DEFINITION OF STRESS REGIMES AT BOREHOLE, MINE AND REGIONAL SCALE IN THE SYDNEY BASIN THROUGH BREAKOUT ANALYSIS

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ABSTRACT

The role of horizontal stress in affecting strata behaviour in underground coal mines has been well documented (Siddal and Gale[1], Hebblewhite[2], Mark[3]). In Australia, the nature and depth of the underground coal resources has resulted in high levels of horizontal stress, typically 2-3 times the vertical stress, and up to 9 times that expected by lithostatic burial. Horizontal stress impacts on all facets of strata behaviour, and is a fundamental input into the geotechnical design process.

Borehole breakout analysis, particularly using high resolution acoustic scanner images, provides the ability to collect large data sets that have significant depth and spatial coverage. In real terms this provides the ability to investigate a range of stress phenomena at different scales, and assess the factors controlling in situ and mining induced stress regimes.

This paper highlights a range of stress phenomena that have been observed through breakout analysis in the Sydney Basin and outlines the impact these have on underground mining operations.

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INTRODUCTION

Borehole breakout is a phenomena associated with overstressing and failure of strata surrounding a borehole. Breakout can occur where the stress concentration around a borehole exceeds the rock strength. The borehole will fail in shear (due to overstressing) with the breakout location oriented at 90 degrees from the maximum principal horizontal stress (σ_H). Breakout is a high quality indicator of stress direction and accounts for 23% of the data used in the compilation of the World Stress Map[4].

As well as logging breakout orientation, by assessing the rock strengths in which breakout is occurring, and conducting an assessment of stress concentrations about the borehole, the stress magnitude can also be constrained.

Work conducted by the author as part of ACARP Project C10009 “Maximising In Situ Stress Measurement Data from Acoustic Scanner and Wireline Tools” has provided the opportunity to research and quantify the phenomena of borehole breakout in coal measure strata in Australia.

This paper describes a range of horizontal stress phenomena primarily observed from acoustic scanner analysis. The resultant data set, both in nature and size, provides an insight into:

- the nature of the horizontal stress regime in the Sydney Basin
- possible controls on the in situ stress regime
- the effect of mining voids, at a mine scale, on redistribution of the stress regime

WHAT IS BOREHOLE BREAKOUT

Process of Breakout

Borehole breakout is a term used to describe 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 (water or mud weight).

For sedimentary basins in Australia (and most coal measure strata), the horizontal stress field is typically anisotropic. One of the horizontal stress magnitudes is 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. Figure 1 details the general concept of borehole breakout.

Dependent on the:

- in situ stress magnitude
- rock strength
- borehole pressure (mud weight)
- pore pressure

shear failure (breakout) initiates at the point of maximum hoop stress, in the direction of the minimum horizontal stress, and is a high quality indicator of stress direction.

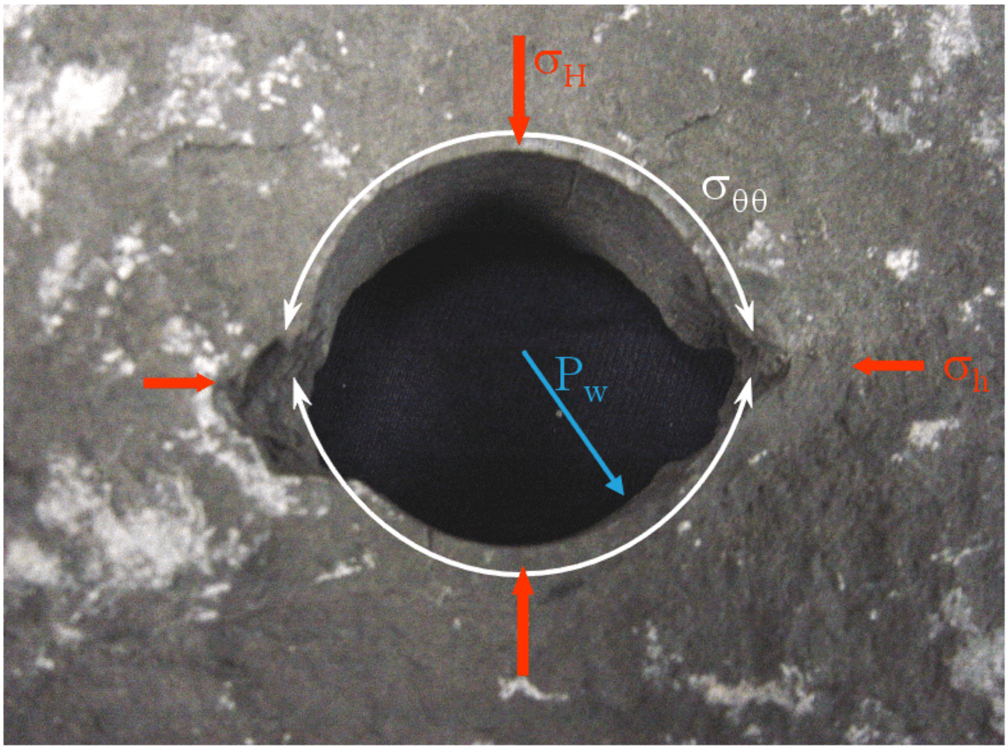

Figure 1 General concept of stress concentration about a borehole leading to breakout.

Breakout Analysis from the Acoustic Scanner

The following general guidelines are forwarded for the proper identification of borehole breakout and subsequent interpretation of the far field stress regime:

- An attenuation of the amplitude and travel time images located nominally 180 degrees apart (two distinct regions of attenuation).
- Breakout to occur on both sides of the borehole.
- One calliper shows an increase in diameter whilst the orthogonal calliper remains similar to bit size.
- Breakout to have well defined margins to breakout edges.
- No visible structure intersects or is immediately adjacent to the breakout.
- Breakout occurs over a minimum 100mm interval.

The criteria for excluding breakout adjacent to joints is due to joints and other structural features locally modifying the stress regime about the borehole and the resultant breakouts are not indicative of the far field stress regime (σ_H and σ_h). This is discussed further in the following section.

An example of breakout using the above guidelines is shown in Figure 2. This details output from Image Pro showing the acoustic scanner image (amplitude and travel time), with the standard wireline suite (gamma, density, sonic). The breakout is clearly identifiable on both the amplitude and travel time images as zones of attenuation in a NNW-SSE orientation. Little or no rotation of the breakout occurs.

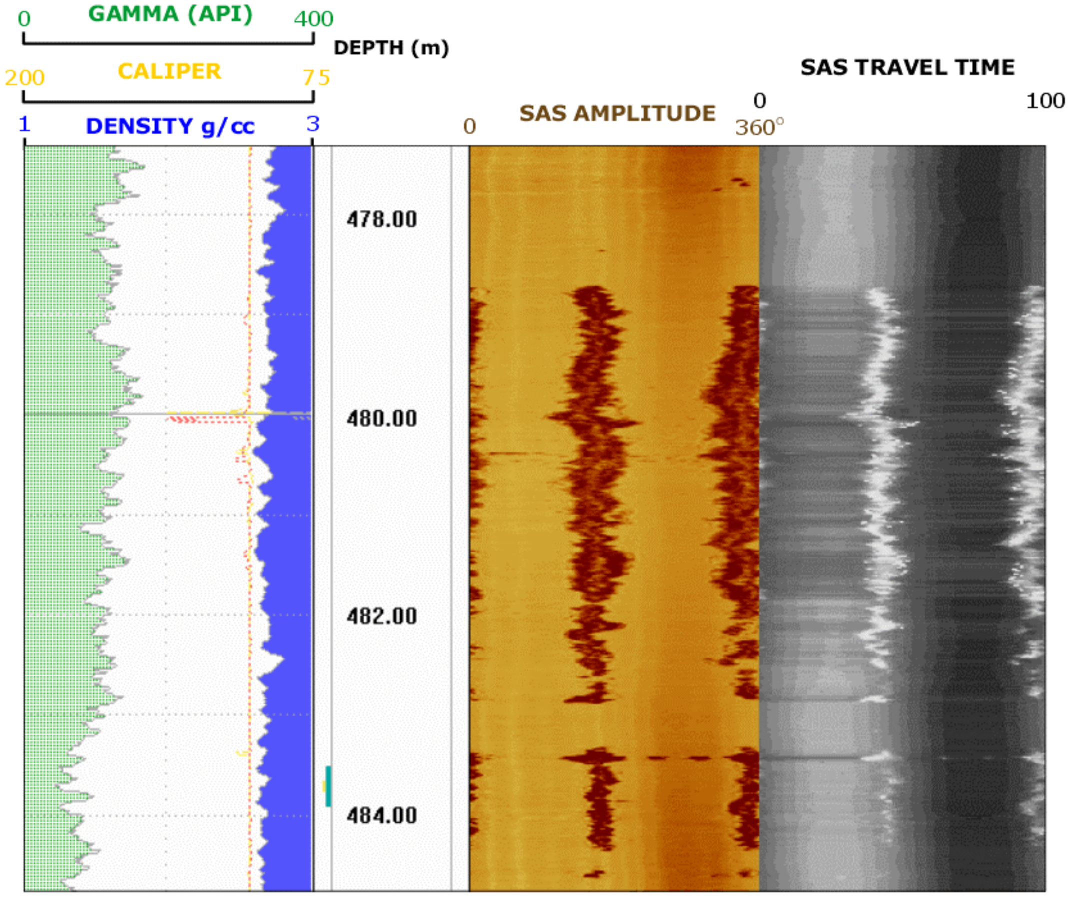

Figure 2 Image Pro output showing example of well developed borehole breakout.

Local Structural Controls on Stresses about Boreholes

Borehole breakout is traditionally used to determine the far field horizontal stress regime. However, local scale factors, notably jointing and faulting intersecting or adjacent to the borehole, can act to modify the stress regime.

Recognising and identifying the potential for stress reorientation due to local structural control is important, both from isolating this data from the far field stress regime data, as well as identifying those areas subject to atypical stress regimes.

An example of the style of behaviour is presented in a case history from Wyong below.

Case History - Wyong

Structural disturbance of varying intensity was noted in the majority of scanner data from a particular domain, with faulting noted in recovered core during routine logging by geological personnel in several holes.

During analysis of scanner data, it was noted that re-orientation of breakout occurred around structural features intersecting boreholes, the most obvious occurrence in borehole C350V300.

Figure 3 details amplitude and travel time images for the hole showing breakout occurring above, below and within the coalesced Wallarah Great Northern Seam. The image shows regions of breakout (attenuation or striped areas on image) with several well developed moderate to high angle structures also noted to intersect the borehole.

It is apparent that the breakout direction varies throughout this section of borehole, with rotation through at least 90 degrees. The rotation would appear to be coincident with the location of structural influence within the hole.

The most obvious rotation as a result of structural interaction is above the WGN Seam, between 302m and 306m. The structures are clearly evident in the hole, as is the rotation of breakout coming into and leading out of the structures.

Inferred maximum horizontal stress directions vary from N-S at 303m, to NE-SW at 304m, to E-W at 306m, to ESE-WNW in the WGN Seam (310m) to N-S below the seam.

There is, however, a general relationship between stress direction and strike of adjacent structure. Figure 4 details the angle between the maximum horizontal stress and strike of the nearest structure (for four intervals of breakout adjacent to structure in this interval). It shows that the maximum horizontal stress realigns to a high angle strike, between 68^0 and 88^0. This is consistent with either an open structure and/or a low shear strength structure that is unable to withstand a significant component of shear stress.

IMPACT OF MINE SCALE VOIDS ON STRESS REDISTRIBUTION

The creation of an opening underground results in a modification to the in situ stress field. The modified stress field may have higher or lower stress magnitudes, and reoriented principal stresses. The nature of the stress redistribution will be a complex interaction of in situ stress direction and magnitude, opening geometry, failure of strata about the opening(s) and other boundary conditions (faults/topography etc).

This phenomena occurs at all scales of mine opening, from boreholes through to longwalls. The ability to provide mine scale characterisation of stress redistribution, both in plan and throughout the geological section, has traditionally been extremely limited. The main reason being the requirement for measurement from underground openings (overcoring) and/or the high cost associated with traditional stress measurement techniques (both surface and underground).

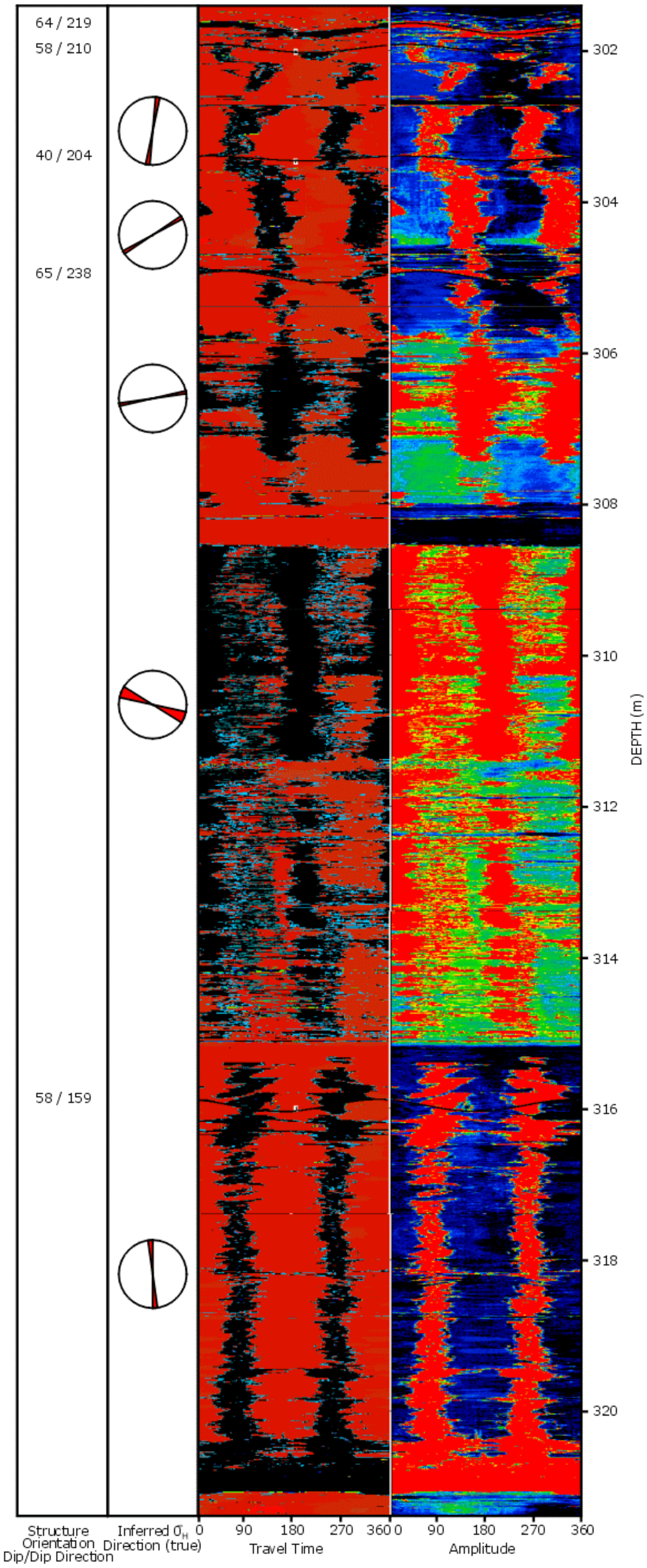

Figure 3 Breakout data from Wyong showing rotated stress directions resulting from structures intersecting borehole.

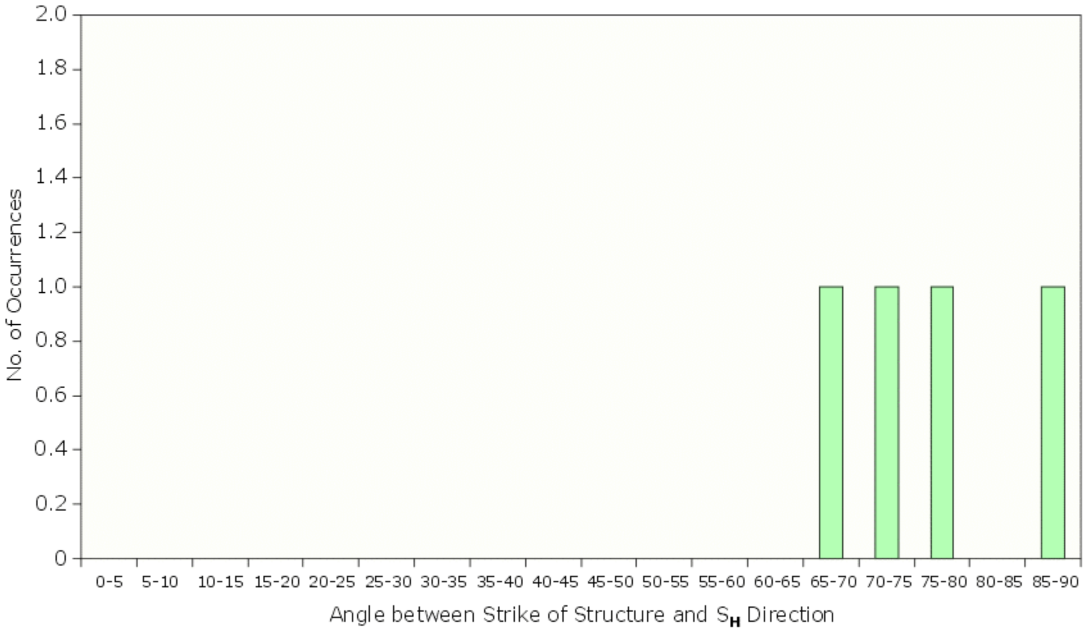

Figure 4 Wyong borehole angle of maximum horizontal stress to strike of structure.

The application of breakout analysis using high resolution acoustic scanner data has provided the ability to characterise the stress regime in brownfield areas surrounding existing mine sites, and has provided an insight into the nature and style of stress redistribution.

Whilst this data is still to be fully interpreted, it highlights several very important outcomes, these include:

- The large scale, up to several kilometres, modification to the in situ stress regime.
- Noticeable stress rotation, both spatially between boreholes, and vertically through the geological sequence.

As noted previously, the relationship between displacements about longwall panels and the in situ stress regime is not clearly understood. Traditional vertical subsidence effects relating to longwall extraction have been well documented and are generally well understood. However, lateral movements associated with coal extraction, and more particularly the mechanism(s) involved with large scale lateral movements, have only more recently been identified.

Reid[5] provides a review of lateral movements associated with mining at South Bulli Colliery and Hebblewhite[6] reports on the impact of lateral movements on the Nepean Bridge due to mining at Tower Colliery.

Observations from recent breakout analysis conducted at West Cliff Colliery are forwarded to shed further light on this phenomena.

Case History – South Coast NSW

A long history of mining along the Illawarra Escarpment has resulted in significant areas of coal extraction. BHP Billiton operates the West Cliff-Appin-Tower complex of Bulli Seam mines. The almost 30 year period of longwalling in this area has resulted in the creation of large expanses of goaf.

As part of recent work for a proposed new longwall area at West Cliff Colliery, borehole breakout analysis of FAC40 acoustic scanner data was conducted on nine surface boreholes. Breakout was generally well developed in all boreholes (as is typically the case in the South Coast), with a total of 252 individual occurrences of breakout in the nine holes.

Further analysis of the data set showed that two clearly defined stress direction domains exist in each of the boreholes. Without exception, the domains were defined as being above and below the Bulli Seam. An example of the breakout data showing the inferred maximum horizontal stress direction versus depth is shown in Figure 5. Points to note from this figure are the:

- Tight grouping of data in each domain.
- Clear separation in stress direction above and below the Bulli Seam.
- Offset in stress direction (in this case approximately 30^0) above and below the seam.

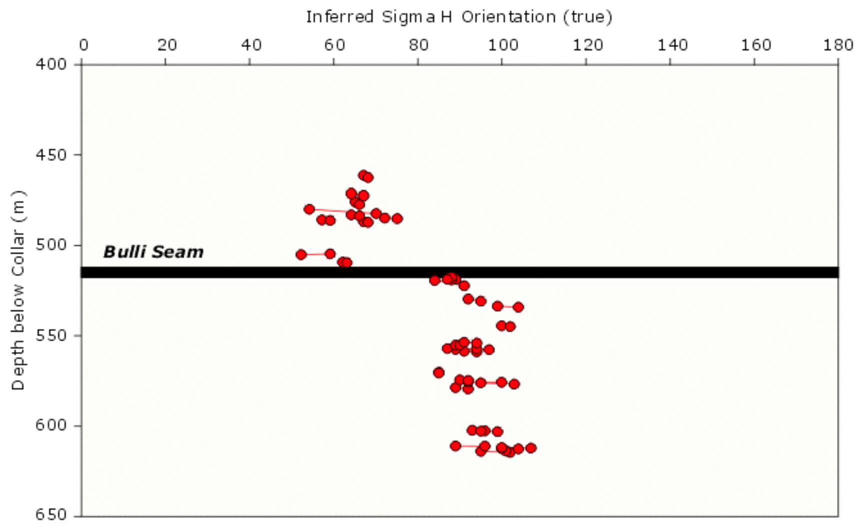

Figure 5 DDH9 maximum horizontal stress direction versus depth highlighting domains above and below Bulli Seam.

Importantly, the rotation of stress direction above and below the seam was not constant, but varied between 0^0-30^0. There was, however, a general relationship between borehole location relative to existing workings and the magnitude of stress rotation. Figure 6 details the Appin-West Cliff workings showing general stress direction data from the area (mapped underground, measured underground and breakout data). The breakout data for each hole shows a direction above and below the Bulli Seam.

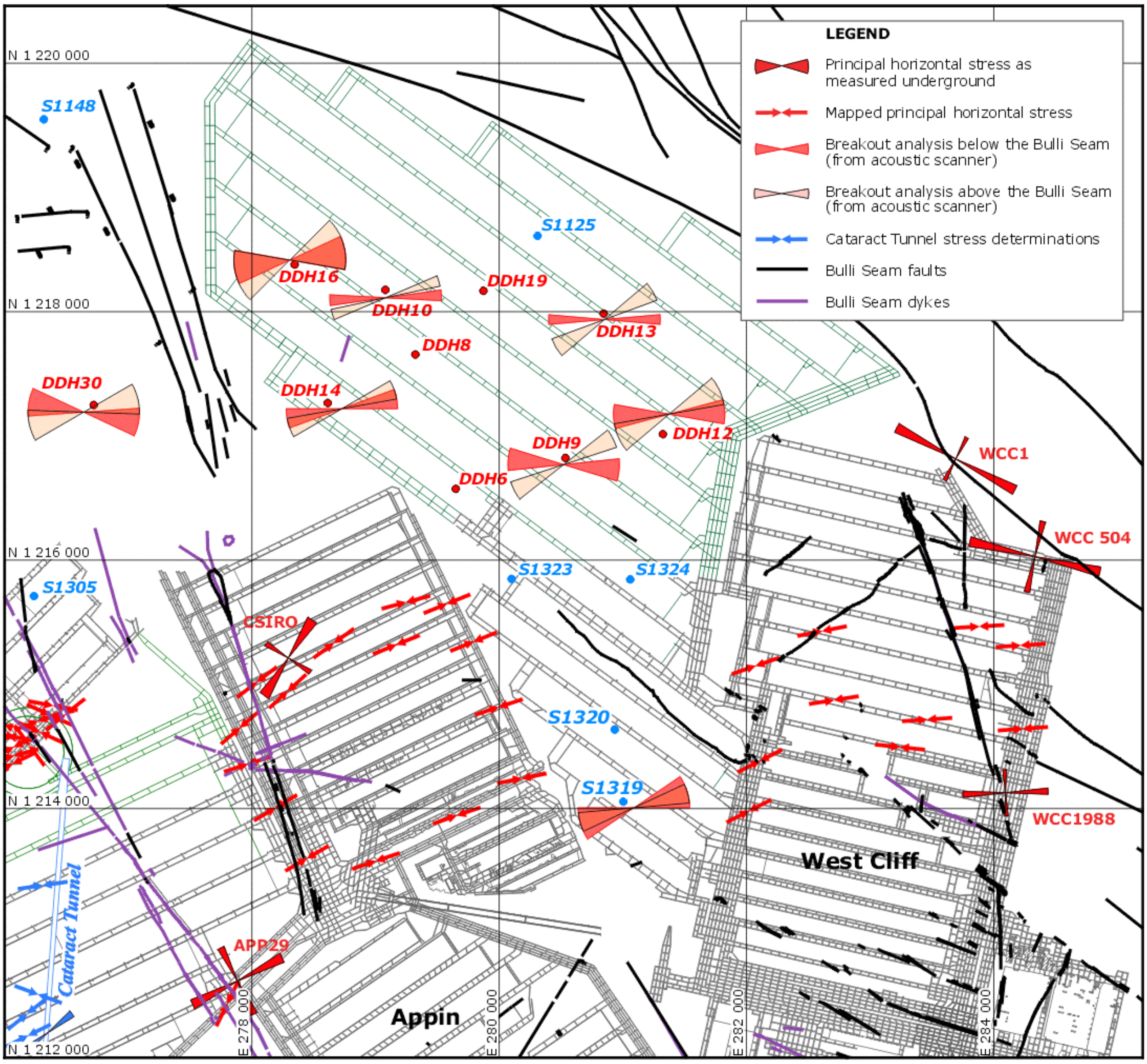

Figure 6 Breakout stress direction data about Appin-West Cliff showing varying rotation in stress direction as a function of location relative to mine workings.

Borehole S1319, drilled between Appin Area 1 and West Cliff, is surrounded by large expanses of old goaf and shows little or no rotation. The remaining boreholes are at varying distances, up to 2km, from existing workings. Boreholes DDH9, DDH12 and DDH13 adjacent to the West Cliff workings all show a noticeable stress rotation above and below the Bulli Seam of between 15^0 and 30^0. Three boreholes to the north of Appin Area 1 show only low levels of stress rotation, between 0^0 and 10^0. The data set would tend to indicate that there is a spatial relationship between the extent of stress rotation and the location relative to goaf void.

A mechanism that would account for the stress rotation is decoupling of the sedimentary sequence, in this instance at Bulli Seam level, with some amount of overburden lateral displacement. Longwall extraction of the Bulli Seam, and subsequent caving, provides the process of overburden decoupling. Lateral relief of strata about the goaf provides the rotation and modification to stress direction.

Reid, in his review of surface horizontal movements about Cataract Dam, noted the general relationship between in situ stress direction and the direction of surface movement, particularly for areas not actively undermined.

Although analysis of the West Cliff breakout data with respect to large scale stress reorientation is in its initial stages, it is likely that both the mining geometry and stress direction will control stress reorientation and surface movements.

To illustrate this point, Figure 7 details a rudimentary elastic numerical model of the Appin – Tower mine sites. It represents a 2D slice at Bulli Seam level and details contours of maximum horizontal stress resulting from mining. It is apparent that modification to the stress field occurs at significant distances from the openings (several kilometres), and that the orientation of the maximum horizontal stress will be re-oriented dependent on the in situ direction and the adjacent void geometry.

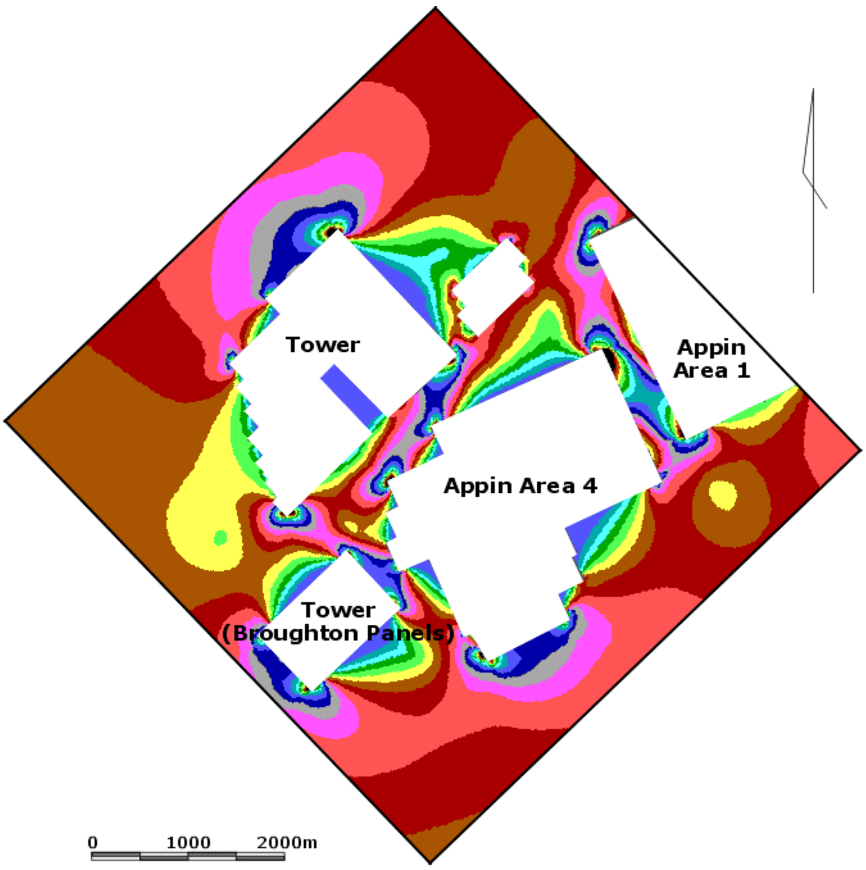

Figure 7 General style of stress redistribution about mine-scale voids.

CONCLUSIONS

Borehole breakout analysis using acoustic scanner data provides a high volume, high confidence data set that provides significantly greater spatial and depth coverage than is available using other techniques.

Analysis of this data highlights the role of various boundary conditions in modifying and controlling the state of stress in the ground. Care needs to be exercised when looking to characterise far field in situ stress directions in structurally complex regimes, so as to distinguish local scale effects from far field conditions. However, analysis of stress directions due to local structural controls can provide further insight into the nature of stress redistribution about faults and other structure for ongoing geotechnical studies and design.

Analysis of breakout data from West Cliff Colliery confirms the wholesale stress reorientation about the Bulli Seam due to mining. The variation in stress rotation relative to longwall voids further highlights the impact of void geometry and in situ stress direction on the nature of stress reorientation. The data is consistent with previous research which postulated a link between lateral movements about longwall panels (in this case decoupling at Bulli Seam level) and the in situ stress field. Further work is required to fully understand this phenomena.

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