ACOUSTIC SCANNER ANALYSIS OF BOREHOLE BREAKOUT TO DEFINE THE STRESS FIELD ACROSS MINE SITES IN THE SYDNEY AND BOWEN BASINS, AUSTRALIA

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ABSTRACT

The role of horizontal stress, its orientation and magnitude, in defining the behaviour of strata in underground coal mines has been well established. Poor panel layouts have led to gate end stress concentrations, roof falls and lost production.

The ability to define the horizontal stress regime over a mine site has historically been limited to point measurements, in part due to technology and cost. Recent advances in the application of geophysical tools, notably the acoustic scanner (borehole televiewer) have resulted in a new technique to conduct stress measurements. By quantifying the nature of borehole breakout and the mechanical properties of rocks in which they occur, this technique provides the ability to:

- obtain a vastly greater number of measurements, both at different depths and spatial distribution, than other techniques such as overcoring or hydraulic fracturing
- readily obtain depth versus stress relationships
- define geotechnical domains on the basis of stress direction and in-situ stress magnitude for mine planning purposes

This paper presents an overview of the technique and presents case histories in its application at a mine site in the Sydney Basin, Australia.

INTRODUCTION

Background – Horizontal Stress in Coal Mines

The role of horizontal stress in coal mine strata control is well established (Mark, 2000[1] & Siddall and Gale, 1992[2]). Rock at depth is subject to stress, with the principal components usually vertical and horizontal (refer Figure 1). Defining the orientation and magnitude of the horizontal stress is fundamental input into strata control design.

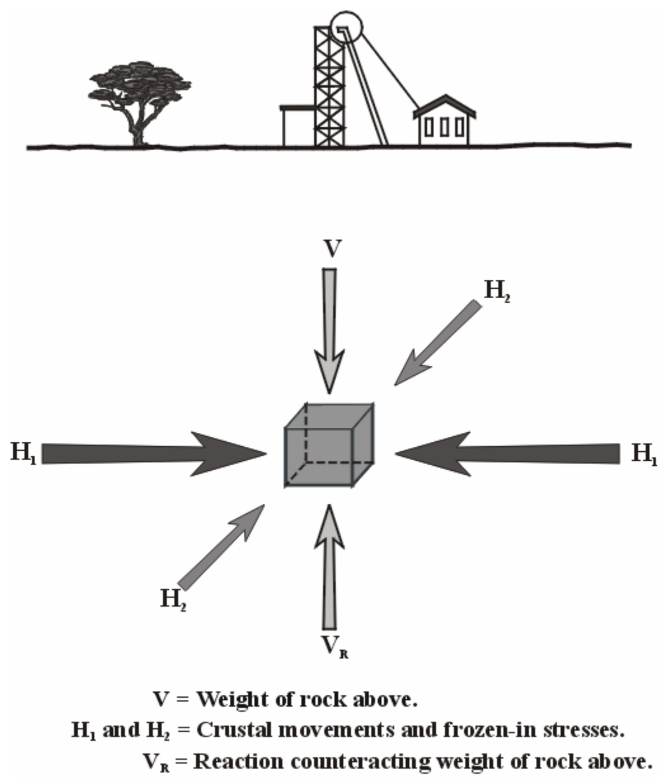


Figure 1 General state of stress acting on strata at depth.

The action of creating an underground opening results in a modification to the in situ stress field. The modified stress field is strongly influenced by the orientation of the roadway/longwall to the maximum horizontal stress direction. During longwall extraction, the concentration of the in situ stress about the gate ends can result in a mining induced stress up to 100% greater in magnitude, with potential for extreme conditions in gate ends.

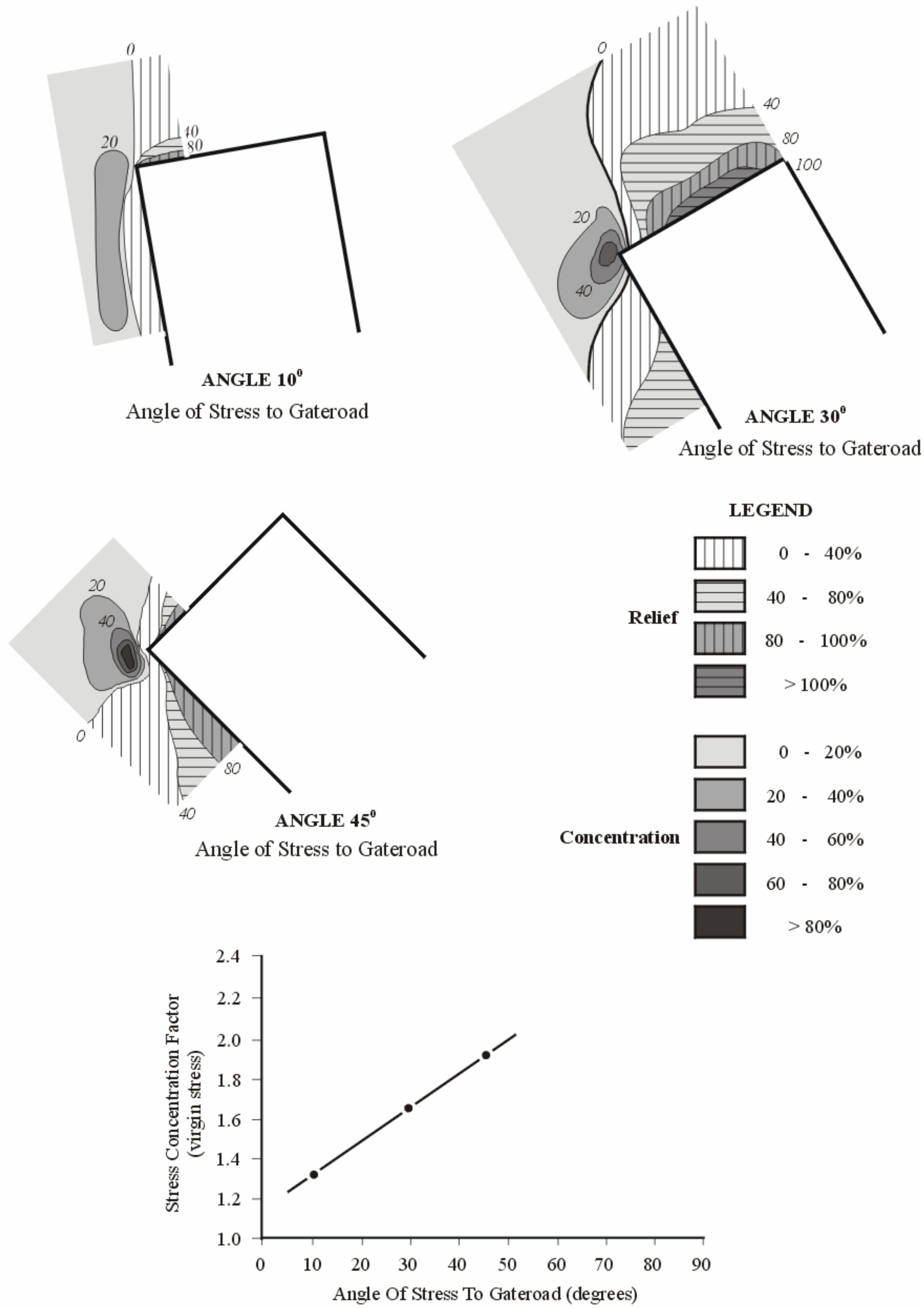


Figure 2 Measured horizontal stress concentrations occurring about a retreating longwall panel.

Figure 2 details the concept of horizontal stress concentration about the longwall face based on actual field measurement. The magnitude of the concentration increases with increasing angle to the horizontal stress, with the potential to double the magnitude of the pre mining horizontal stress.

By being able to accurately define the orientation of the horizontal stress, poor longwall layouts can be avoided.

Quantification of the horizontal stress magnitude can be used in the construction of a “stability curve” to assess roadway and reinforcement behaviour. Figure 3 details an example of a stability curve for a Bowen Basin (Queensland.) longwall mine. It quantifies how the roof behaves when subject to increasing horizontal stress. This allows the designer to avoid layouts that concentrate stresses to unacceptable levels, or where this is not possible, design and budget for appropriate reinforcement strategies.

The ability to accurately predict the orientation and magnitude of the horizontal stress has traditionally been restricted to point measurement and been cost prohibitive. By assessing borehole breakout with the acoustic scanner, a technique is available that allows stress domains to be identified, both across the mine and with increasing depth. The approach is outlined below.

Overview of Stress Measurement using the Acoustic Scanner

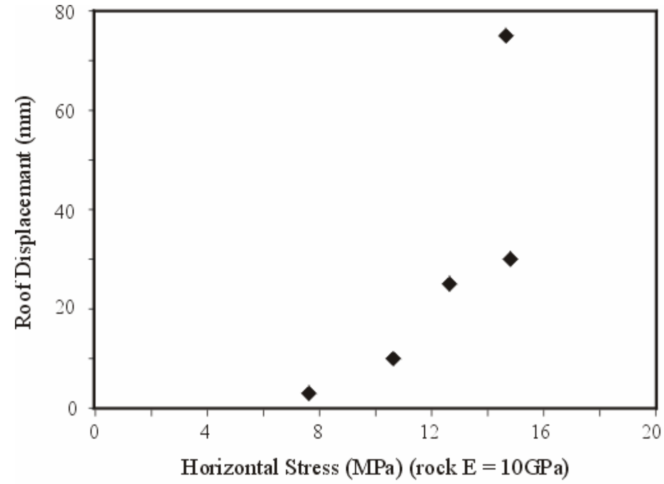
Stress measurement using an acoustic scanner utilises existing surface exploration equipment to image borehole shear fracturing that occurs naturally during the drilling process. The technique requires:

- a water filled surface exploration borehole (over 90mm diameter)
- wireline tools including acoustic scanner and sonic
- the presence of borehole shear fracturing in sections of the hole

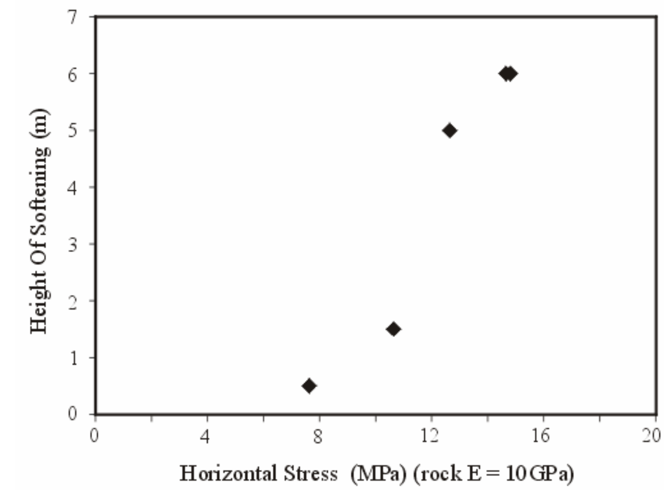
The acoustic scanner, or borehole televiewer, provides an oriented 3D image of the borehole wall. Depending upon the proprietary tool and software, the resulting visual image can resolve open joints less than 1mm and have an angular resolution of less than 1^0. The following description is taken from Elkington[3].

"The tool contains a rapidly rotating transducer which emits repeated short bursts of sound energy. Each burst produces a borehole wall reflection whose amplitude and travel time characteristics are measured by the tool and recorded at surface. As the tool traverses the hole, a continuous helical scan is made. This is transformed into a series of circumferential scan lines which are then rotated into a common frame of reference to remove the effects of tool orientation and borehole trajectory. Continuous false colour images are constructed by adding successive scan lines one above another on a display screen or plotter."

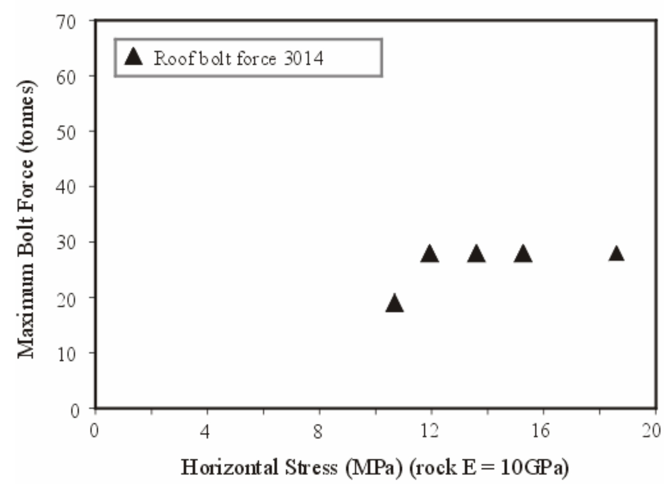
The false colour images produced can be analysed on appropriate software and are typically presented as oriented “unrolled” amplitude and travel time images.



a) Roof displacement versus horizontal stress.



b) Height of softening versus horizontal stress.



c) Rock bolt forces for various sections.

Figure 3 Example of roof stability pathway for roadway subject to increasing levels of horizontal stress.

Mechanism of Borehole Breakout

Borehole breakout is a term used to describe borehole collapse that results from failure of the borehole wall due to overstressing. The overstressing is a function of the strength properties of the strata and the magnitude of the two horizontal in situ stresses, pore pressure and borehole pressure (drilling mud weight).

Figure 4 details the general concept of borehole breakout (after Plumb[4]).

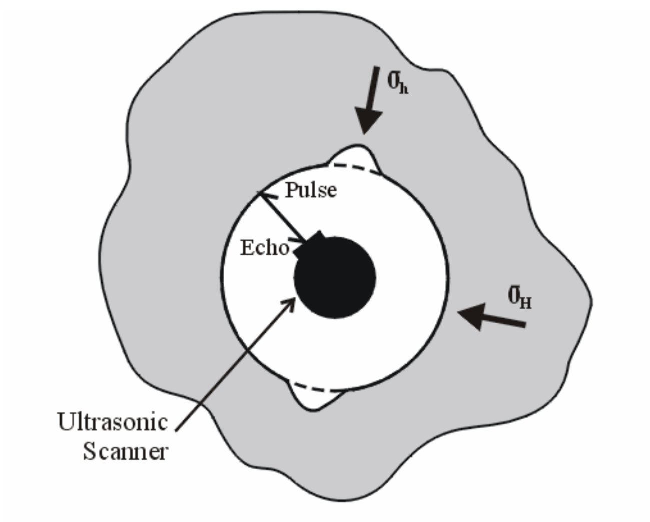


Figure 4 Borehole profile showing the ultrasonic scanner and the orientation of borehole elongation with respect to the far-field stresses σ_h and σ_H. (After R.A. Plumb, 1989).

In most cases, the horizontal stress field is not isotropic. One of the horizontal stress magnitudes is typically greater than the other, resulting in a major and minor principal horizontal stress (σ_H & σ_h), by definition orthogonal to each other. The stresses act to generate a tangential (hoop) stress about the borehole whereby the hoop stress has a maximum value in the direction of the minimum horizontal principal stress, and conversely a minimum value in the direction of the maximum horizontal stress.

Borehole breakout occurs where the hoop stress exceeds the strength of the strata, and is normally found to occur at 90^0 to the maximum horizontal stress. By mapping the location of the breakout, the orientation of the horizontal stress field can be determined.

The general state of stress about the borehole outlined in Figure 4 assumes the borehole to be drilled in the plane of one of the principal stresses and the remaining two principal stresses (σ_H & σ_h) to intersect the borehole at right angles. For vertical boreholes this assumption is typically met in the Bowen Basin and Sydney Basin where numerous direct measurements of the 3 dimensional stress field using overcoring have shown the stress field is typically aligned vertically and horizontally.

CONDUCTING THE MEASUREMENT

Defining the Orientation of the Stress Field

Attenuation of the acoustic scanner amplitude and travel time signals allow various features to be mapped within the borehole. These include identification of distinct lithologies, lithological boundaries and intersecting structural features such as jointing, cleat and faulting which can be oriented using sine wave picking on the unrolled images.

Similarly, areas of breakout and washout will exhibit distinct amplitude and travel time images and are easily distinguishable. Interpretation will depend upon the tool and processing software, however, breakouts are best identified as zones of attenuation/contrast on the amplitude image located 180^0 apart. As breakouts form in the direction of least horizontal principal stress, by inference the direction of maximum horizontal principal stress is at 90^0 to the breakout direction.

Physically quantifying breakout direction can depend upon the software, either through interactive screen output from the amplitude or travel time images or the use of virtual cross-sections (360^0 calipers generated by calibrating sonic travel time through the drilling fluid). This style of plot is most useful as it provides an additional independent assessment of breakout intensity based on the depth and shape of borehole failure.

It is worth noting that the borehole elongation, or ellipticity, used in breakout analysis described in this paper is a result of mechanical failure of the borehole. It is the experience of the author that borehole ellipticity due to elastic strain relief is:

a) of such a magnitude that it is not resolvable by current acoustic scanning tools.
b) of such a magnitude that it is lost amongst the "noise" of the drilling process including things such as drill string rotation and out of round, key-seat or bearing of the drill string against the side of the borehole and so on.

Constraining the Stress Magnitude

Quantifying the stress state about the borehole, and determining the far field state of stress, presents several problems. Firstly, assumptions regarding the stress state around the borehole must be made. The "Kirsch" solution is used to describe the general mechanical state of stress acting on the borehole (1):

$$\sigma_{\theta\theta} = 3\sigma_H - \sigma_h - P_w \qquad (1)$$

where $\sigma_{\theta\theta}$ = Hoop stress; σ_H = maximum principal horizontal stress; σ_h = minimum principal horizontal stress ; P_w = internal borehole pressure

The borehole wall will fail in shear where the hoop stress exceeds the in situ rock strength. Solving for the maximum horizontal stress provides (2):

$$\sigma_H = (\sigma_{\theta\theta} + \sigma_h + P_w) / 3 \qquad (2)$$

The borehole pressure is typically taken as the head of water at the investigation point (or mud weight where appropriate).

To constrain the magnitude of σ_H requires quantification of the:

- magnitude of the minor horizontal stress
- in situ strength of the rock (as distinct from the laboratory strength)

Where hydraulic fracture data is available, the minor horizontal stress can be directly determined. Otherwise, it must be related to a known variable. Typically, σ_h is expressed as a ratio of either the maximum horizontal stress or the vertical stress (overburden weight).

Determining the in situ strength of the strata is described in the following section.

Once an estimate of σ_H is made, it is normalised to a common rock stiffness to take account of the plane strain assumption of stiffer rocks having proportionally higher stress than softer rocks. This allows measurements from different stiffness rocks to be compared directly.

Defining Material Properties

Two strength parameters that must be defined for the breakout analysis are in situ rock strength and stiffness.

Determination of rock strength at the breakout location can be achieved through laboratory testing of recovered core or through correlation with geophysical tools. The latter approach is typically used as laboratory testing is both expensive and time consuming (as it requires additional preparation of core in the field to maintain moisture content). Additionally, acoustic scanners are often run in open holes (where the borehole wall quality allows), where no core is available for laboratory testing.

Most mine sites develop “synthetic” UCS profiles for mine design and planning purposes. A standard approach is to correlate Unconfined Compressive Strength (UCS) with sonic transit time.

McNally[5] (1987) reviewed the appropriateness of this technique (including a study of other geophysical relationships to rock strength) for various Queensland and NSW coal measure strata. The best results were obtained by assessing data on a site specific basis and deriving relationships for specific rock types. Typically, the regression curve takes the form of an exponential function.

As with UCS, rock stiffness (Young’s Modulus) can also be related to the sonic transit time (the compression and shear wave velocity within an elastic medium is a function of the shear and bulk modulus of the material and many logging companies provide curves showing dynamic values derived from the sonic tool).

CASE HISTORY VALIDATION – CENTRAL COAST, NSW

The application of borehole breakout as part of a greenfields site investigation for a new coal mine is outlined below. A comparison of hydraulic fracturing, four-arm caliper and core relaxation is worked through to examine the use and appropriateness of each technique.

Overview

Coal Operations Australia Limited (COAL) are currently conducting an extensive greenfields exploration program at Wyong, NSW, targeting the Wallarah, Great Northern and Fassifern Coal Seams.

As part of the mining feasibility study, SCT Operations have been involved with geotechnical characterisation of the mining leases and detailed design studies of longwall caving, roadway and pillar behaviour.

Validation Work Program

A broad program of investigation was implemented by COAL to determine the nature of the in situ stress regime using a range of techniques that included:

- borehole breakout using traditional wireline four-arm caliper
- core relaxation using laser micrometer
- hydraulic fracturing and step-rate tests
- borehole breakout using acoustic scanner analysis

The initial program involved running the respective techniques in the same hole (a total of three holes were completed for the validation) to assess the repeatability of the technique, type and quality of information gained and an overall confidence in the result.

Results

Three 96mm diamond core holes were drilled from surface to a depth of up to approximately 450m. The sequence consisted of a series of interbedded sandstones, siltstones and shales.

Acoustic Scanner

QUANTIFYING σ_H ORIENTATION

A total of 37 instances of borehole breakout were observed in the 3 boreholes – Borehole 1 (11), Borehole 2 (11), Borehole 3 (15). Figure 5 details an example of acoustic scanner output showing unrolled amplitude and travel time images for borehole Borehole 1 highlighting key features of breakout:

- attenuation of amplitude and travel time signal on both sides of the borehole oriented 180^0 apart
- significant and measurable increase in hole diameter noted on both sides of the borehole oriented 180^0 apart (as interpreted from the travel time and caliper images)
- hole size remaining similar to bit size in the other (orthogonal) direction
- breakout being confined (typically) to a stratigraphic unit

Figure 6 details a 360^0 caliper at the same location with a breakout direction of 116^0 (mag.), indicating a σ_H direction of 26^0 (mag.).

Generally, the breakout was well developed in all three boreholes, with noticeable spalling of the borehole wall up to 20-25mm into the formation, as shown in the borehole cross section in Figure 6, providing for a high confidence data set.

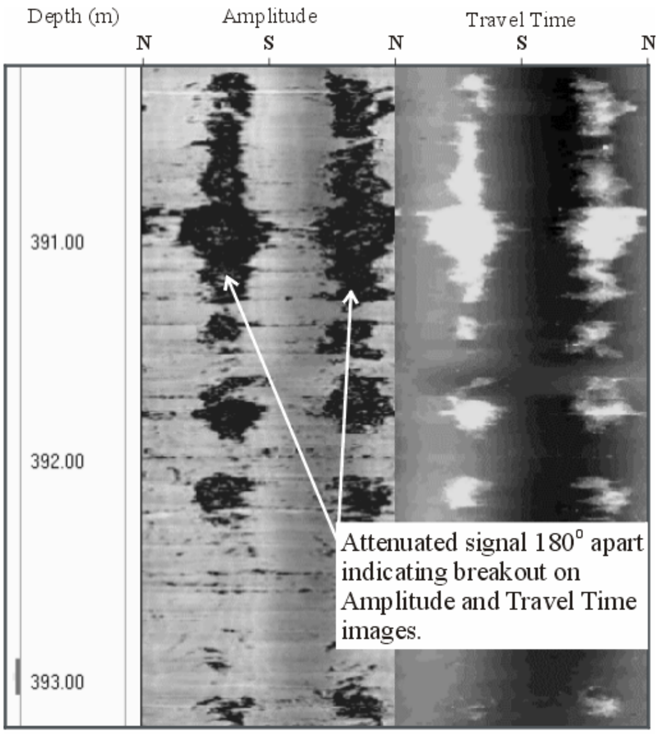


Figure 5 Output from acoustic scanner showing unrolled amplitude and travel time images highlighting breakout in seam for Borehole 1.

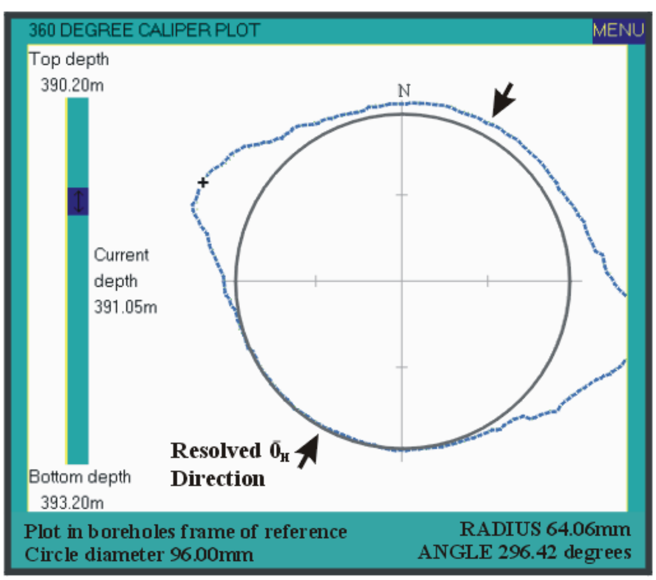


Figure 6 360° caliper plot from acoustic scanner showing mapped breakout profile at 391.05m for Borehole 1.

The relatively large number of breakout measurements allowed for statistical analysis of the orientation data. As each individual breakout typically spans an orientation range, the number of occurrences of a breakout within each 5 degree range was recorded. These were then represented as rose plots to determine the preferred orientation (most number of occurrences). Figure 7 details a example of a rose plot showing the inferred maximum principal horizontal stress directions for borehole Borehole 1.

Plotting the preferred σ_H orientation range for each borehole on a plan provides a good feel as to the variation in stress direction across the lease and provides confidence in the repeatability of the technique. Noticeable variation in stress direction across a lease may also indicate a changing stress regime. Plotting relevant information such as seam contours, geological structures, lithological boundaries and surface topography can assist in defining discrete geotechnical domains. Additionally, quantification of stress magnitudes (refer below) can be combined with the orientation data to better characterise domains.

To date at Wyong approximately 36 boreholes have been scanned, resulting in a total of 432 observations of borehole breakout. Figure 8 details a plan view highlighting the inferred σ_H direction for each borehole.

The data covers a large areal extent of up to 200 square kilometres, with the investigation area intersected by several geological features including local faulting and major regional features including the Macquarie Syncline.

Thus, a large areal extent of lease can begin to be divided into geotechnical domains for further analysis and planning with information that is not readily available through other means.

QUANTIFYING σ_H MAGNITUDE

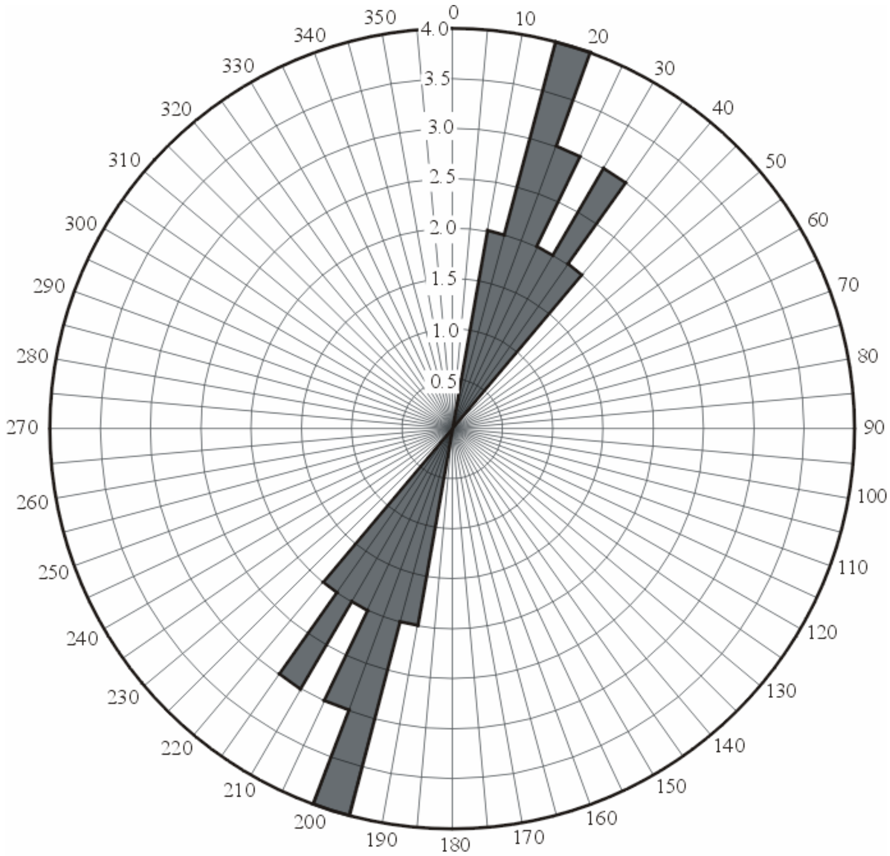
A program of laboratory testing was conducted on recovered core to determine the general relationship of laboratory UCS and E to sonic transit time.

Figures 9 and 10 detail the general relationship between sonic velocity and i) Young's Modulus and ii) laboratory UCS respectively. A good correlation was found for both parameters with a one standard deviation value of 8MPa for the UCS correlation and 2GPa for the Young's Modulus correlation.

Using the general Kirsch solution outlined in equation 2 with an appropriate field strength reduction factor and a likely range of σ_h ratios, the magnitude of the maximum horizontal principal stress can be constrained. This is shown in Figure 11 as a depth versus normalised maximum horizontal stress for an upper and lower bound σ_h range.

The data should tend to an upper limiting value, that is, for a given stress magnitude, rocks with a range of UCS will breakout. This is analogous to stronger rocks showing shallow incipient or faint breakout and weaker rocks showing extensive deep-seated breakout. In Figure 11, this is apparent as a scattering of data to the left of the data set approaching an upper limiting line that extends from approximately 15MPa at 150m to 19.5MPa at 450m.

From this it can also be seen that a general increase in horizontal stress exists with depth which is consistent with experience from other investigations.



Note: Number of breakout occurrences per 5 degree range.

Figure 7 Rose plot showing inferred σ_H orientations from breakout analysis for Borehole 1.

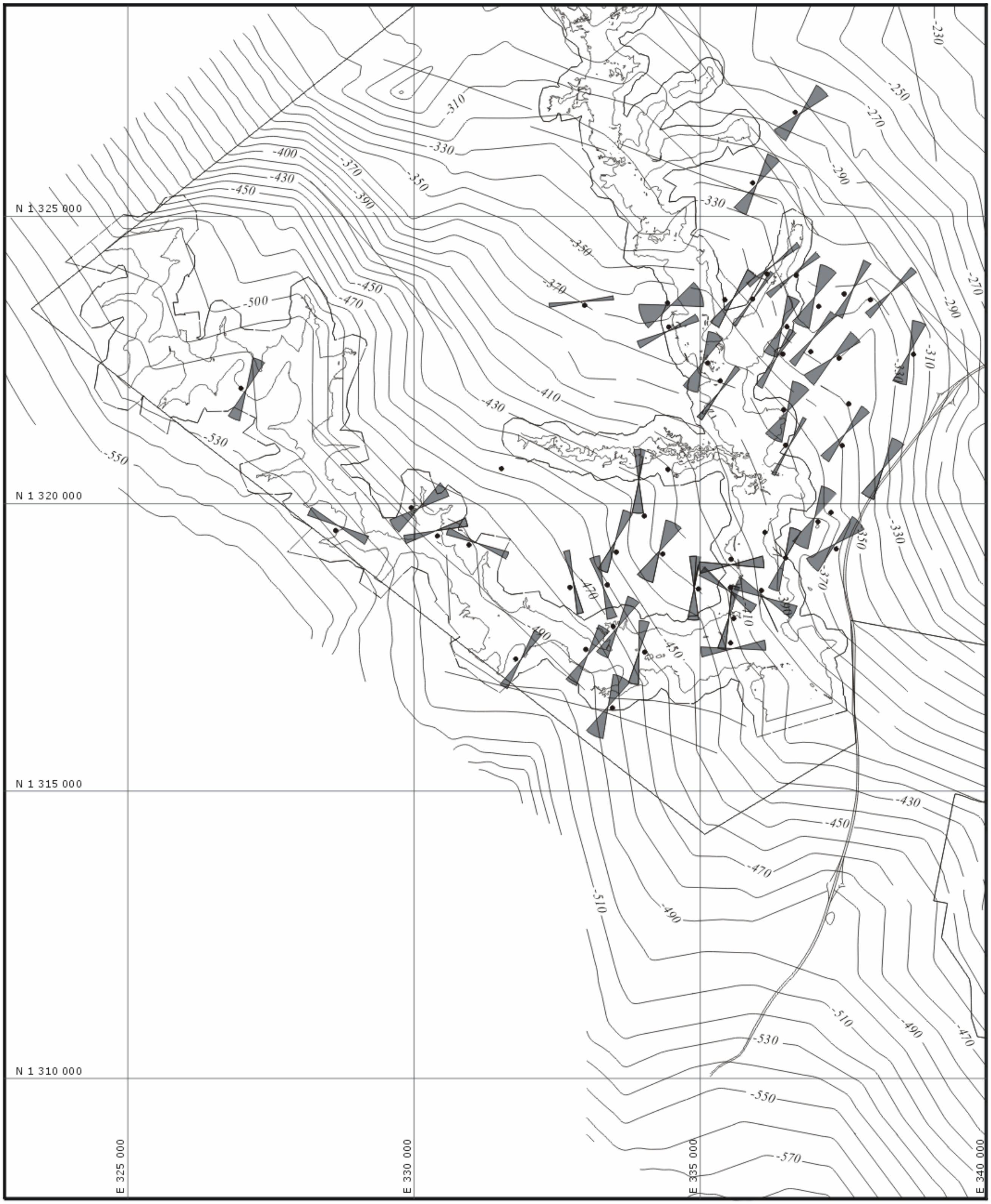


Figure 8 Wyong Lease Area - Plan of inferred σ_H orientations occurring about target seams from breakout analysis.

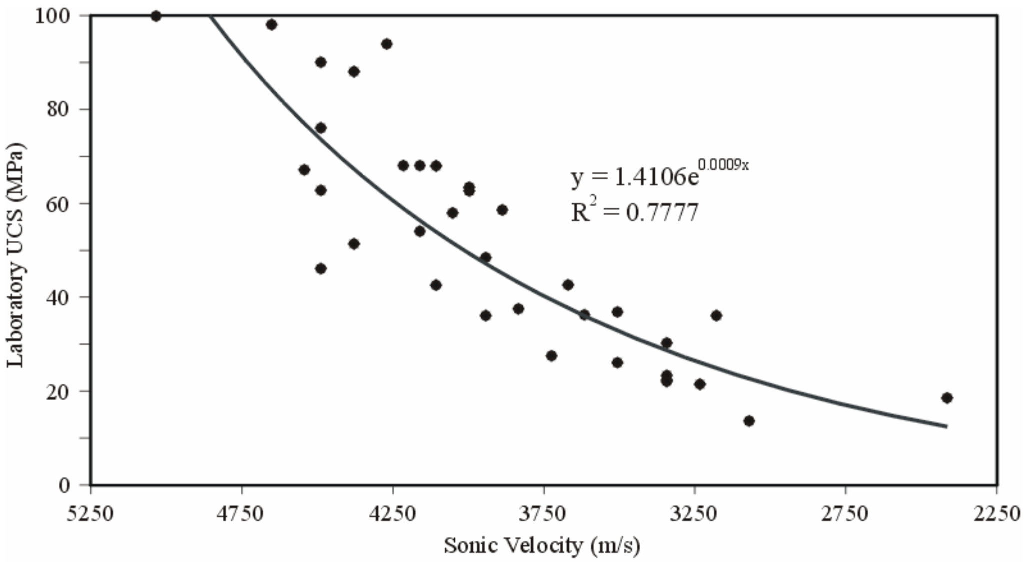


Figure 9 Wyong - Laboratory UCS versus sonic velocity.

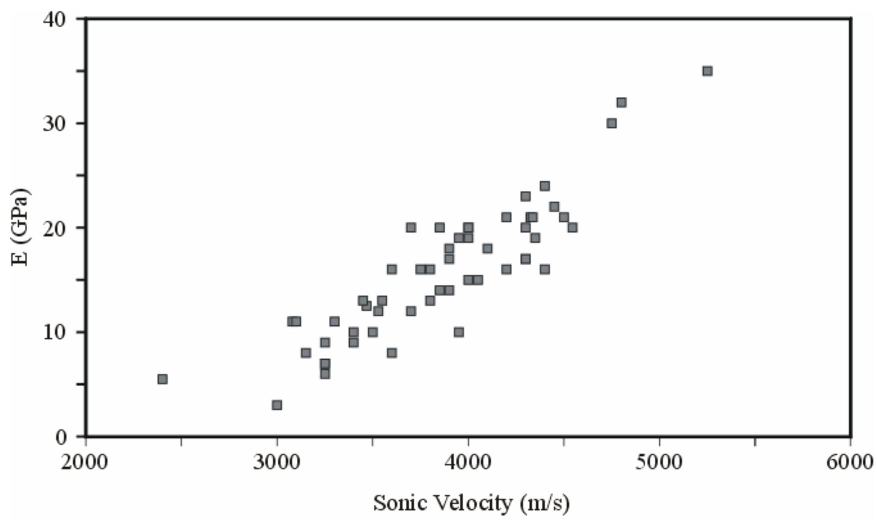


Figure 10 Wyong - Laboratory Young's Modulus versus sonic velocity.

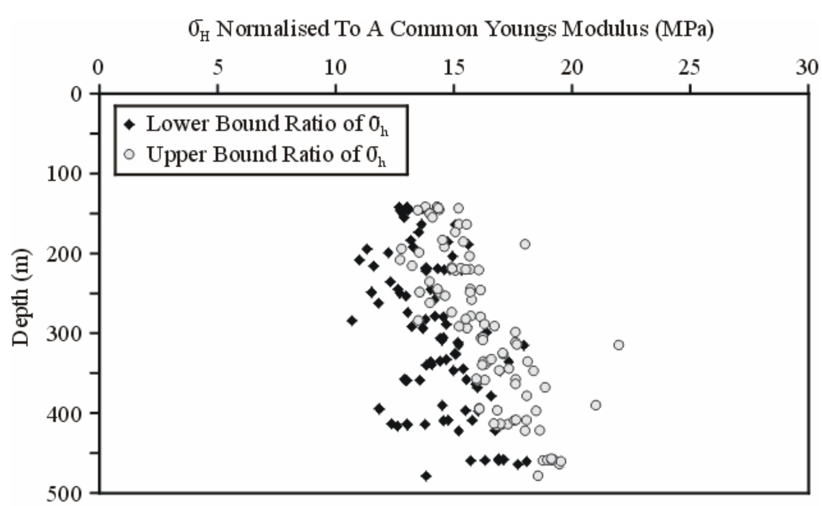


Figure 11 Wyong - depth versus constrained σ_H magnitude from breakout analysis.

CONCLUSIONS

Borehole breakout is a well-established mechanism of borehole instability, used extensively in the minerals and petroleum industry. The use of acoustic scanners to map borehole breakout provides for improved confidence in determination of stress directions than traditional wireline calipers, as a function of their resolution and ability to generate virtual 3-D profiles of the borehole.

The magnitude of the maximum horizontal stress can be constrained to values suitable for inclusion into mine design studies where:

- rock strengths can be determined, either directly from laboratory testing, or through correlation by other means.
- the likely range in ratio of the minor horizontal stress to either the maximum horizontal stress of the vertical stress can be established.

Experience of running this technique in a large number of boreholes at Wyong has demonstrated the repeatability of the technique. The large number of measurements provide confidence in the final result. Additionally, the spatial variation in stress direction and magnitude can be readily defined allowing discrete geotechnical domains to be identified. Comparison against hydraulic fracturing shows good correlation.

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