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## Statistical analysis of underground stress measurements in Australian coal mines

This paper presents a summary of 235 underground stress measurements conducted in the virgin ground of NSW and Queensland mines. The main objective of this study is to analyse the statistical information from the measurements that are relevant to strata control and mine planning with a view to providing help with a practical approach to estimate the risks involved with strata failure.

Major findings include the statistical increase of maximum horizontal stress with depth in Queensland and NSW mines, a comparison of normalised lateral stress magnitudes and measurements in rock of a different stiffness, 'Tectonic Factor' concept, and maximum lateral stresses and their directions in NSW and Queensland coalfields. These findings can provide a valuable benchmark for mine planning and strata control with potential savings in mine operating costs.

### INTRODUCTION

To date, SCT has conducted some 430 successful underground stress measurements in Australian and overseas mines. From these, 349 measurements were conducted in Australian mines and 235 tests measured pre-mining stress conditions. All stress measurements used the overcoring method of 3-dimensional stress determination predominantly using the ANZI stresscell (Mills, 1997). The overcoring method is currently considered to be the most accurate method of determining the *in situ* stress in underground mines.

The aim of this paper is to present the stress measurement data and methods to interpret these measurements made in typical coal measure strata. The measured stress levels are sensitive to parameters such as rock stiffness, geological discontinuities, pore water pressure and gas desorption. It can be misleading to use stress measured in different types of rock and locations without taking these parameters into consideration. Some of these parameters are addressed here to provide understanding how they influence stress flow in rock and what methods can be used for the correct data interpretation.

### Influence of strata stiffness on stress

The vertical stress is driven by the gravitational load of the overburden strata. Horizontally bedded strata of different stiffness compress fully until they are able to carry the full overburden weight. The vertical stress will therefore be the same in all types of rock or coal strata. On the other hand, a

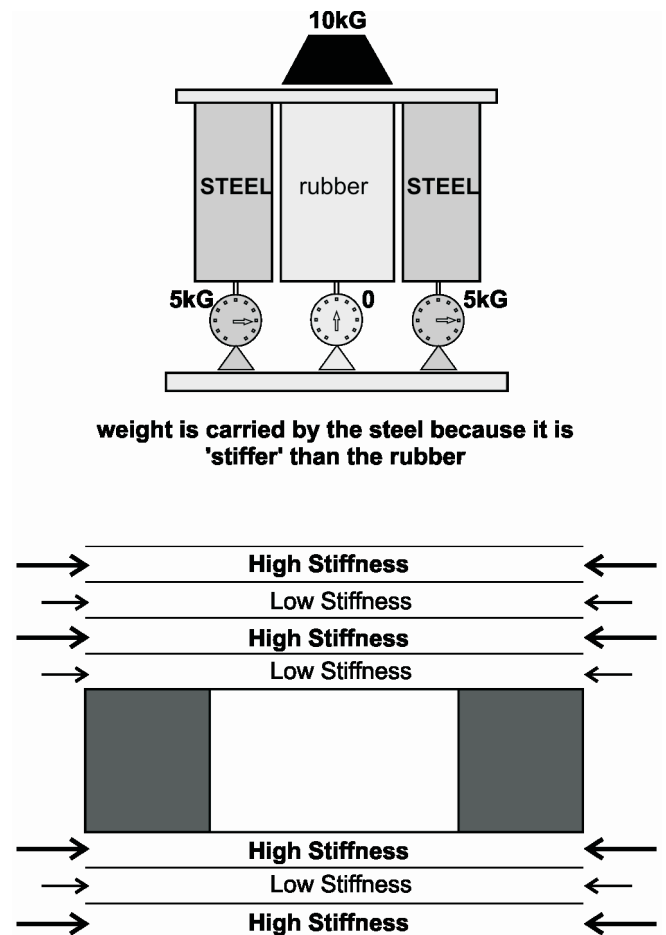


Figure 1: Variation of stress in different layers

large portion of the regional lateral compressive stress is usually of the tectonic origin caused by the movement of the Earth's crust. In the horizontally bedded strata, stiffer rock would attract more of a tectonic lateral stress than strata of a low stiffness. The principle of stress distribution in materials of variable stiffness is illustrated in Figure 1.

In many cases the maximum compressive stress in rock strata is expected to be horizontal and oriented in directions typical to the region. Experience indicates that rock stiffness and therefore the measured lateral stress magnitudes vary considerably in stratified roofs. To compare stress levels between two sites, stresses in rock of the same stiffness must be known. It would be impractical to look for rocks of similar properties during the measurements and therefore a 'normalising' (scaling) technique was developed to calculate stress in rock of any stiffness.

## Normalising stress tensor

Three principal stresses  $\sigma_1, \sigma_2, \sigma_3$  describe the 3-dimensional stress tensor oriented in the unique direction at which all shear stresses are equal to zero (Herget, 1988). A change in magnitude of any principal stress would influence other principal stresses via the Poisson's Ratio ( $\nu$ ). The vertical stress in continuous bedded strata would be the same in all types of rock while the lateral stress would vary with rock stiffness. When scaling the 3-dimensional stress tensor to a rock of different stiffness, the vertical stress must remain the same while the lateral stress components would change.

The gravity driven vertical stress ( $\sigma_v$ ) induces a lateral compressive stress in strata equal to  $\sigma_v \nu / (1 - \nu)$  (Goodman, 1989). Assuming that the *in situ* Poisson's Ratio ( $\nu$ ) is similar in most rock types ranging 0.2–0.3 in value, the gravity induced lateral stress within the adjacent rock beds will range from 0.25 to 0.42 times the vertical stress. However, the *in situ* stress measurements indicate that the lateral stress magnitudes are in most cases much larger than the gravity induced lateral stress with a typical range from 1.5 to 4 times the vertical stress depending on location and the overburden depth. In virgin ground the 'excess' lateral stress is usually of a tectonic origin (Herget, 1988) and proportional to the rock stiffness (see Figure 1).

To normalise (scale) the lateral stresses to a chosen rock stiffness, the 'tectonic' component of lateral stress is multiplied by the ratio of Young's Modulus of chosen and measured rock stiffness. To summarise the 'normalising' process:

- choose a convenient Young's Modulus to normalise the lateral stress into,
- subtract the gravity induced lateral stress component from the measured lateral stress to obtain the 'tectonic' portion of lateral stress,
- multiply the 'tectonic' lateral stress with the ratio of Young's moduli ( $E_{\text{normalised}}/E_{\text{measured}}$ ), and
- add the newly calculated 'tectonic' lateral stress to the gravity induced lateral stress component.

The 'Normalising' process is summarised in the equation below:

$$\sigma_{\text{NL}} = E_{\text{N}}/E_{\text{M}} \{ \sigma_{\text{ML}} - \sigma_v \nu / (1 - \nu) \} + \sigma_v \nu / (1 - \nu)$$

where:

$\sigma_{\text{NL}}$	=	Normalised Lateral stress
$E_{\text{N}}/E_{\text{M}}$	=	Ratio of Normalised and Measured Young's Moduli
$\sigma_{\text{ML}}$	=	Measured Lateral stress
$\sigma_v$	=	Measured Vertical stress
$\nu$	=	Poisson's Ratio

Consider a hypothetical case where the overcore stress measurements were conducted at two underground sites. At a depth of 290m a maximum compressive lateral stress of 19MPa was measured in siltstone with elastic modulus of

24GPa while at a depth of 400m the maximum compressive lateral stress equal to 18MPa was measured in sandstone with Young's Modulus of 15GPa. The lateral stress at 290m depth was scaled down to what it would have been if the measurement was conducted in rock with elastic modulus of 15GPa. Calculations indicate that the normalised (scaled) maximum lateral stress at a 290m depth is 13MPa, 5MPa lower than at a depth of 400m. The higher lateral stress at 400m depth is consistent with the increase in overburden depth.

Figure 2 shows measured and normalised maximum lateral stresses versus the overburden depth in Australian mines (SCT measurements only). The overall stress distribution shows no significant differences between the measured and normalised values of stress indicating a good selection of 'average rock stiffness' chosen for normalisation. When considering single measurements at a particular mine, the normalised lateral stress values describe the true nature of the lateral stress state at a mine site. Note that many existing discontinuities in underground mines may vary the stress flow and it is sometimes possible to experience unusual stress fields at the same depth in the same mine.

*Note:* Typically, coal has a lower stiffness than surrounding rock and therefore the maximum lateral stress in coal is usually much lower (often less than the vertical stress). Complex stress changes that occur during pore pressure loss and gas drainage within the coal can further reduce the measured stress magnitudes in coal strata. At this stage the normalisation process is not recommended for coal due to the complex issues affecting the stress in coal.

## INCREASE IN STRESS MAGNITUDE WITH OVERBURDEN DEPTH

Numerous stress measurements in Australia and overseas compiled on the World Stress Map (Reinecker, 2003) indicate that the vertical and also the horizontal stresses increase with overburden depth. The normalised values of maximum lateral stress measured by SCT in NSW and Queensland coal mine roofs (Figure 3) clearly indicate increase of lateral stress with depth.

To explain the possible mechanisms of lateral stress increase with depth, several issues need to be considered. In response to a constant tectonic interaction within the ground, the rock mass on a large scale is literally broken (intercepted with many discontinuities such as faults, bedding planes, weathered dykes etc). When subject to loading, these large rock geometries would exhibit complex post failure behaviour. This behaviour can be compared to a triaxial test on broken rock sample where the maximum load ( $\sigma_1$ ) that the rock sample is able to sustain without further failure increases with the confining stress ( $\sigma_3$ ) applied to the sample. The triaxial test is described in Figure 4.

The exact nature of the ground behaviour may not be known, however the confining stress ( $\sigma_3$ ) that increases with the depth of cover would provide a mechanical lock to the

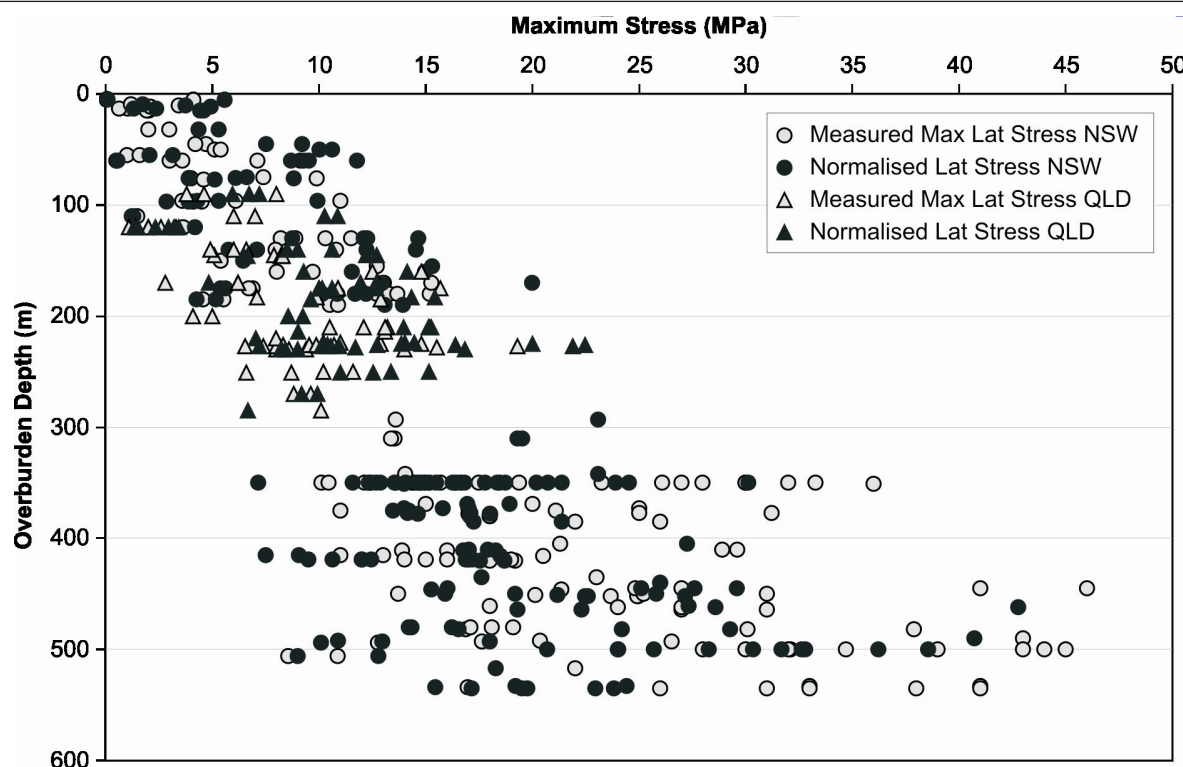


Figure 2: Measured and normalised maximum lateral stresses vs. overburden depth in Australian coal mines (SCT measurements only)

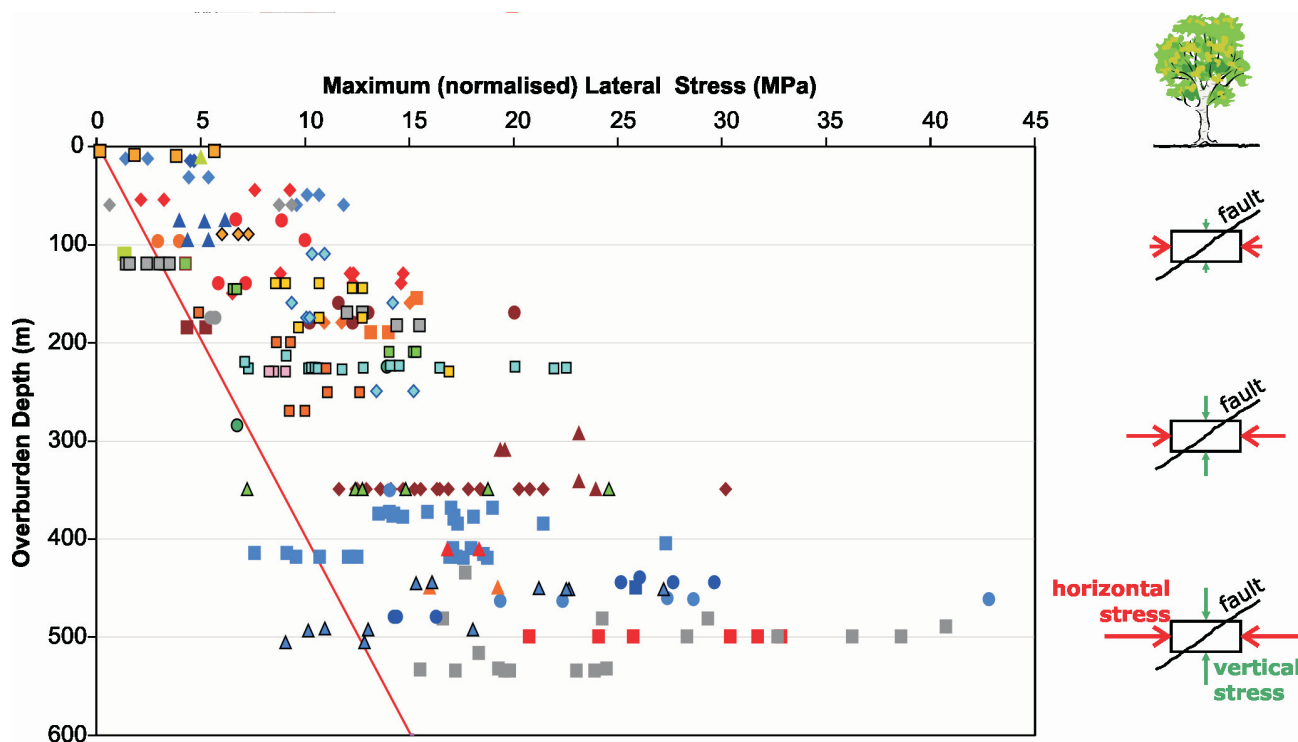
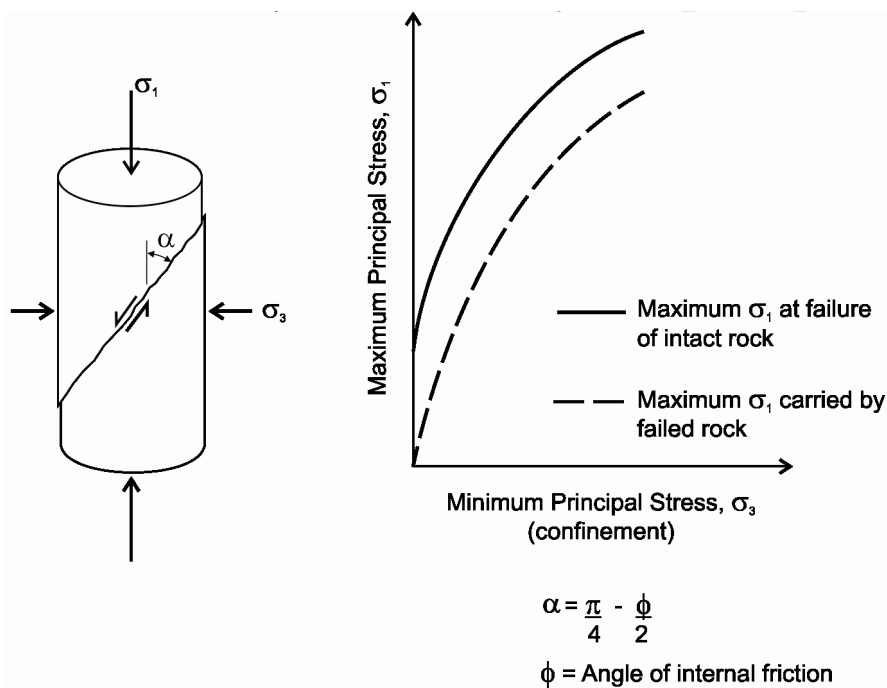


Figure 3: Increase in horizontal stress with depth in Australian coal mines as measured underground (SCT measurements only)

discontinuities within the ground rock mass. It is therefore not surprising that when loaded, deeper sections of a broken rock mass would sustain larger lateral strains while near the surface where the confinement stresses are low, displacements (slips) along the discontinuities would occur more often relieving excess lateral stress until stress

equilibrium is reached. The principle of this mechanism is depicted on the right hand side of Figure 3.

The stress measurement data clearly indicate that the lateral stresses measured in NSW and Queensland sedimentary strata are considerably higher than the vertical stress. These



**Figure 4: Increase in rock strength versus applied confinement during the triaxial rock strength test**

large lateral stress magnitudes and their increase with depth appear consistent with an active tectonic plate movement that would provide stress equilibrium within the ground (as discussed above).

A wide spread of lateral stress values is typically attributed to many discontinuities and non-homogeneous rock that exist within the ground. The faulted or otherwise disturbed ground can either concentrate or reduce the stress field depending on their location and depth. The probable range of lateral stress (Figure 3) versus the overburden depth can be used effectively together with geophysical logging and borehole breakout analysis (MacGregor, 2004) to estimate the probable stress at green field sites.

While substantial amount of stress measurement data has been compiled all around the world and presented in the compilation of the World Stress Map (Reinecker, 2003), SCT measurements are unique to the Bowen and Sydney Basins. The role of horizontal stress and its affect on strata behaviour in underground coal mines has been well documented (Siddall & Gale, 1992; Hebblewhite, 1997; Mark, 2002). In most mines it can be expected that both, the vertical and the lateral stresses will increase as the mine advances to deeper ground.

### Tectonic factor

The Tectonic Factor is a useful parameter that describes the amount of lateral strain induced by tectonic forces within the ground. The regional tectonic factor can be used to estimate an average 'background' lateral stress in undisturbed virgin ground where no discontinuities or other major structures exist.

The Tectonic Factor can be calculated by dividing the 'excess tectonic lateral stress' by Young's Modulus. The calculations can be described by:

$$TF = \{\sigma_1 - \sigma_v \nu / (1 - \nu)\} / E_M$$

Tectonic factors calculated for all SCT virgin stress measurements in Australian mines are plotted in Figure 5.

The results indicate that the tectonic factors increase with the overburden depth. This is consistent with the higher strain equilibrium present within the deeper ground. The lateral spread of the Tectonic Factor data is attributed to the geological discontinuities and non-homogeneous rock that exist underground.

### Directions of major horizontal stress

Underground stress measurements indicate that lateral stress directions can vary substantially due to a large number of geological structures underground. In the Bowen Basin the directions of major lateral stress are in most cases confined to the North to North-East quadrant as shown in Figure 6. In NSW coalfields the maximum lateral stress directions can vary with the location and are best plotted on the regional map. Currently, other stress direction maps are being constructed in SCT to provide better understanding of the regional stress.

Variations in lateral stress direction that are sometimes measured in the mine are usually caused by at least two factors:

1. The *in situ* geological structures that can change directions of the stress flow in the mine.

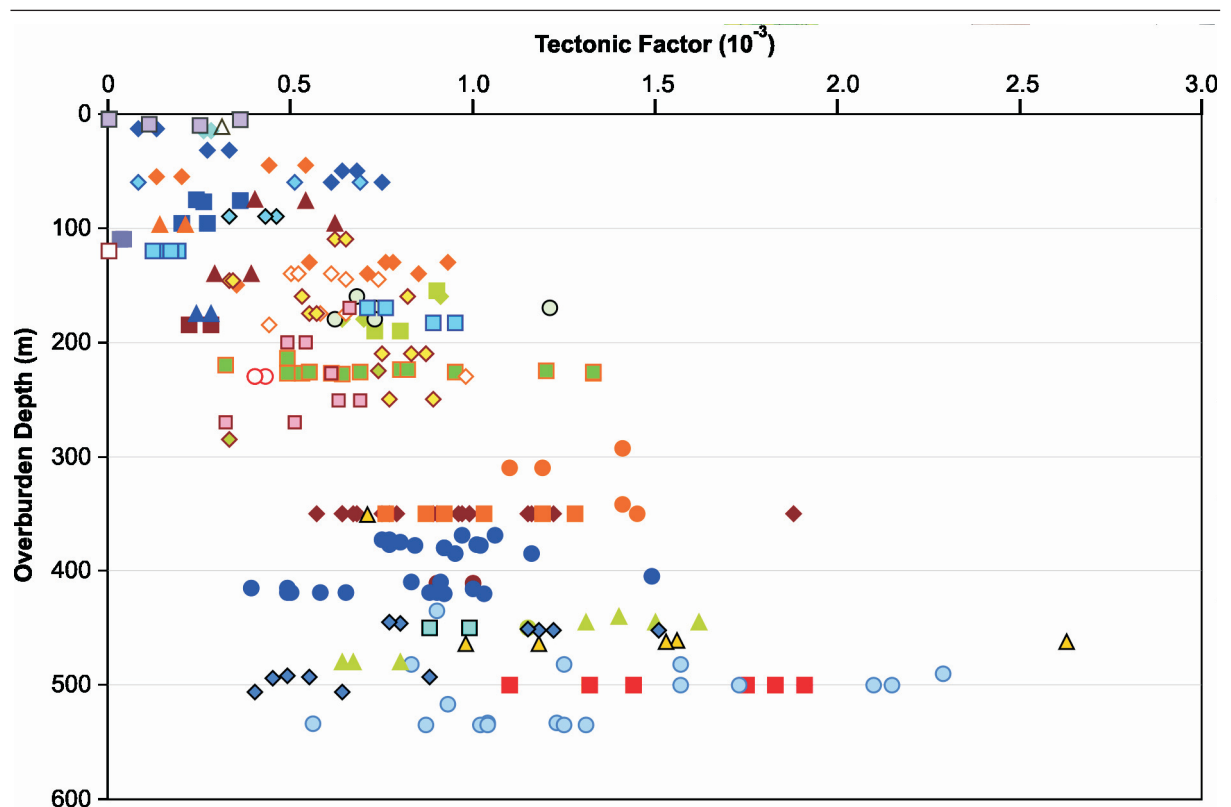


Figure 5: Calculated Tectonic Factors from stress measurements in Australian coal mines (SCT measurements only)



Figure 6: Range of maximum lateral stress directions in Bowen Basin (SCT measurements only)

2. If the lateral stresses are almost equal in all directions, the direction of maximum lateral stress can vary with even a slight change in stress.

The borehole breakout survey that is usually undertaken as part of the geophysical investigations during the exploration

drilling is the best method to accurately determine the directions of maximum lateral stress flow in the explored area (MacGregor, 2004).

## CONCLUSIONS

This study presents numerous *in situ* virgin stress measurements conducted by SCT. The complexity of the *in situ* ground behaviour suggests that it may be difficult to accurately predict stress levels in the mine without actual measurements, however, a preliminary stress estimation is possible using the data presented in this paper together with other nearby stress measurements and borehole surveys.

Several important points can be deduced from this study:

- the measurements clearly indicate that in most cases, the lateral stresses are considerably higher than the vertical stress,
- an increase in lateral stress with the depth of cover can be expected in the Sydney and Bowen Basins, and
- geological discontinuities and non-homogeneous sedimentary strata can significantly influence the stress directions and magnitudes in the mine.

The data presented here strengthens the understanding of stress behaviour in underground coal mines. In response to the stress range in rock of various stiffness, normalisation (stress scaling) technique was developed that allows calculations of stress in rock of any stiffness. Recognising



that a large portion of the lateral stress is probably of a tectonic origin, the tectonic factor was developed to help identify areas of highly stressed ground. Construction of stress maps showing detailed lateral stress directions in selected areas is currently in progress to help with mine layout designs.

Many geotechnical methods including numerical modelling are commonly used to predict ground behaviour. These methods require a detailed knowledge of stress distribution in the ground. A reliable source of stress information is now available to provide realistic estimates of stress in underground workings and to establish correct boundary conditions in numerical models.

Further research is in progress to enhance current understanding of stress and its influence on stability of underground workings in coal mines.

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