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Geotechnical data from geophysical logs: stress, strength and joint patters in NSW and QLD coalfields

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GEOTECHNICAL DATA FROM GEOPHYSICAL LOGS: STRESS, STRENGTH AND JOINT PATTERNS IN NSW AND QLD COALFIELDS

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ABSTRACT: In order to appreciate the geotechnical regimes operating at any mine site a comprehensive database accessing all available borehole data is crucial. An extensive geotechnical database across the mine site area must be considered for mine planning and design. Some geotechnical parameters can be defined through the analysis of an appropriate suite of geophysical logs, including the acoustic scanner and sonic velocity logs and by incorporating a strict hybrid logging classification system. The acoustic scanner tool is becoming part of the standard geophysical logging suite used today in all stages of exploration drilling. Analysis of the acoustic scanner log can provide accurate and reliable geotechnical orientation data including joint and horizontal stress orientations. Rock strength data, including massive unit identification, can be calculated using the sonic velocity, gamma and neutron log responses. The study of patterns across three separate sites in eastern Australia shows lateral stress, strength and joint set variability brought about by variations in the geological domain. While vertical variability in rock strength downhole is often observed, the range of downhole variation in borehole breakout orientation and joint set patterns is usually minor.

INTRODUCTION

In the Australian coal sector, geophysical logs are routinely run in both cored and non-core holes. The primary use of the logs is the identification of coal seams, for which the density and gamma logs are particularly useful. The sonic velocity log is also used to provide estimates of the uniaxial compressive strength (UCS) of the rock and the coal. The acoustic scanner log has replaced the dipmeter and caliper logs in providing information on bedding dips and borehole breakout and has the additional capability to provide orientation information on the joints and other discontinuities that are able to be identified. ASIMS was established in the late 1990's to focus on the interpretation of geophysical logs for geotechnical purposes with the objective of providing reliable estimates of the orientation of horizontal stresses from borehole breakout, the strength of the rock and coal, massive unit identification and the orientation of the dominant joint sets. To date, in excess of 1500 holes have been examined by ASIMS from coalfields throughout the Hunter Valley, Central Queensland, Western Australia and the Southern Highlands, as well as several overseas deposits.

The details of the logging tools and responses have been extensively discussed by others (Weatherford, 2012, 2013). The acoustic scanner tool provides extremely valuable orientation data and there is a strong preference to run this tool in the vertical holes that are typical of coal exploration. The acoustic scanner needs a reasonably smooth borehole wall, and the borehole must be water-filled where the fluid medium is reasonably clear.

Images from the acoustic scanner tool can be used to identify discontinuities within the borehole. The acoustic scanner tool transmits ultrasonic pulses and records both the amplitude and travel time of the returned signal. The amplitude represents the properties of the rock, which is useful for identifying changes in lithology, texture or structure. The travel time represents the shape of the borehole when viewed transversely, and assists in recognising caving due to weaker lithologies, structures or stress.

Vertical holes, both non-core and cored, are of primary interest, where in most cases both the stone and coal intervals produce clear and reliable images. Generally data is interpreted without direct reference to the core, although in many cases core has been available. It is logistically more efficient and cost effective to analyse the scanner data independently as analysis occurs off site. However, a hybrid logging system (Gwynn, *et al.*, 2013) utilising additional data obtained from the core can facilitate a greater understanding of the discontinuities identified.

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Analysis of the sonic velocity log produces rock strength data that is extracted via a standard sonic velocity/strength regression relationship. Additionally, massive unit identification is possible utilising the sonic velocity, gamma and neutron logs. Massive overburden units are of particular interest for longwall and pillar extraction.

The full suite of geophysical logs is used to extract reliable stress, strength and joint orientation data. Incorporating the acoustic scanner tool within the suite of geophysical logs used in an exploration program is a relatively inexpensive method of obtaining accurate orientation data, important for both open cut and underground mine planning and development.

STRESS MEASUREMENTS

Borehole breakout versus drilling induced fractures

Stress conditions around a borehole may induce compressive or tensile failure in the rock or coal in the hole wall. For compressive failure, the drill fluids may dislodge the failed material and the resulting deformation is referred to as Borehole Breakout (BBO) and appears as two rounded zones 180^o apart. It has a distinct elongated or lemon shaped appearance in cross section. If tensile stresses develop, it may be possible to observe Drilling Induced Fractures (DIF). For BBO, the major principal stress is normal to the plane defined by the axis of the lemon, while for DIF the major principal stress direction is parallel to the axis of the fractures (Figure 1). Zoback *et al.* (2003) suggest they can be readily differentiated, where DIF appears as an open crack and BBO as a zone. BBO is accepted as a very good indicator of the direction of the major principal horizontal stress.

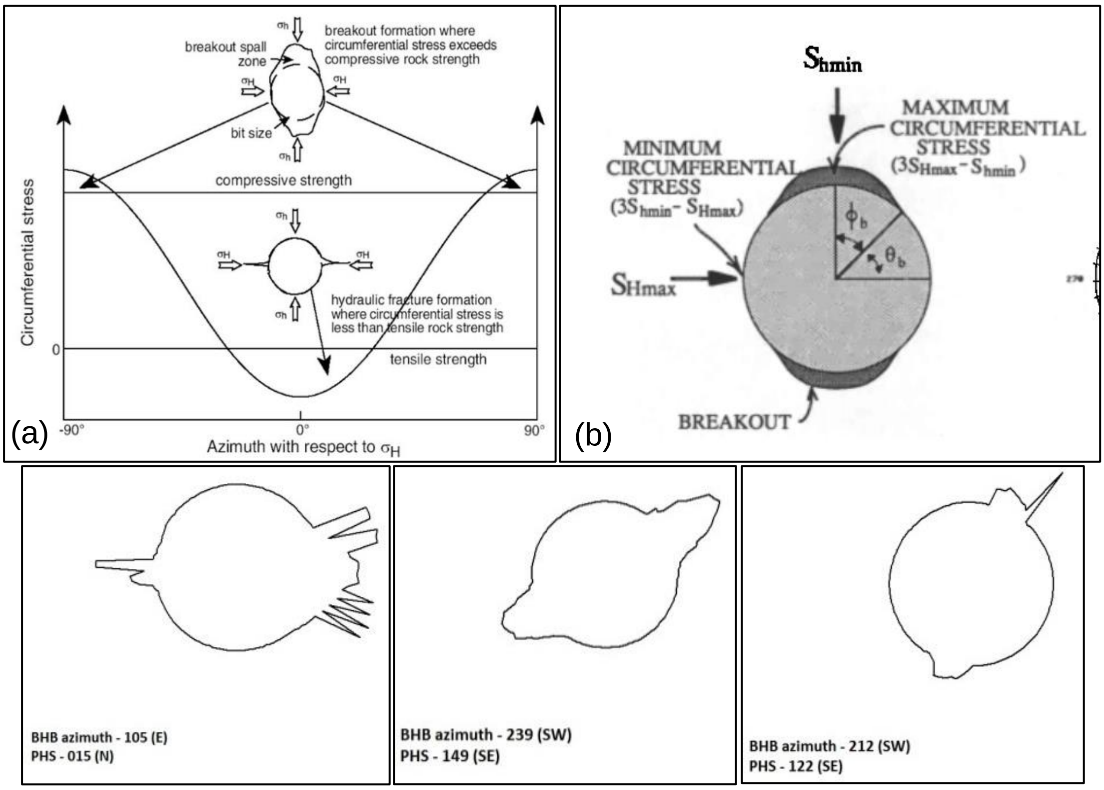

Figure 1 - Borehole Breakout and Drilling Induced Fractures ((a) Tingay, *et al.*, 2008; (b) Barton *et al.*, 1998) and examples from NSW and QLD coalfields

Determining stress magnitudes from BBO has been discussed extensively in the oil sector (Zoback, *et al.*, 2003). The elastic stress redistribution about a hole leads to compressive and shear stresses that can exceed the rock strength. The magnitude of the shear stresses is a function of the stress magnitudes and also the difference between the major and minor horizontal principal stresses. The lemon shape is not reproduced in either elastic or plastic analysis and Zoback *et al.* (2003) suggests that the depth is the result of erosion of failed rock by the drilling fluids. Zoback *et al.* (2003) further suggests that the width of the breakout is the appropriate parameter to use in a simple elastic analysis and defines the angle of breakout initiation (θb, Figure 1b). Ignoring temperature effects and assuming the vertical stress is a principal stress, the major principal horizontal stress (σ_{hmax}) can be estimated as:

$$\sigma_{hmax} = [(UCS + H*0.0098) - \sigma_{hmin}(1+2 \cos 2\theta b] / (1 - 2 \cos 2\theta b)$$

UCS = uniaxial compressive strength, H = depth, θb = angle from the major principal horizontal stress to start of breakout, σ_{hmin} = minor principal horizontal stress.

It is noted that this model does not include consideration of brittle behaviour (Martin, *et al.*, 1999). It can be seen that independent estimates of the UCS and σ_{hmin} are needed if the major horizontal stress is to be estimated. To demonstrate the sensitivities, if the angle of breakout initiation is 55^0 in 50 MPa rock at 400m depth, the inferred major principal horizontal stress is 24 MPa if the minor horizontal stress is assumed to be 12.5 MPa or 22.7 MPa if the minor horizontal stress is assumed to be 15 MPa. More significantly, if the UCS is 40 MPa, the major principal horizontal stresses are 18.3 MPa and 17.8 MPa respectively. A 25% change in the assumed strength gives a 25% change in the stress magnitude and a 25% change in the assumed minor stress gives a 6% change in stress magnitude.

Borehole breakout in Australian coal mines

To demonstrate patterns, sites have been selected in the Southern, Hunter, and Bowen Basin coalfields. Client confidentiality prevents revealing the locations. In some cases the depth and/or orientation data has been transformed to further disguise the sites. The purpose is to discuss the extent of variation at a site, and not to discuss absolute directions. One direction is reported for each depth recorded, being the orientation of a line drawn to the maximum extent of the identified breakout. In some cases the lemon shape is difficult to detect due to other damage to the borehole (Figure 1) possibly associated with additional breakout along joints or small faults.

Variation within a borehole

The World Stress Map (WSM) project (Tingay, *et al.*, 2008) suggests the highest quality breakout data has a standard deviation of no more than 12^0. In Figure 2 and Table 1 it can be seen that the stress direction is generally consistent down the hole for the Hunter and Bowen Basin examples with a standard deviation of 12^0 in the Hunter hole and 15^0 in the Bowen Basin hole. This suggests that the horizontal stress direction in these two holes is well defined.

Table 1 - Orientation data from a single hole and a number of holes in three Australian coalfields

	Hunter	Southern	Bowen Basin
	Single hole		
Number of readings	62	24	9
Direction	133^0	143^0	30^0
Standard deviation	12^0	37^0	15^0
WSM quality ranking	A : within +/-12^0	D: questionable	B: within +/-20^0
	All holes		
Number of holes	19	31	21
Number of readings	350	248	93
Average	136^o	119^o	38^o
Standard deviation	28^o	45^o	41^o
WSM quality ranking	D: questionable	E: not reliable	E: not reliable

Areal variation of stress direction

When all the orientation data are combined from all holes in a project/lease area (Table 1, Figure 3), the average direction for the Hunter and Bowen Basin cases remains very similar although the standard deviation is higher. For the Southern Coalfield example, the variation within the borehole extends across the project area. In both of the NSW sites, the strike of the major joint set was the same as the direction of the major principal horizontal stress. In the Bowen Basin site, the strike of the major joint set was perpendicular to the direction of the major principal horizontal stress.

No relationship was found between the onset of breakout, the sonic derived UCS (see later) and the estimated vertical stress. It was concluded that the accuracy of the sonic derived UCS and the variation in the ratio of the major to minor principal horizontal stress for the Australian coalfields (Figure 4) masks any patterns. ASIMS does not provide estimates of the horizontal stress magnitudes.

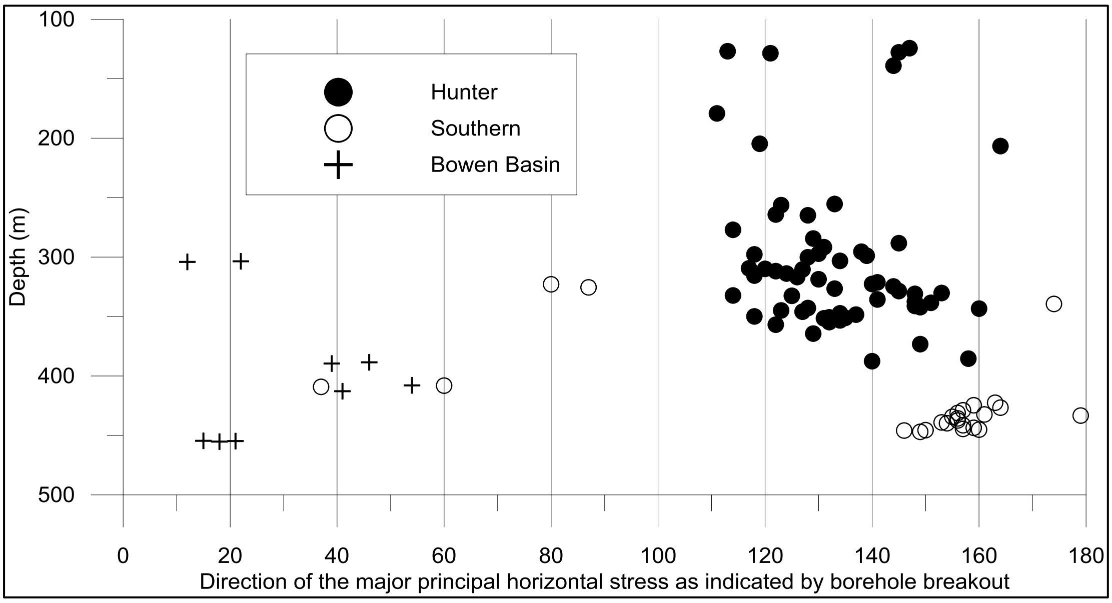

Figure 2 - Variation of direction of the major principal horizontal stress in selected boreholes in three coalfields

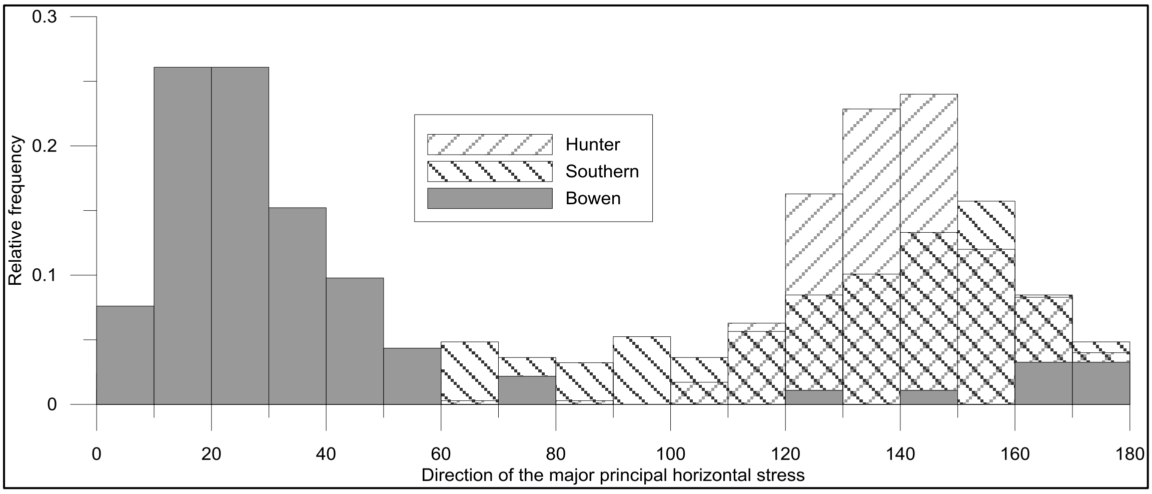

Figure 3 - Areal variation in the direction of the major principal horizontal stress

No DIF has been seen in logs from Australian coalfields. Tensile conditions only generate if the ratio of the major to minor horizontal stresses is greater than 3.33 which is not shown in the Australian data in the WSM (Figure 4). The controversial stress field proposed for coal (Seedsman, 2004) does not produce DIF in a horizontal plane, but could produce BBO in a very low strength coal.

DISCONTINUITIES

Acoustic scanner image

It is important to emphasise that the acoustic images are differences in false colour in digital images. There needs to be a significant amount of judgement in interpreting the digital image in terms of their geological and particularly their geotechnical significance. Geotechnically, the interest is in discontinuities defined as features in a rock mass with zero or negligible tensile strength. This translates to bedding partings (not textures) and joints/cleats that are not healed or cemented.

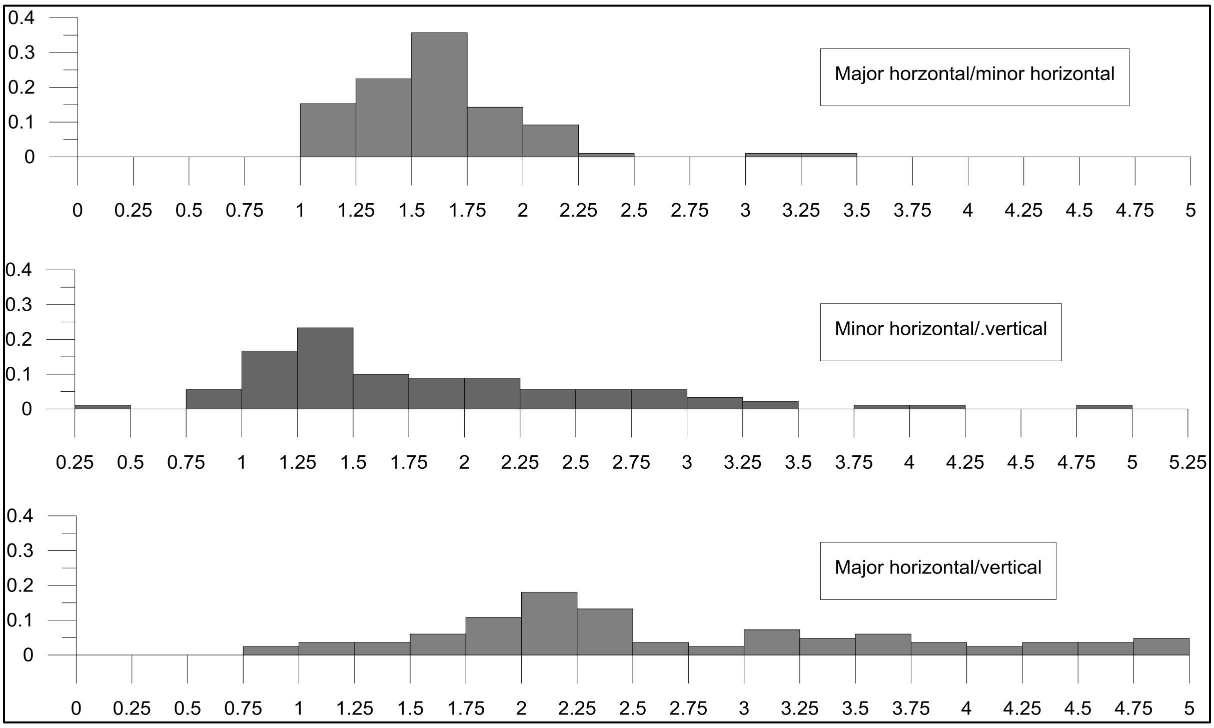

Figure 1 - Summary of horizontal to vertical stress ratios for NSW and QLD Coalfields (extracted from World Stress Map, 2008)

Without core, it is necessary to use all the geophysical logs to determine changes in rock properties and lithology, and to identify possible discontinuities in the scanner image. Density is useful for determining stone/coal interfaces and gamma can be used to identify clay units.

There should be an emphasis on picking quality data, where the focus is on identifying small, meaningful data sets from features that fit a strict classification system. By adhering to this system, between one and four major joint set directions can usually be identified within each borehole, using 20 or more features. The most frequent number of joint sets identified is two. Occasionally, these occur as conjugate sets.

Bedding is identified along coal/stone boundaries, such as the top and base of a coal seam or the claystone bands within a seam. Reliable bedding orientations can be identified along these prominent boundaries. Other bedding partings may have textural interest but they are not of geotechnical significance.

Joints and other structures, such as faults, are distinguished by looking at contrast either side of the trace, smoothness and continuity of the trace, and caving in the travel time image.

Coaly bands and siderite can be determined by the colour of the scanner image and the density log.

Another aspect of acoustic scanning that warrants highlighting is the advantage over oriented core. Most oriented core boreholes require angled holes so that the bottom of the hole can be identified by a system relying on gravity. Orientation data collected via this method tends to produce a much larger database, where small insignificant discontinuities are difficult to screen from the larger defects so that meaningful data sets are difficult to obtain (Fowler, 2013).

In Australia most of the coal seams of interest dip at less than 10^0 to 15^0. With the joints dominantly being normal to bedding there is a bias against intersection of joints in vertical holes. Fortunately the observation that joint spacing in slightly deformed sedimentary rocks tends to be equal to the spacing of the dominant bedding (Price and Cosgrove, 1990) appears to lessen the impact of the orientation bias. Generally, a joint can be identified within the scanner image on average every 10 m to 20 m. Appling the Terzaghi (1965) correction to a 15m spacing and a 5^0 dip this apparent spacing implies a joint spacing of 1.3m, which is a reasonable value for typical bedding spacing within an Australian coal deposit.

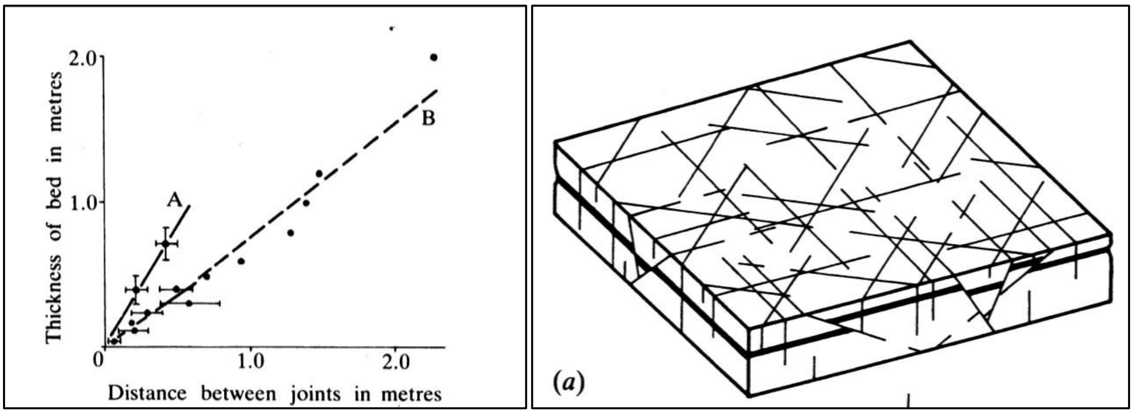

Figure 5 - Joint models in slightly deformed sedimentary formations (after Price and Cosgrove, 1990)

Hybrid logging versus traditional logging

The acoustic scanner image is analysed by experienced geologists who have an understanding of the geotechnical implications of the quality and type of discontinuities picked. The quality of data interpreted is further enhanced where additional detailed geological data collected from the core has been made available. This is known as a hybrid logging system (Gwynn, *et al.*, 2013).

When available, detailed examination of lithology logs, geotechnical logs and core photographs provide further clarity to the discontinuities identified in the scanner image.

For example, a significant horizontal defect such as a fault identified in the geotechnical and lithological logs can be correlated against the scanner image and assigned an accurate orientation. Orientations can be easily obtained for horizontal features in the scanner image. However displacement or truncation of bedding, both indicators of faulting, may not always be readily visible to the examining geologist. In this case without the availability of the additional core data this feature may not be classified as a fault. The hybrid logging system further enhances the identification process such that significant discontinuities are not misinterpreted.

Joints in Australian coal measures

Price and Cosgrove (1990) define four joint sets over large areas of weakly deformed horizontal sedimentary deposits, two strongly developed, two weakly developed (Figure 5). On borehole to borehole basis, very good data can be obtained, with generally two major joint sets with no rotation down the hole (Figure 6). But over the whole deposit, there is more variation (Figure 7) possibly reflecting the presence of the other sets in the Price and Cosgrove model.

STRENGTH AND MASSIVENESS

Estimating compressive strength

For Australian coalfields, it is preferable to use a standard sonic velocity/strength regression line, and one originally developed by BMA and ANGLO for Queensland's Moranbah and German Creek Coal Measures which has a particular focus on the lower strength rocks, has been chosen and is depicted by:

UCS (MPa) = $5785\ e^{(-17374/vel)}$, where vel = sonic velocity (m/s)

The method is unlikely to give an accuracy of better than +/-10 MPa at all strength ranges.

This equation has wide applicability and can be used in the Hunter and Southern coalfields of the Sydney Basin. In fact, it is recommended that rock strength testing should be conducted to justify the continued use of this standard rather than to develop a site specific relationship. If developing a site specific line a few points of advice are offered. Firstly the trend lines available in Excel are not adequate to fit over the full range of data. There is a need to assess the engineering application – for roof support design better accuracy at the low strength range is required, for excavatability better accuracy over the high strength range is preferred.

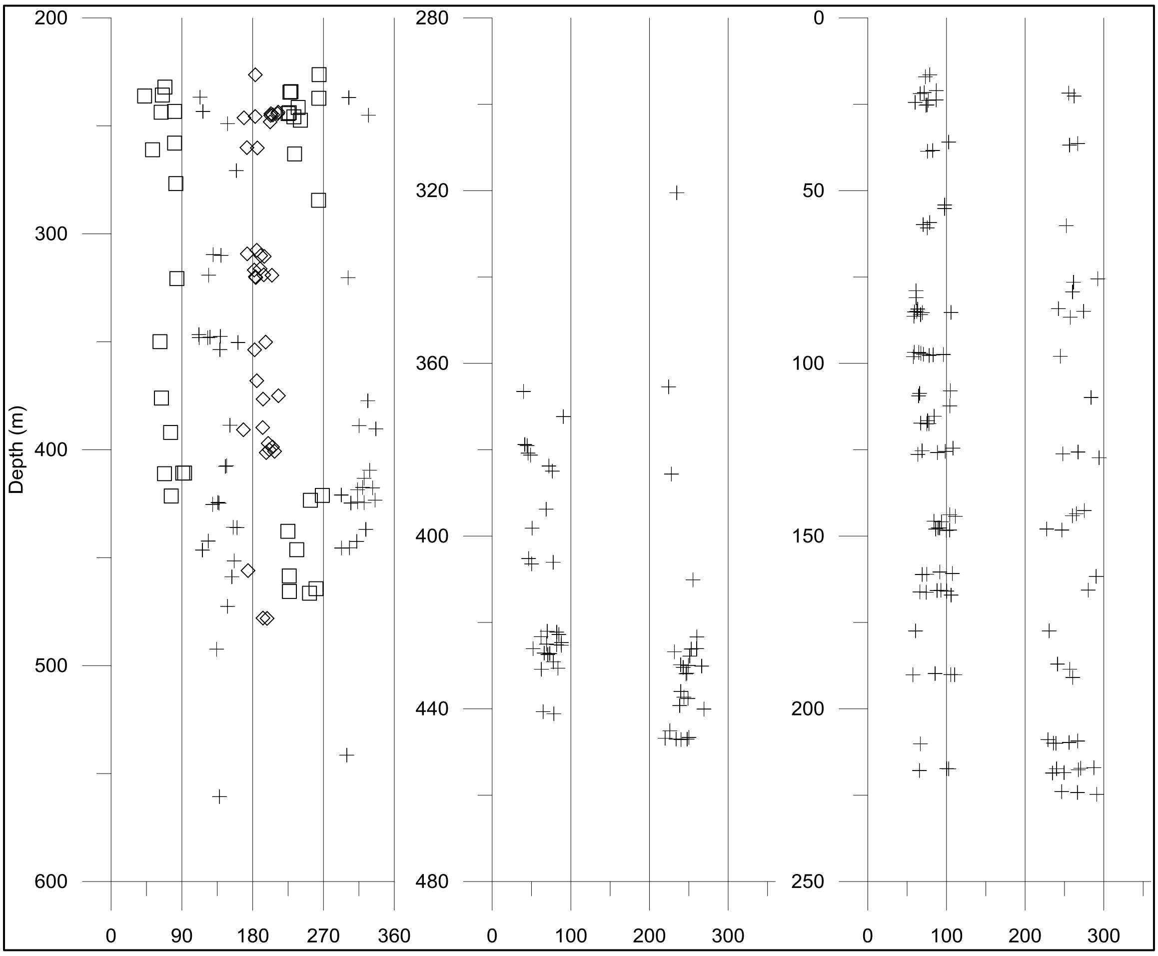

Figure 6 - Typical orientations on a hole by hole basis

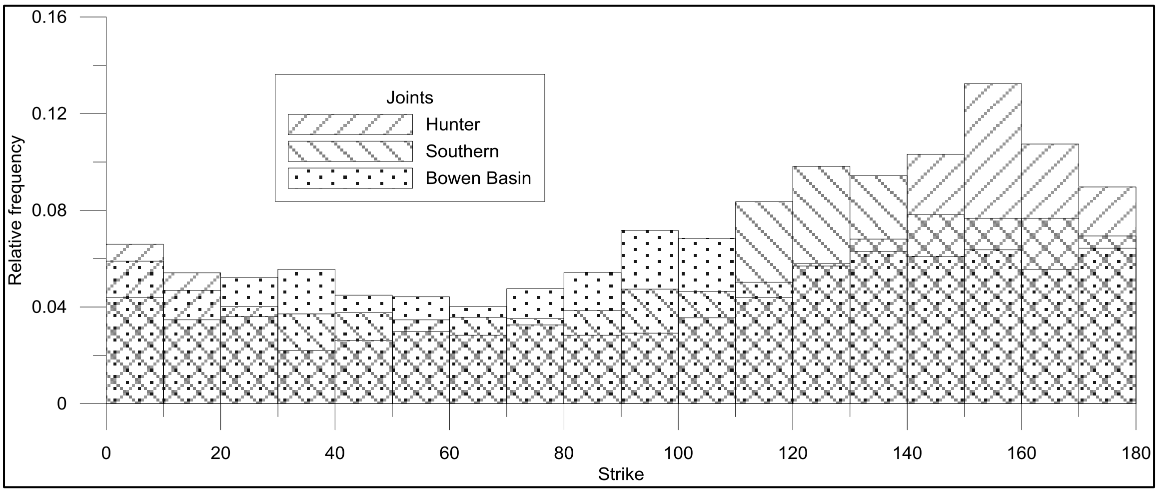

Figure 7 - Compilation of joint orientation over a large area

The data in Figure 8 is provided as a case study on some of the dangers in a site specific line (note that data has been randomised to some extent to maintain confidentiality). In this case study, a small database of high quality testing results had been established which had no low strength rocks. This site specific relationship was used to extrapolate in the lower velocity/strength range. It was apparent that the inferred strengths were much higher than those from the standard line so more testing was conducted. The larger database resulted in a relationship much closer to the standard. There were potentially very large errors introduced into the engineering design by extrapolating the site specific line for roof support and floor strength purposes (where the concern is with low strength strata).

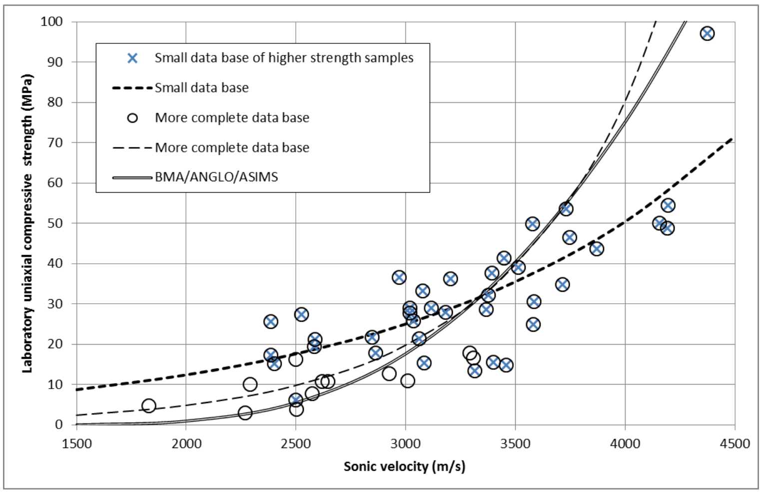

Figure 8 - Modified data from a case study on the perils of developing a site specific sonic velocity/strength equation

Identifying potential massive units

Of interest for longwall and pillar extraction is the possibility of massive overburden units which can be distant from the target seams and so are often not cored. The presence of massive units may be identified from a uniform sonic velocity (suggesting no change in lithology), or a high energy sandstone/conglomerate unit separated by laterally persistent thinly bedded units. A combination of sonic velocity, natural gamma, and neutron logs can be used to provide an initial estimate of such ground conditions.

For the sonic trace, there are key thresholds in signal noise that can be empirically related to massive units previously identified in core. Coal slivers (for example remnants of trees/branches in a coarse grained sandstone channel deposit) can disrupt the sonic velocity although they do not represent a laterally continuous surface that could disrupt a spanning unit. Also noted, finely interbedded units can produce a consistent sonic trace if the lithological variability is at a scale much less than the spacing of the source and detector in the sonic tool. Fortunately the gamma log can identify this possibility and can be used to dismiss sonic units if they have a high gamma response.

The gamma log can be used to identify laterally persistent bedded units. Here the assumption is made that the bedded units contain the clay mineral illite and that the massive units have negligible illite. In coal measure rocks, illite is one of the very few minerals that contain potassium so its presence can be identified by the gamma daughter product of the potassium to argon decay. As a geotechnical aside it is highlighted that a gamma log will not identify the presence of the other main clay minerals – kaolinite or montmorillinite. In some cases the neutron log is also used to assess massiveness and in this case the assumption is made that the massive unit has a low porosity and low clay content so that there is little hydrogen in the system. The neutron response in the thinly bedded units is assumed to be associated with hydration of any clay minerals.

CONCLUSIONS

Understanding the geotechnical domain of a deposit is crucial for both open cut and underground mine planning and design. It is clear that extensive and quality geotechnical data is necessary for this understanding to occur. The acoustic scanner log facilitates the collection of this valuable data from all open and vertical holes. It is imperative to use a rigorous classification system to extract only reliable and quality data. Evaluating the nature of the stress, strength and joint patterns within a deposit using the acoustic scanner is further enhanced when incorporating a hybrid logging system. Rock strength and massive unit identification gives extended detail to the geotechnical parameters operating within a mine site.

Identifying patterns on a borehole by borehole basis for an individual site will yield a good range of data but given the broad lateral variation between boreholes will not represent the mine site as a whole. Understanding the geotechnical parameters can only be achieved with a comprehensive database that encompasses the total area to be mined. This approach takes into account lateral variability caused by various geological dynamics.

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