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BACK ANALYSIS OF ROOF CLASSIFICATION AND ROOF SUPPORT SYSTEMS AT KESTREL NORTH

Sabine Stam¹, Glen Guy² and Nick Gordon³

ABSTRACT: Kestrel Mine is a Rio Tinto owned underground longwall operation that mines the German Creek coal seam in Queensland's Bowen Basin. Kestrel Mine can be separated into two parts North and South. Kestrel North has been in operation since 1990 (called Gordonstone at the time) while Kestrel South is a comparatively new mine having begun in-seam development in the first quarter of 2011. Over the recent history of Kestrel North several methodologies have been employed to characterise the roof and floor conditions, with a view to optimising the roof support design system and process.

The objective of this study was to review various roof classification systems against actual conditions encountered during extraction of coal from the 300 series longwall panels at Kestrel North. The aim was to determine what systems would work well in the deeper Kestrel South environment. The study also reviewed different UCS sonic relationships in use and derived a new correlation for the entire Kestrel area.

The back-analysis for the primary support was conducted by comparing the actual conditions and installed bolting patterns versus the rock mass conditions predicted using a variety of different roof classification systems. For secondary roof behaviour, extensometer data was used to review roof performance. The systems reviewed were the Roof Strength Index, sonic derived UCS and Roof Mass Rating.

The study confirmed that UCS is a good first predictor for the primary roof conditions, whereas the Roof Strength Index showed the best correlation with the secondary roof conditions. It is inferred that formation of a beam in the primary support horizon is more closely related to rock strength, compared to the secondary support horizon where the influence of the stress regime appears more critical.

INTRODUCTION

Currently Rio Tinto is constructing the Kestrel Mine Extension (KME or "Kestrel South"), located to the south and deeper than the current Kestrel operations. There is an opportunity to back analyse the various roof classification systems at Kestrel North in order to provide Kestrel South with the best system to predict upcoming roof conditions. This will allow optimisation of the roof support systems and improve the geotechnical input into the Life of Mine (LOM) model. The layout of Kestrel North and South areas is shown in Figure 1.

In addition a full review of the UCS vs. Sonic relationship has been carried out to ensure the most appropriate equation is used in the future.

BACKGROUND

Various roof classification systems are being or have been used at Kestrel.

There are many classification systems available in the underground coal mining industry, but since Kestrel is in an environment where, with the exception of bedding laminations there are not many significant rock mass discontinuities. This presents a comparatively geotechnically benign environment for which many of these systems have been determined not to be practical for Kestrel. This does not imply that those systems are incorrect or do not work.

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It is noted that rock mass classification systems are designed to assign a value to a rock mass competence. This is a relatively generic number and these systems do not always take external factors like mining direction and anisotropy into account. They should be used in conjunction with local experience and knowledge. They are not the sole input for engineering design.

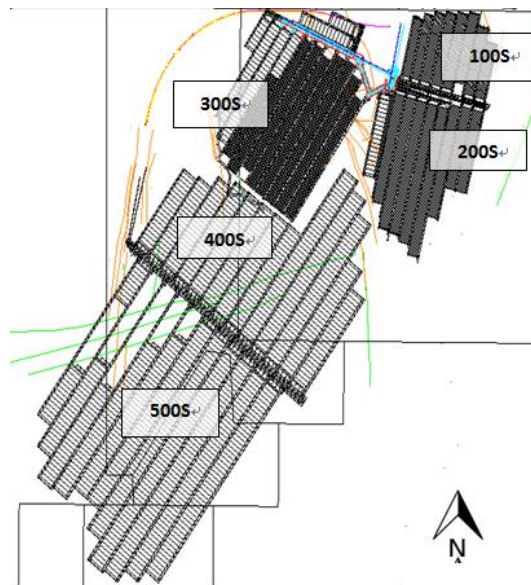


Figure 1 - Kestrel mine plan

ROCK MASS CLASSIFICATION SYSTEMS

There are three main systems that are currently used in various applications at Kestrel.

Roof mass rating

Strata Control Technology (SCT) has developed roof and floor class maps or Roof Mass Rating (SCT_RMR) that are being used by mine planning staff (SCT, 2007). It originates from work by Coffey Partners (1995) in the Gordonstone period and used by the site geotechnical engineer at the time Lawrence (1997) and continued at Kestrel by Gordon (2000) as shown in Figure 2. The roof and floor class maps produced by SCT are a refinement of this original work. The primary and secondary roof and floor ratings developed were based not only on strength, but also on the number of bedding laminations and the presence of weaker layers. It was identified that as well as strength, these weaker layers and bedding laminations play a role in roof behaviour. It should be noted that this rating system was first utilised in the 100 and 200 Series area of the mine where the range in depth of cover was relatively consistent, mostly between 210 m and 260 m.



Figure 2 - Comparison of roof ratings (Gordon, 2000)

Roof strength index

The Roof Strength Index (RSI) is a numerical value developed by Gordon and Tembo (2005) using sonic derived UCS values and depth of cover. This system has been used in a number of areas of the Kestrel North mine to explain roof conditions.

Sonic velocity derived UCS

The development hazard plans at Kestrel have historically used sonic derived UCS values per 100 m (per 'cut through') in 2 m roof intervals to predict roof conditions. Primary and Secondary support plans refer to this information as part of the design process. This system has been in place for all the 300 Series development roadways and operational staff are trained in using these hazard plans.

Other classification systems

Coal mine roof rating (CMRR)

CMRR (Mark and Molinda, 2003) assumes that the structural competence of coal mine roof is determined primarily by discontinuities that weaken the rock structure. CMRR is specifically designed for bedded coal measure rocks, concentrating on the bolted interval (and its ability to form a stable mine roof). This rating system is applicable to all coal mine roof types. Inputs into the CMRR calculations comprise the UCS of the intact rock, the spacing and persistence of discontinuities, the cohesion and roughness of discontinuities and the presence of groundwater and the moisture sensitivity of the rock.

Work undertaken at Kestrel by Colwell as part of the ACARP Rib Support project (Colwell, 2004) describes the CMRR at Kestrel as weak with a CMRR value varying between 30 and 45. Geotechnical staff at Kestrel at the time found that the CMRR derived did not give a better prediction of roof conditions compared to the sonic derived UCS values. It is not implied the CMRR does not work at Kestrel as a predictive tool but data required to determine the CMRR was not routinely collected. The system has not been used operationally at Kestrel North due to the reliance on the comparatively simpler sonic to UCS data.

Geophysical strata rating (GSR)

The GSR has been developed through various ACARP projects by Hatherly *et al.* (2004; 2009). It is based on geophysical logging where the p-wave velocity is the main input, but includes inputs from porosity, clay content and depth.

GSR has not been used operationally at Kestrel as a roof condition prediction tool, but data from Kestrel has been a significant input in the development of the system. As part of a test case four holes were used to create a GSR on the Kestrel lease. Given the sparse coverage it is not sufficient to compare this method with the other available methods.

SONIC TO UCS CONVERSION

In the Australian mining industry the exponential relationship between geophysically derived sonic velocity and inferred UCS values as proposed by McNally (1987) is widely accepted (Equation 1). It is also recognised that there is a specific relationship for every site.

$$UCS = 1000 * e^{\left(-0035 * \text{sonic velocity} \left(\text{in } \frac{\mu\text{S}}{\text{ft}}\right)\right)} \quad (1)$$

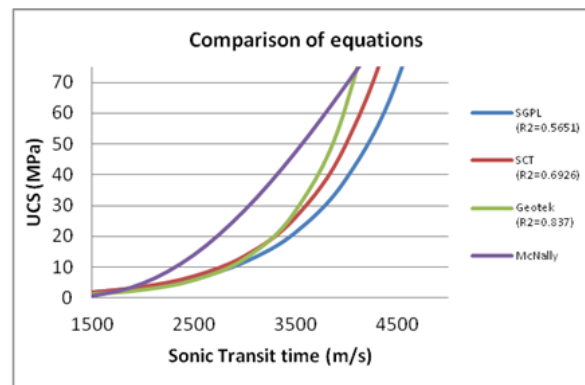
At Kestrel (and Kestrel South) three separate equations have been used on different occasions. This is predominantly due to data ownership and the different consultant involved in various projects. A summary of these correlations is presented in Table 1

In comparing the three equations in Figure 3 to the original McNally equation it can be seen that:

- in the lower strength range (0-15 MPa) the formulae correlate quite well;
- in the stronger ranges the Seedsman correlation is more conservative;
- The Geotek equation is the least conservative but probably reflects the variety of material tested;
- All three equations show a significant difference from the McNally formula;
- It is interesting that the Kestrel data sets are different, except for three holes that have been used by both SCT and SGPL.

Table 1- Summary of Kestrel specific UCS sonic correlations

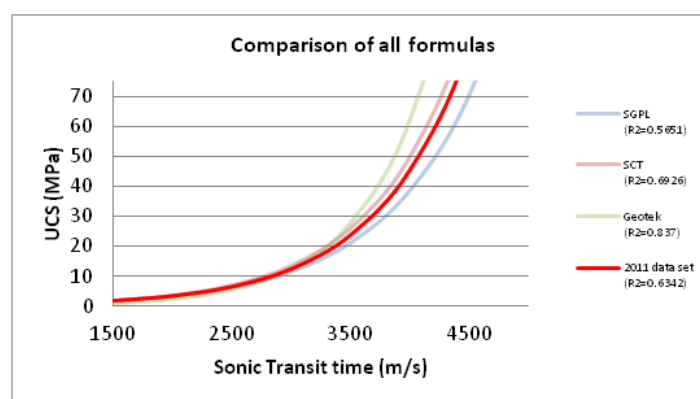
Author	Formula	Data Points			R ²	Comments
		North	South	Other		
SGPL	$UCS = 0.3196 * e^{(0.0012 * \text{sonic velocity} (\text{in } \frac{\text{m}}{\text{s}}))}$	131	52	32	0.57	32 unknown or Kestrel West data points rejected for 2010 set
SCT	$UCS = 0.2769 * e^{(0.0013 * \text{sonic velocity} (\text{in } \frac{\text{m}}{\text{s}}))}$	12	117	0	0.69	2 outliers rejected by both SCT and 2010 set
Geotek	$UCS = 0.104 * e^{(0.0016 * \text{sonic velocity} (\text{in } \frac{\text{m}}{\text{s}}))}$	131	0	0	0.84	All holes located in Kestrel South drift area

**Figure 3 - Comparison of various Kestrel Sonic vs UCS correlations**

After reviewing the full dataset available, it was decided to remove any Kestrel West holes, as well as the holes that were drilled only for the Kestrel South drifts (Geotek, 2007). The Kestrel West holes were removed as they are relatively far removed from any current mining areas. The drift holes were removed as they spatially skew the dataset and samples taken from these holes were not necessarily targeted at the German Creek seam, but at shallower areas.

After undertaking this and combining datasets over Kestrel North and South a new site specific equation was developed (Equation 2).

$$UCS = 0.2512 * e^{(0.0013 * \text{sonic velocity} (\text{in } \frac{\text{m}}{\text{s}}))} \quad (2)$$

**Figure 4 - Comparison of various older equations with new 2011 equation**

BACK ANALYSIS

The original back analysis of the three predictive systems was undertaken with the UCS equation that was used by the consultant responsible for the system at the time. With the new equation having been developed, the back analysis was then redone, to ensure its validity.

Primary support

The primary roof at Kestrel is classified as the 0-2 m of immediate roof above the German Creek Seam. Support is installed directly off the continuous miner and consists of either 6 or 8 x 2.1 m bolts per metre. When comparing the contour plots for the RSI, SCT_RMR and sonic derived UCS in Figures 5-7, it is clear that the SCT_RMR and UCS plots show a very similar overall pattern with competent and less competent areas highlighted. There are exceptions, for example RSI does not predict bad conditions in the western panels but it does show deterioration in the outbye areas of panels 303 to 308.

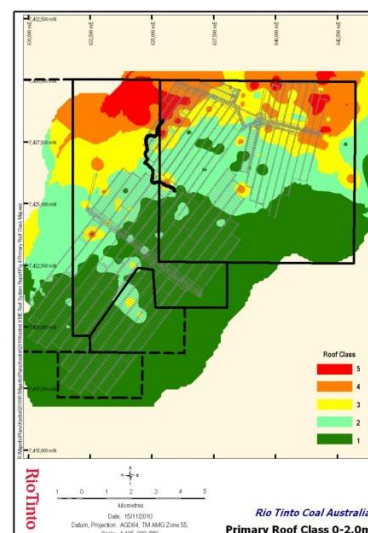
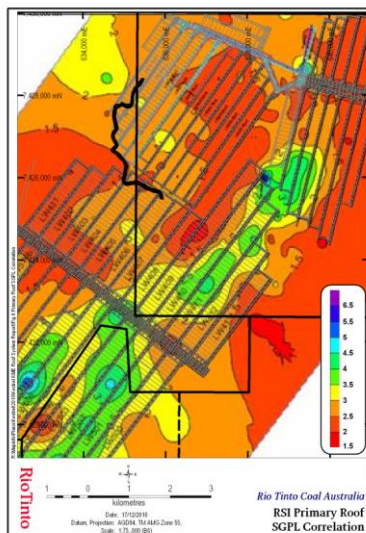
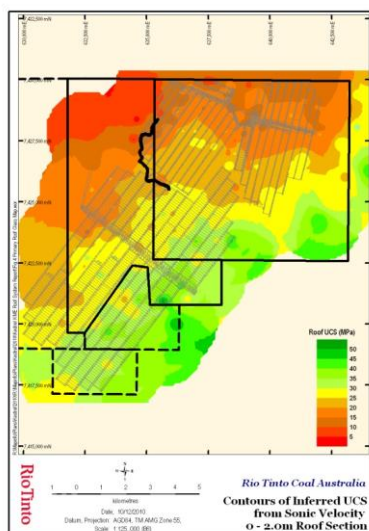


Figure 5 - Inferred UCS 0-2 m roof

Figure 6 - RSI 0-2 m roof

Figure 7 - SCT-RMR 0-2 m roof

When comparing the methods, the following support predictions have been used:

Table 2 - Support predictive systems suggested bolting density

No of Bolts/m	Support Predictive System		
	RMR	RSI	Sonic to UCS
4	N/A	>4.5	N/A
6	1	>3.5	>20 MPa
	2		
	3		
8	4	<3.5	<20 MPa
	5		

For comparison of the systems it was assumed that the bolting pattern that was installed is regarded as the “pattern required for adequate stability”. When a system would have predicted (based on Table 2) more bolts than actually installed it is called “oversupported”. When the same pattern is used as predicted it is called “equal” and when a lighter pattern than installed was predicted it is called “undersupported”.

For the oversupported cases it is almost impossible to tell if in the cases where 8 bolts per metre were installed, that in fact six bolts may have been sufficient, apart from roof stability observations. The corollary is true that where six bolts per metre have been predicted and either six or eight bolts were installed. In these areas of oversupport Kestrel crews typically notify the geotechnical engineer that the roof conditions are good, with low levels of roof movement.

On this basis it was expected that the UCS rating system would more accurately predict the required primary support pattern than the other two systems, as this is what the original support plan would have been based on. Adjustments to the support patterns would only be made in significantly worse conditions or if conditions were so good that after an extended period of installing eight bolts per metre the pattern would have been dropped back to six bolts.

Figure 8 presents the comparison of the three systems prediction vs. actual.

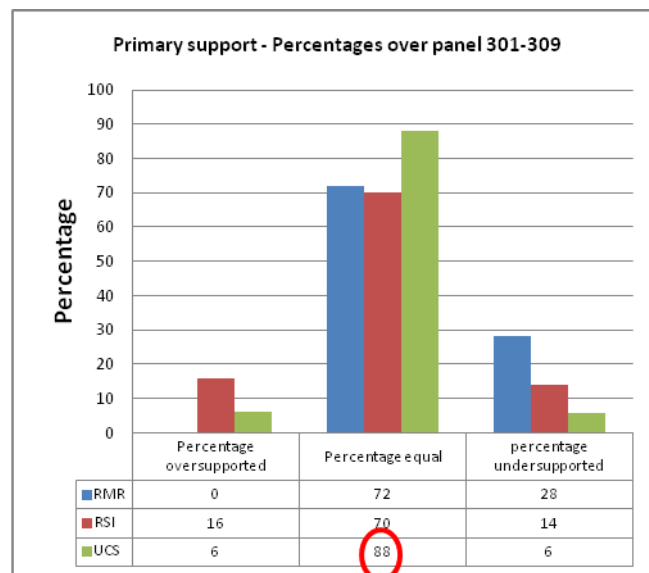


Figure 8 - Primary support back analysis overall results

Development rates have been reviewed to see if a correlation between the various systems and these rates exists. No correlation could be developed for the data analysed. This is in part due to the fact that development rates are influenced by many other factors including the experience of personnel, maintenance, the introduction of a monorail system, motivation, belt and machinery delays and of course strata control. To filter all these factors from the data would be a major project in itself.

It should be noted that with all the geological and geotechnical data interpretation, the accuracy is dependent on the spatial presence of the data. Borehole spacing at Kestrel varies from 400 m in general to less than 100 m in faulted areas. Lithology changes can occur fairly rapidly at Kestrel. It is noted that systems based on borehole data will not always be able to accurately predict these changes.

The overall outcome of the comparison is that in general the RSI would tend to oversupport in the deeper areas of the 300 series. The RMR system on the other hand would typically undersupport in the development of 303 to the 307 panel when this study was undertaken.

After development of the 2011 UCS correlation (Equation 2), the analysis was revised to compare the outcomes with the results using the equations developed previously.

As can be seen in Figure 9, the results do change slightly, but the overall result does not differ from the original data set. The most interesting finding is that all three systems do not improve significantly better with the new dataset. This is thought to be due to the fairly broad cut-off range for bolting pattern prediction.

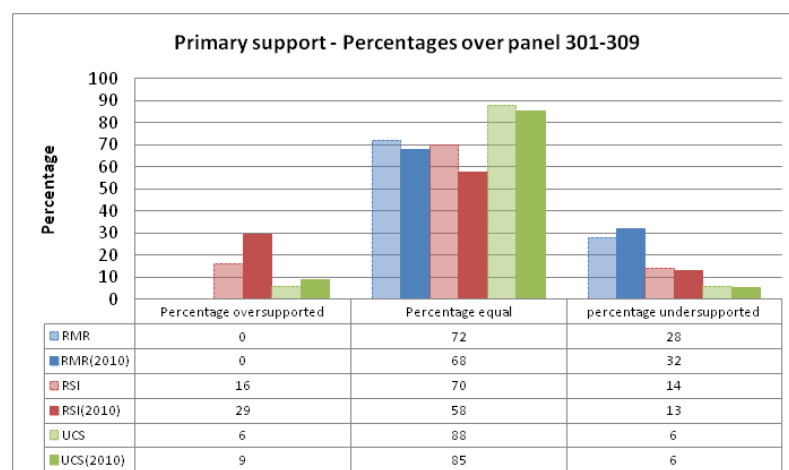


Figure 9 - Primary roof results old and revised data sets

SECONDARY SUPPORT

Methodology and assumptions

The secondary support methodology was not as straight forward as the primary support. No method is currently employed to give a direct prediction of what support to use.

As a rule Kestrel installs secondary support in all maingate areas. It is accepted that there will be areas in the mine where the secondary support density may not have needed to be as intense. From a risk perspective the current system maintains stable maingate conditions for longwall retreat. Only occasionally is the timing of tendon installation shortened due to adverse conditions on development.

Comparison of the various systems was therefore not a straightforward exercise especially as different support tendons have been installed.

Secondary support patterns at Kestrel have been designed by using a dead weight calculation. In this calculation the strength of the anchorage horizon is used to determine the anchorage length required to mobilise the full capacity of the tendon (Figure 10). The capacity of the support pattern is also calculated to ensure the dead weight can be supported.

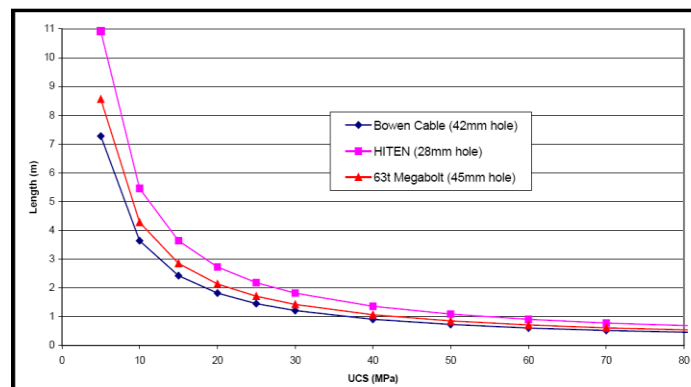


Figure 10 - Anchorage length outside roof softening zone versus UCS (SGPL, 2006)

Depth of cover is not regarded in this method rather the strength the roof strata in the anchorage horizon. As weaker ground has been encountered in the 300 Series area the cable support has gradually increased from 6 m HITENS installed in 28 mm holes to 8 m Megastrands in 42-45 mm holes to ensure sufficient anchorage is available.

In order to compare the available predictive methods an attempt was made to compare production rates with predicted conditions, but the production rates are influenced by many factors non-strata related and therefore this exercise was deemed unsuccessful.

At Kestrel, roof movement is monitored with the use of "Clockits". Clockits are installed at every intersection and every roadway with "unusual dimensions" such as drillers' niches and driveheads. The anchors are installed at 2 m and 6 m to differentiate between primary and upper roof movement. To be able to reconcile the secondary support, the upper movement from the Clockits has been assessed.

Significant movement (>30 mm) in the 2-6 m region suggests the secondary support is only just sufficient in that location or additional support is required. It should be noted that the accuracy of Clockits is dependent on the quality of installation. The frequency of reading them will also influence the quality of the data. At Kestrel the reading on development happens on a very regular basis (since Maingate 303), but tailgate and maingate readings are not as regular once longwall production has commenced.

The maximum value of upper movement of all Clockits around a cut through was plotted in Figure 11. Data from longwall installation roadways and takeoff areas were not taken into account for this analysis. The support in these areas is designed with a different timeframe, roadway span and loading in mind.

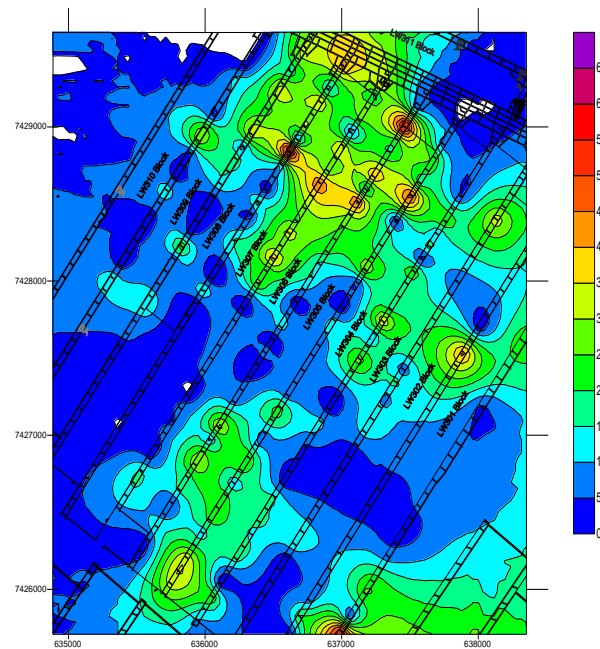


Figure 11 - Maximum upper movement in clockits in mm

Results

As discussed above, the prediction of secondary support patterns at Kestrel are not as clear and objective as the patterns for the primary roof horizon.

Maingate roadways

The secondary support comparison is based on the contour plots for the various systems, as well as the experiences of the author and other previous geotechnical engineers at Kestrel.

A few particular areas of interest are focussed on:

- Significant strata control issues occurred in the tailgate for LW303 around 16 cut through. Both RMR and RSI secondary roof plots indicate these as weaker areas. UCS does not recognise this as an area of particular concern.
- LW304 encountered serious issues regarding the maingate in 4-5ct where spiling and shot firing was required to continue producing. This area is most clearly identified in the RSI plot. In the UCS contour plot, this is an area where roof strength is reducing but it does not identify this exact area as weaker than the surrounding roadways. LW305 had serious issues in the tailgate in the same area.
- Again there were issues in the outbye areas with LW305 and 306. In both the tailgate and Maingate of these panels significant roof convergence was encountered requiring the installation of standing support. These areas are most clearly defined in the RSI plots, but UCS and RMR show some weaker areas as well (Figures 12-14).

All the previously discussed events were at relatively shallow depth of cover. Two significant incidents happened in the deeper areas.

- A roof fall occurred in a partly driven installation road where the roof was highly laminated. This fall was due to a lack of secondary support related to operational constraints. There was no incorrect design or unexpected weak conditions.
- A face fall occurred on LW305 at the start of the panel. This fall was entirely due to leg pressure issues on the longwall. This incident had no direct relation to strata conditions but was inferred to be an operational issue.

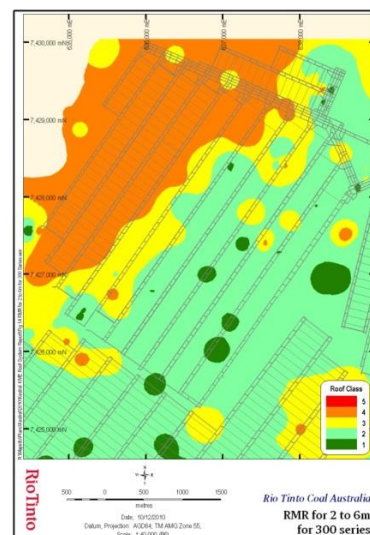
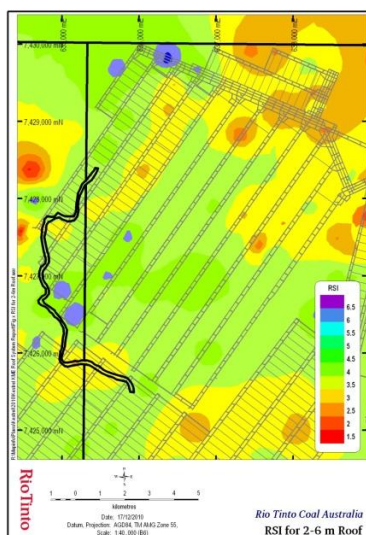
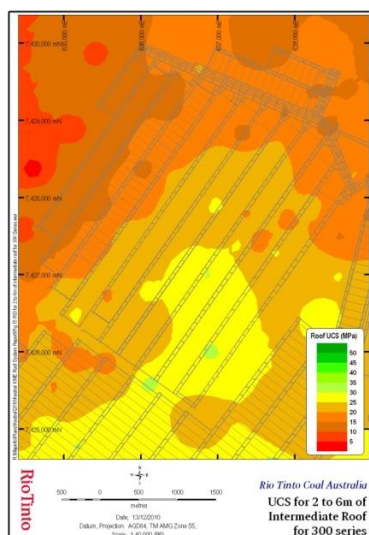


Figure 12 - Inferred UCS 2-6 m roof Figure 13 - RSI 2-6 m roof Figure 14 – SCT-RMR 2-6 m roof

When comparing the last three plots with the Clockit data presented in Figure 11, the RSI plot has the best match regarding the shape of the contours. The RSI system is also the only method that does not predict the worst conditions in the panels up dip from 307. Clockit data and current underground experience confirms this.

Installation roadways

All installation roads are at the deeper parts of the 300 series. A separate comparison has been undertaken on strata conditions for the different installation roads. It is important to keep in mind that drivage strategies and different support patterns for these roads have changed over time. Drivage direction (up dip or down dip) and lifespan of these roadways differ significantly.

Secondary roof conditions for 300 series face road Clockit measurements are compared in Table 3. The most obvious point of comparison is that roof movement in the 308 face road was minimal (<5 mm) with a similar support pattern to 307. When looking at the classification systems the RSI is the only one that predicts 308-310 as the best conditions, where both sonic derived UCS and RMR do not show a significant improvement.

Table 3 - Face road secondary roof comparison for 300 series

Face road (7.5m)	301 ⁽¹⁾	302	303	304	305	306	307	308	309	310
UCS 0-2m	25-30	25-30	25-30	20-24	20	15	20	18-24	14-20	8-12
UCS 2-6m	25-30	25-30	25-30	20-25	20-25	20-25	20-25	15-20	10-20	10-15
RSI	3.5-4	3.5-4	3.5-4	3.5-4	3.5-4	3.5-4	4-4.5	4.5-5	4	3.5-4
RMR	3	2	2	3	3	3	2	3	4	4
Total average movement before widening				19mm	37mm	20mm	20mm	<5mm	<10mm	<10mm
Total average movement after widening	47mm ⁽²⁾	60mm ⁽²⁾	19mm ⁽²⁾	26mm	44mm	62mm	60mm	<5mm	<10mm	<10mm

(1) 301 face road had a "bleeder road";

(2) Support material and patterns were different than later face roads.

Conclusion secondary support

When comparing all the data discussed above, the RSI appears to give the most accurate prediction for secondary roof conditions. This is different from the primary roof outcome, where sonic derived UCS was the best prediction tool for immediate roof conditions.

The variation could lie in the fact that both support systems serve different functions. The primary support is installed initially to create a beam in the immediate, laminated roof. Whereas secondary support is installed to ensure the weight of the area softened by longwall abutment stress is securely anchored to the overlying strata. The depth of cover will obviously be proportional to the magnitude of stress.

Based on the results of the assessment the question is raised can the Roof Strength Index be used in a similar way as the sonic derived UCS for primary roof, predicting longer term roof conditions and consequently specify secondary support patterns. It is noted that this will be investigated by Kestrel South geotechnical staff once coal driveage has commenced and there is confirmation of roof conditions at greater depths of cover.

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