seismic velocity, attenuation and anisotropy*. (Taylor & Francis: London and Netherlands).

Deere, D.U., Hendron, A.J., Patton, F.D. and Cording, E.J., 1967. Design of surface and near-surface construction. In: *Rock failure and breakage of rock* (ed. Fairhurst, C.) (Society of Mining Engineers of AIME, New York)

Eberhart-Phillips, D., Han, D.–H. and Zoback, M.D., 1989. Empirical relationships among seismic velocity, effective pressure, porosity and clay content in sandstone. *Geophysics*. *54*:82–89.

Hatherly, P., Sliwa, R. Turner, R. and Medhurst, T., 2003. Quantitative geophysical log interpretation for rock mass characterisation. *End of Grant Report*, ACARP Project C11037.

Hatherly, P.J., Medhurst, T. and MacGregor, S.M., 2007. A rock mass rating scheme for clastic sediments based on geophysical logs. In *Proceedings of the International Workshop on Rock Mass Classification in Underground Mining*. (US Department of Health and Human Services, National Institute for Occupational Safety and Health, IC 9498.)

Hatherly, P., Medhurst, T. and MacGregor, S., 2008. Geophysical Strata Rating. *End of Grant Report*, ACARP Project C15019.

Medhurst, T. and Hatherly, P., 2005. Geotechnical strata characterisation using geophysical borehole logs, in: *Proceedings of the 24th International Conference on Ground Control in Mining* (eds: Peng, S.S., Mark, C., Tadolini, S.C., Finfinger, G.L., Khair, A.W., Heasley, K.A.) pp. 179–186. (West Virginia University, Morgantown, WV).

Payne, D., 2008. Crinum Mine,15 longwalls in weak roof, what did we learn about supporting the ground? In *Proceedings Coal 2008. 8th Underground Coal Operators Conference*. (The Australasian Institute of Mining and Metallurgy: Melbourne).

Sjøgren, B., Øfsthus, A. and Sandberg, J., 1979. Seismic classification of rock mass qualities. *Geophysical Prospecting 48*:815–834.

Ward, B., 2007. Guidelines for the acquisition and processing of geotechnical data from exploration drilling. *Draft internal report, Crinum Mine*.

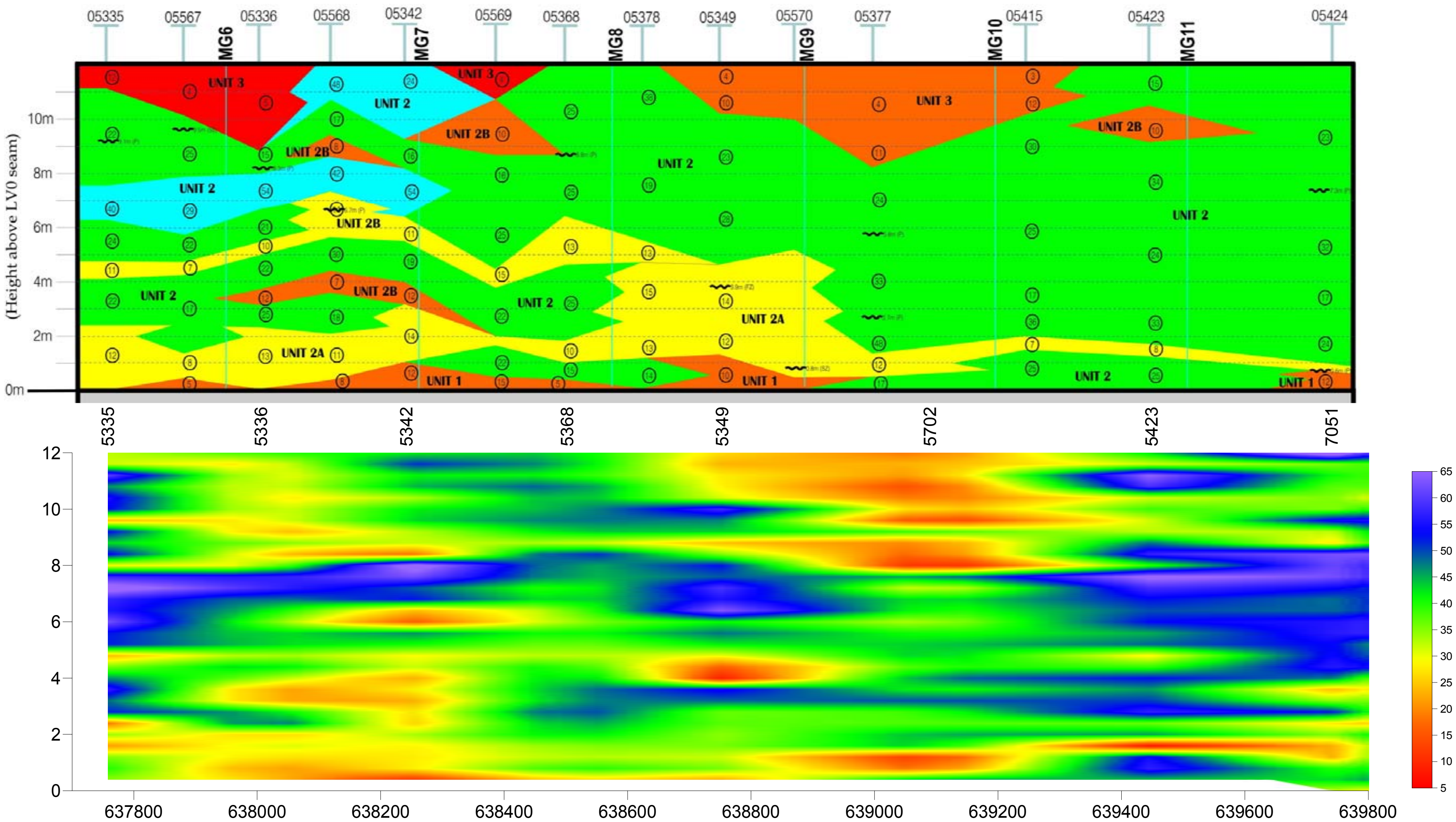

Figure 3 - Comparison of UCS (top) and GSR (bottom) values over a 12 m roof section across 2 km of longwall takeoff roads. The boreholes utilised for each are indicated at the top of each section.