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A method for weighted ranking of full tensor in situ stress test results

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Abstract

Accurate characterisation of the in situ stress field is essential for the design and operation of cave mines, where long-term stability and tactical controls depend on reliable stress inputs. However, early project stages often suffer from sparse and inconsistent stress data, complicating the development of representative site-wide stress models. This paper presents a pragmatic methodology for building confidence in stress measurements by a weighted ranking of full tensor in situ stress test results. The ranking is achieved by incorporation of overburden stress modelling from density block models and borehole breakout observations. The approach adapts Euclidean averaging techniques to produce a depth-dependent stress gradient tensor, with individual test results weighted based on alignment with vertical stress models, breakout orientations, and semi-qualitative test quality assessments. Application of this method to a dataset comprising overcoring, acoustic emission, and deformation rate analysis tests resulted in improved confidence in the site's virgin stress field, including a 24° refinement in major principal stress orientation and magnitude adjustments of ±3 MPa. The proposed ranking system enhances the robustness of stress models used in mine planning and supports early-stage geotechnical decision-making in cave mining environments. Discussion surrounds considerations when applying the method to different mine sites and the opportunity to include other stress proxies, such as hydrofrack tests.

Keywords: *in situ stress, stress field, stress model*

1 Introduction

Accurate assessment of the in situ stress field is key to forecasting ground behaviour in underground mines. The magnitude and orientation of the virgin in situ stress field is a primary input to empirical relations and numerical modelling simulations (Brown & Hoek 1978; Martin et al. 2003). Knowledge of the in situ stress magnitudes and orientations are essential for ensuring long-term stability for high capital cost excavations, like those present in mines utilising caving methods (Shelswell et al. 2018; Flores & Catalan 2019). Cave mines are often planned 5–10+ years in advance where the required geotechnical data availability is often misaligned with the time frame required for design guidance. Some major design considerations include the orientation and stability of major excavations (such as crusher and conveyor transfer chambers), cave stand-off distances (for life of asset development like ventilation shafts), pillar dimensions, ground support requirements, footprint overcut lengths, and cave initiation sequences. Failure to control block cave footprint stability is a major cause of ore loss and underperformance in cave mines (Beck et al. 2024).

In situ stress also has impact on tactical controls, for example, preconditioning enhances caveability and can be used as a response to cave stall or as a pre-planned program. Effective preconditioning programs require complex fracture interaction between injection sites, with fracture propagation dependent on the relative in situ stress orientation and magnitudes (Zoback 2010; He et al. 2017). Therefore, accurate knowledge of in

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situ stress is required for proactive optimisation of cave mines from both a strategic and tactical perspective (Campbell et al. 2016; Puller et al. 2016; Xu et al. 2021; Musolino et al. 2022; Roy et al. 2023)

Operators face numerous complexities with the holistic analysis of in situ stress tests to inform mine planning. Some of these challenges include:

1. low number of full tensor in situ stress test data early on in projects, resulting in uncertainty and confidence concerns
2. the inability to mathematically compare methods that resolve the full stress tensor and observations that only show some tensor components.
3. calculating the average stress field considering orientation and magnitude simultaneously
4. the quantity of methods differing in the dataset (i.e. more data from one measurement technique over another)
5. the quality of each test in terms of how the result relates to usefulness for practical purposes (i.e. test was carried out well and results are highly accurate but potentially impacted by nearby structure or mine-induced stresses).

We propose a pragmatic methodology to overcome the aforementioned challenges and develop an in situ stress model using additional datasets commonly available to mine operators.

Indirect in situ stress measurements in Australian underground metalliferous mines are primarily from overcoring methods utilising the CSIRO Hi-Cell (Commonwealth Scientific and Industrial Research Organisation Hollow Inclusion Cell) or ANSI (Australian New Zealand Inflatable) Cell. Additionally, due to costs and underground access, operations also commonly utilise acoustic emission (AE) or deformation rate analysis (DRA) methods (Kurita & Fujii 1979; Worotnicki 1993; Mills 1997; Seto et al. 1999; Yamamoto et al. 1990). We note there is a myriad of other methods and the reader is directed to Morawietz et al. (2020) for a comprehensive explanation of loading, relief, observational, and 'other' stress measurement methods.

Methods for calculating an average full stress field from individual in situ stress measurements are robust (Gao & Harison 2019; Javaid et al. 2023). Gao & Harrison (2019) argue for the use of Euclidean averaging methods and applied it to nuclear repository overcore tests. The Euclidian averaging methodology correctly honours the tensorial nature of stress, which is not correctly accounted for with simple regression analysis on principal components. However, in situ stress test programs in the mining industry are often not as systematic. Less tests are carried out and generally spaced out over larger areas. This is unlike the systematic sampling done in nuclear repositories demonstrated by Christiansson & Martin (2009). Mining environments offer additional challenges and the desired goal generally is characterisation of the virgin in situ stress field, but some individual tests may be accurate for that location but not representative of the virgin in situ stress environment. The reason that individual tests may not represent the virgin stress field in mine settings could be due to proximity to induced stresses from development, caves, stopes, or large faults (Figueiredo et al. 2014; Camac et al. 2006). Additionally, localised temporal effects are possible where the same location may yield different results over time due to different stages of mine development, i.e. cave growth.

Other factors have an additional impact on in situ test results such as temperature, humidity, rock anisotropy, rock grain elasticity variance, uncertainty in the Kaiser point (in AE testing), opposite strain gauge correlations, and biaxial testing results (Amadei 1982; Ask 2003, 2006; Lavrov 2003; Ali et al. 2021; Musolino et al. 2022; Puller, pers. comm., 19 July 2022).

Reviews of overcore studies have shown that even in good conditions there is still expected stress orientation and magnitude variability (Amadei & Stephansson 2012; Sjöberg et al. 2003; Heidbach et al. 2016). AE methods are contentious with some researchers finding low correlation with other methods (Tuncay & Obara 2012). Variability in Kaiser point, and therefore in situ stress estimation, is also observed due to loading rate and lithology (Zhang et al. 2021a). Conversely, good correlation between AE and other stress measurement methods can also be found in literature (Kent et al. 2002; Villaescusa et al. 2006; Li et al. 2022). The discrepancies in correlation observed in the literature may stem from whether the resolved stresses are current at the specific location and/or the biaxial loading technique employed. However, even when controlled using polyaxial techniques, the accuracy of stress magnitude was found to have uncertainty of ±15–30% (Holcomb 1993; Pestman et al. 2001; Lehtonen et al. 2012). Lehtonen et al. (2012) ultimately concluded that AE can sometimes provide excellent results, despite the challenges. Lehtonen et al. (2012) have higher confidence in results when there is simple geologic history and the rock mass is isotropic, unfractured and heterogenous. Deformation Rate Analysis (DRA) is the other rock memory method based on cyclic loading and determination of the strain difference function (Yamamoto et al. 1990; Dight et al. 2012).

Stress test databases can vary in quantities of each in situ stress test method. Methods using the rock memory effect (AE and DRA) are cheaper than overcoring and since underground access is not required, can become numerically more prominent in stress tests databases, especially in early pre-feasibility studies. Including a higher quantity of AE and DRA methods would inadvertently result in the over-weighting of certain methods which can be problematic for analysis. When detecting AE in Brazilian disks, Lavrov et al. (2002) found degradation of the Kaiser effect by rotation of the disk >10° from the previously applied principal stress orientation. The principal stress orientation may not be accurately known early in mine development and planning. Due to the complexities and accuracy issues associated with overcoring and memory effect methods, it would be prudent to rank and weigh these tests according to how they correspond with observations of stress. Doing this will result in higher confidence in the general applicability and robustness of the in situ stress model. It is important to state the pragmatic approach suggested in this paper does not aim to predict the stress accurately at any specific point; rather the goal is to produce a virgin far field stress model that is a general representation for the whole site.

The World Stress Map (WSM) project (Zoback & Zoback 1991; Heidbach et al. 2016) has supplied a quality ranking scheme categorising stress test quality based on stress orientation consistency. The WSM project assigns an A-quality to overcore derived stress orientations, where Maximum Horizontal Stress (SHmax) is believed to be within 15°, when there is ≥11 measurements greater than 300 m depth with a standard deviation of less than 12°. For borehole breakouts, A-quality is assigned when there are more than 10 distinct breakout zones with a combined length of over 100 m in a single well with standard deviation of less than 12°. The WSM quality ranking scheme, however, ranks the dataset as a whole and does not provide direct guidance on individual tests and their use.

In this paper, ranking is based on in situ stress measurement alignment with:

1. An overburden stress model (Sv), derived from specific gravity measurements of diamond drill core. Where σ_v (vertical stress derived from in-situ stress test) and S_v (overburden stress derived from block model).
2. Observations of borehole breakouts.
3. Test result quality, determined semi-qualitatively from multiple components of the test.

The key benefit of having the average stress field more closely aligned with overburden and borehole breakouts is that they represent key primary stress components where decisions are actively made on their outcome (Musolino et al. 2022). For example, for most intraplate deposits in Australia, Minimum Principal Stress (σ_3)is near overburden stress (S_v) which provides the confining stress (Hillis & Reynolds 2003, 2000; Rajabi et al. 2017). Accurate confining stresses are needed for effective pillar design (Mark & Agioutantis 2019; Larson et al. 2020) and is the key input, along with rock strength, to the prediction of rockburst (Bruning et al. 2018). The induced differential principal stresses (σ_1–σ_3) around excavations in numerical models is directly impacted by the estimated virgin σ_3 and is used for estimating failure (Martin et al. 1999; Hoek & Brown 2019).

Observing the orientation of borehole breakouts in near vertical holes (≥70°) provides the best evidence of stress orientation (Zoback et al. 1985; Mastin 1988; Zoback 2010). While some decisions can be made on elucidation of relative stress magnitudes, such as ground support levels, having accurate knowledge of horizontal stress orientation heavily influences subsurface design through optimisation of excavation orientation with respect to stress orientations (Li 2016; Musolino et al. 2022). Furthermore, these borehole breakout and overburden models can be built early in the project and increase confidence in full tensor in situ stress tests results.

The results of this study provided higher confidence in the average in situ stress field for the site with a refinement in σ_1 orientation of 24°, 3.8 MPa adjustment in σ_1 magnitude, and a -2.2 MPa σ_3 decrease at 1,000 m when applying the weighting.

2 Dataset and approach

Gao & Harrison (2019) demonstrated the calculation of the Euclidean mean stress tensor by averaging each component individually. We adapted their approach and applied a weighted linear fit of stress versus depth to each Cartesian component. This yields a stress tensor whose components vary linearly with depth, rather than a single constant tensor obtained by averaging each component. When ignoring any locked-in stresses at a depth of zero, this reduces simply to a stress gradient tensor. From there, a specific depth can be selected to define the Euclidean mean stress tensor at that depth. The following stress components can then be derived from the Euclidean mean stress tensor:

- maximum (σ_1), intermediate (σ_2) and minimum (σ_3) principal stress magnitudes and orientations determined from the eigenvectors and eigenvalues of the Euclidean mean stress tensor
- σ_v (vertical stress) magnitude, specified by σ_z (vertical stress when in the Euclidean mean stress tensor)
- maximum (σ_{Hmax}) and minimum (σ_{hmin}) horizontal stress magnitudes and orientations determined by finding the minimum and maximum stresses in the horizontal plane using fundamental mechanics.

The stress as a function of depth is determined by using a weighted linear fit of the data with the intercept fixed to zero stress at zero depth. Weights are assigned based on quality ranking, giving higher quality tests greater influence on the fitted relationship. The gradient of the relationship is given by Equation 1:

$$m = \frac{\sum w_i d_i \sigma_i}{\sum w_i {d_i}^2} \tag{1}$$

where:

m = gradient of the relationship

w_i = weighting for each measurement

d_i = depth

σ_i = measured stress.

It is important to do a thorough review of the available dataset before engaging in this procedure, including reading original reports and checking depth corrections. The dataset available for this assessment consists of 27 full stress tensor results (Figure 1) (Harris & Wesseloo 2015). Thirteen results are from overcoring methods and are of B-quality with a standard deviation of σ_{Hmax} orientation 13.4° as per the WSM quality criteria. B-quality is where σ_{Hmax} is believed to be within 15-20°, when there are more than 8 measurements at greater than 100 m depth with a standard deviation of less than 20°. Fourteen results are from AE and DRA methods that are not covered by the WSM quality system. The borehole breakout data comes from 32 formation micro-resistivity imaging (FMI) logs with 615 distinct breakout pairs. The standard deviation of the dataset is 17.9°. Borehole breakouts can be length-weighted instead of single-occurrence-weighted so that continuous breakouts are not underrepresented in the statistics (Tingay et al. 2008). The data storage and processing occur within mXrap version 6 which is a geomechanical software tool developed by the mXrap consortium (Harris & Wesseloo 2015).

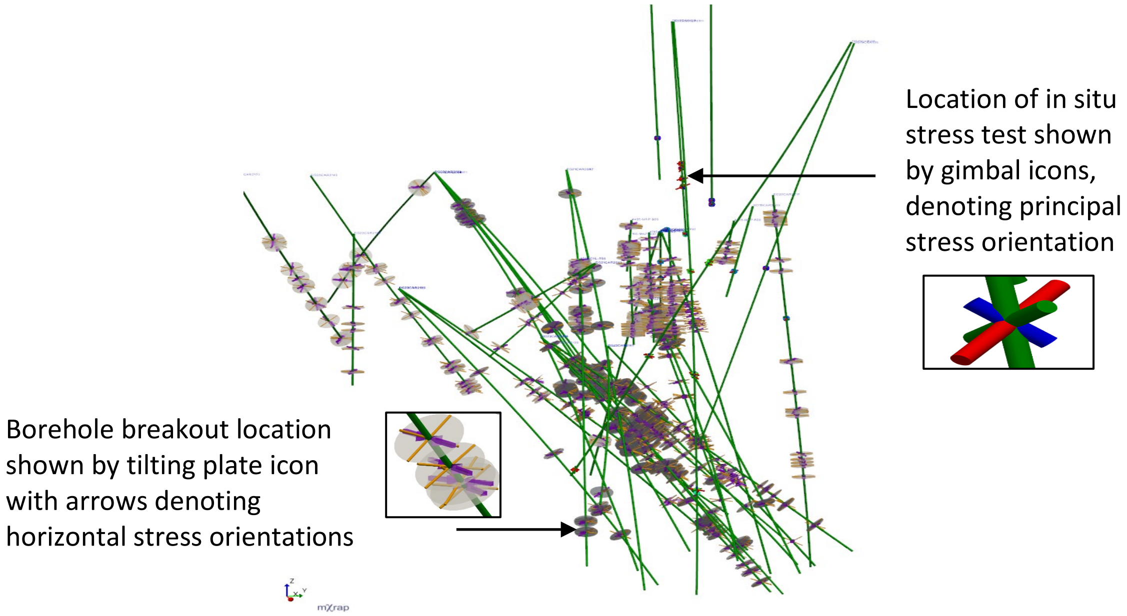

Figure 1 Example of drill holes and borehole breakout occurrence with orientations. Note only boreholes with a dip >70° were use for our analysis

3 Vertical stress from density block model

Overburden stress is often equal to the weight of the overburden rock when the topography is relatively flat and no large open pit exists. Given the large drilling dataset geologists produce for grade modelling, often early in mine development, the overburden stress can be calculated to a high degree of confidence. The first quality ranking consideration is correlation of the in situ stress test σ_v to the expected overburden stress (S_v). This requires the creation of a model of overburden stress to compare with the σ_v component of the individual in situ stress test (Figures 2 and 3). The technique outlined in this section is applied to an area with little topographic relief and no large open pit. We will later discuss the modifications needed for mountainous regions, or where there is significant material extraction above the in situ stress test location resulting modified overburden load (Hooker et al. 1972; Zhang et al. 2021b; Han et al. 2024). The overburden stress is calculated from the density block model and interpolated onto location of each in situ stress test. Higher agreement between the model and in situ stress test in the vertical component of the stress tensor provides higher ranking of that test. To further clarify the 2 vertical stresses discussed, S_v is the vertical stress component that is calculated from the block model, essentially overburden stress and σ_v represents the measured vertical stress value calculated from in situ stress tests.

The integration for S_v is performed per Equation 2 using a linear interpolation between vertically aligned data points:

$$S_v = \int_0^z p(z) g \, dz \tag{2}$$

where:

S_v = estimated overburden vertical stress

$p(z)$ = overburden density at depth (z)

g = gravitational acceleration constant.

The three-dimensional locations of each in situ stress test and the magnitude of the vertical stress component, σ_v, were determined from the stress tensor. The S_v model was interpolated onto the locations of the in situ stress tests using 'Paraview 5.13' software and compared (Figure 3). The tests are then categorically ranked based on 2 MPa bins and provided a categorical quality from 0–5 (Table 1, Figure 2). The decision was made not to use the quality ranking nomenclature (A,B,C,D,E) outlined by the WSM as not to confuse how the ranks are determined. Discussion surrounds the use of log ratio between σ_v and S_v as an alternative method to determine the agreement between the 2 datasets.

Table 1 Ranking in situ stress tests based on their agreement in magnitude to the overburden stress model. Removed category is reserved for if a test does not pass quality control procedures. S_v relates to the calculated vertical stress from the block model and σ_v the in situ stress test result

Quality rank name	Quality rank number	$\lvert Sv\text{-}\sigma_v \rvert$ (MPa)
Excellent	5	0–2
Good	4	2–4
Okay	3	4–6
Poor	2	6–8
Caution	1	>8
Removed	0	n/a

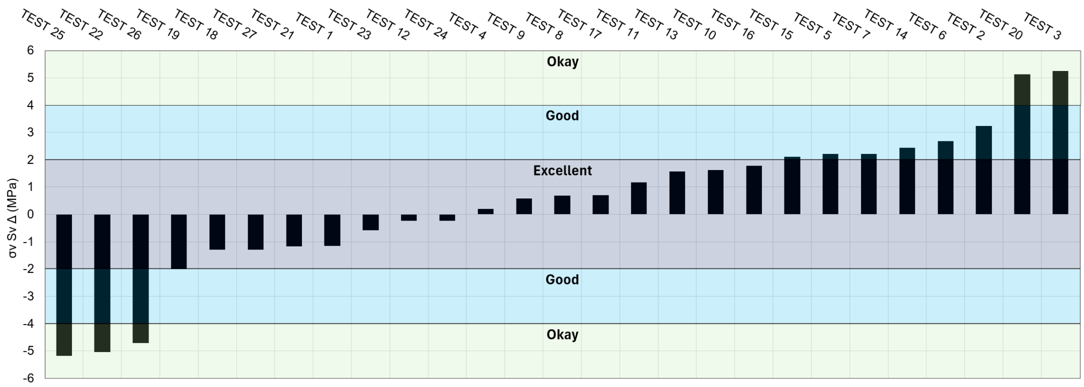

Figure 2 Vertical stress delta from in situ stress test (σ_v) versus vertical stress model from density (S_v). The clustering around 2 MPa is considered excellent as many individual tests from the same location have shown that level of variability

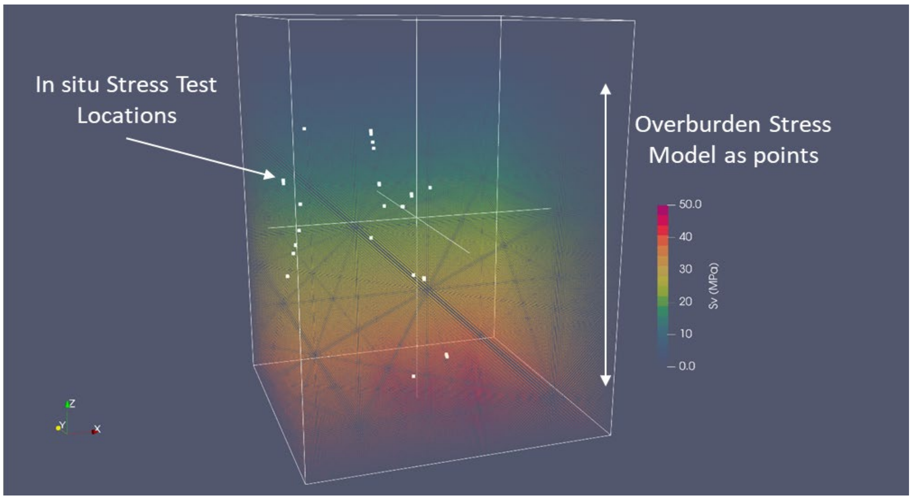

Figure 3 Block model converted to vertical stress (S_v) points coloured by Sv magnitude. In white is the test/sample location of the individual overcore, acoustic emissions or deformation rate analysis test. The image demonstrates how the location of each test is matched in relation to the block model derived S_v. X is easting, Y is northing and Z is depth (relative level)

4 Wellbore breakout database

Observations of the orientation of borehole breakouts in near vertical boreholes (≥70°) are excellent indicators of the minimum horizontal stress orientation (Mastin 1988; Goodfellow et al. 2017). Knowing the orientation of the horizontal stresses is a key decision-making factor when designing long service life underground excavations (Hao et al. 2021). Therefore, weighting in situ stress tests by correlation with borehole breakout data is a pragmatic use of the data, helping to determine if the individual stress tests is reflecting the mine scale stress trend. All borehole breakout data was separated into 100 m intervals to account for any rotation of the stress field with depth and to better match the depth of the tests with the breakouts of similar depth. Significant outliers greater than the standard deviation were investigated and excluded from analysis if associated with specific structure or faulting. Figure 4 shows the wellbore breakout orientations from the database coloured by borehole (borehole name not shown) to allow for identification of holes that are outliers. There are 2 options for creating the wellbore breakout alignment rankings: the first is the WSM quality ranking scheme which proposes A–E rankings ±15°, ±15-20°, ±20-25°, ±25-40° and >±40° (Heidbach et al. 2016), and the second is based on the range of the available dataset. Given the standard deviation of the dataset, we found larger brackets to be appropriate (Figure 5). In the discussion, we propose that in laterally extensive mines the method for associating borehole breakouts and in situ stress test alignment requires a search ellipse, not just vertical level separation shown in this paper.

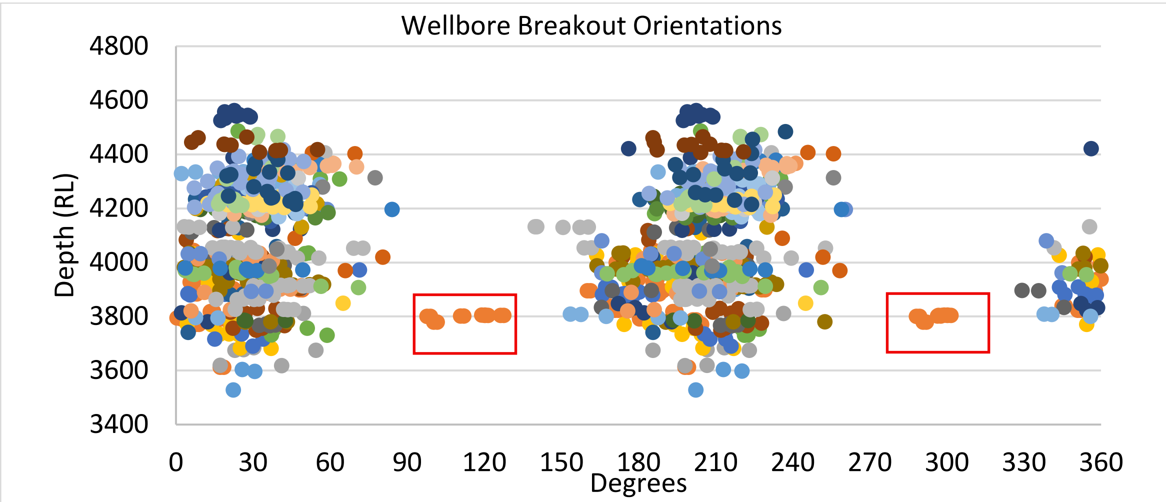

Figure 4 Plot of borehole breakout orientation with respect to depth (relative level). Highlighted in red were breakouts associated with highly veined fractured rock near a fault structure

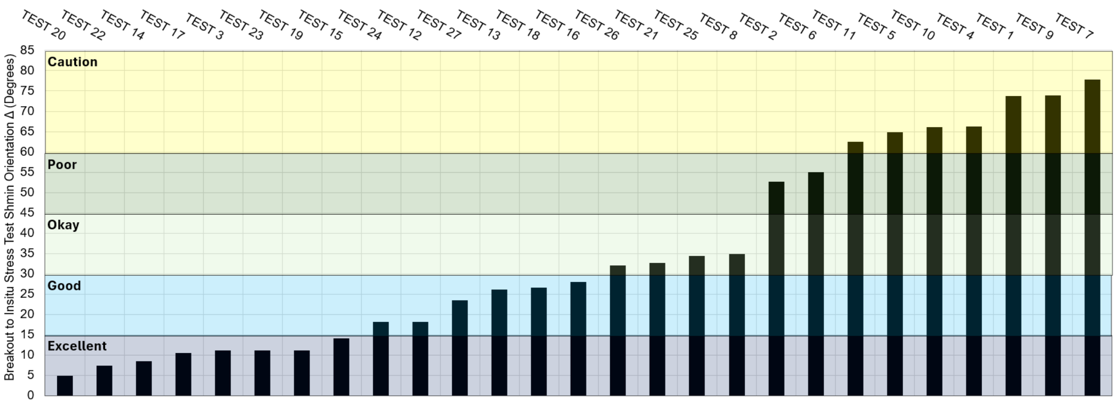

Figure 5 Categorisation of in situ stress test results in relation to the average borehole breakout orientation for all breakouts within 100 m vertically for the test. Brackets are based on average per 100 m standard deviation (5. Excellent 0–15.3; 4. Good 15.3–30.6; 3. Okay 30.6–45.9; 2. Poor 45.9–61.2; 1. Caution >61.2–90)

5 Test result quality

Test result quality is a semi-objective ranking applied based on known factors that affect the confidence in situ test results. Most in situ stress test providers have a methodology and criteria against which they assess test result quality. It may, however, be preferable to apply a site specific quality criteria assessment to account for local conditions. The following is a list of considerations for each testing method. In our case, overcore tests were assigned a 1–5 quality based on the providers internal quality ranking methodology. Acoustic emissions and DRA tests were ranked based on the methodology by De Alwis et al. (2025).

Overcore:

- number of individual overcores per site and result distribution
- operable strain gauges and degree of opposite strain gauge agreement
- geological factors such as foliation or grain size, which could lead to different elastic properties over the length of the strain gauge, which are then not reflected due to scaling in the biaxial test (i.e. consistent elastic properties of the tested area)
- borehole temperature
- strain gauge reading stability during overcoring procedure
- any compensation strain applied to the result
- biaxial test confidence
- temperature at which Young's modulus is determined
- glue plasticity and bondage
- evidence of pre-discing strain.

AE/DRA:

- orientation accuracy
- uncertainty in the applied stress
- difficulty in determining the exact point of AE increase.

6 Weighted quality ranking

There are 2 weighting methods applied in this analysis. The first is the quality ranking weighting whereby the 3 quality rank numbers (vertical stress alignment, borehole breakout alignment, and test quality) are weighted. The second is the calculation in mXrap shown in Equation 1. In our case, the decision was to provide a final rank for each test based on Equation 23

$$(\sigma v_a * 0.4) + (Wbo_a * 0.4) + (Q_m * 0.2) = int(Q_r) \quad (3)$$

where:

σv_a = vertical stress alignment

Wbo_a = wellbore breakout alignment

Q_m = quality of the method

$int(Q_r)$ = weighted quality ranking rounded to the closest integer.

The rationale for ranking on a 40/40/20 split is due to 3 factors:

1. The importance of having the final in situ stress regime reflect accurately the confining stress and horizontal stress orientation

2. The large borehole breakout dataset that due to the mines smaller footprint is relevant in location to in situ stress testing results as well as a high number of tests showing strong σv_a
3. While including the quality of the testing procedure is important, if the test results show strong Wbo_a and σv_a, then the semi-objective quality ranking system may not have accurately reflected the quality of the outcome and therefore is weighted lower. Explanations for a high quality test and poor alignment to the models could be explained by localised stress effects such as structures.

7 mXrap weighting

When the number of tests in each category is the same, 'excellent' and 'good' test results will make up 68% (or 1 standard deviation) of the final average in situ stress field. 'Okay', 'poor' and 'caution' results make up precipitously less (Table 2).

Table 2 Weighting matrix used in mXrap software. Details on weighting calculation outlined in Equation 1

Quality rank name	Quality rank number	Weighting
Excellent	5	40
Good	4	28
Okay	3	17
Poor	2	10
Caution	1	5
Removed	0	0

8 Results

The results show that σ1 trend is rotated 24˚ N. The borehole breakout average orientation (Sh_{min}), accounting for the number of in situ tests at each depth bracket, is 29.6/209.6. The results show the applied weighting moves σ_{hmin} within 9.4° of 29.6°. Without weighting, the difference is 14.6° (Table 3).

Table 3 Stress components at 1,000 m

Method	σ1	σ1	σ1	σ2	σ2	σ2	σ3	σ3	σ3	σHmax	σHmax	σhmin	σhmin	σz
	M	**P**	**T**	**M**	**P**	**T**	**M**	**P**	**T**	**M**	**T**	**M**	**T**	**M**
	(MPa)	**(°)**	**(°)**	**(MPa)**	**(°)**	**(°)**	**(MPa)**	**(°)**	**(°)**	**(MPa)**	**(°)**	**(MPa)**	**(°)**	**(MPa)**
Unweighted	**39.3**	**1.2**	**105**	35.2	6.1	195	**28.6**	**83.8**	**4.2**	39.3	285	**35.1**	**15**	28.7
Weighted	**43.1**	**0.6**	**309**	32.2	5.8	219	**26.4**	**84.2**	**44.9**	43.1	309	**32.2**	**39**	26.4
Δ*	**3.8**	**-0.6**	**24**	-3	-0.3	24	**-2.2**	**0.4**	**40.7**	3.8	24	**-2.9**	**24**	-2.3

Magnitude (M), plunge (P), trend (T)
* The calculation of trend Δ is done with respect to 0 plunge (i.e. 105(+180) – 309 in σ1 (T))

9 Discussion

We have provided a pragmatic approach to producing an average in situ stress field that weights the contribution of overcores, AE, and DRA methods by alignment to borehole breakout observations and rock density datasets. While in situ stress models are imperfect, we believe the approach presented provides a stronger foundation for decision-making over simple scalar regression of stress magnitudes and unweighted datasets. The approach, when implemented, could enhance understanding of the stress field without more primary data, which is particularly useful in pre-feasibility stage studies.

We acknowledge the approach was developed for a single asset with a specific set of data available. When we applied this technique to another asset, we found that stress domaining was required as the lateral extensive nature meant it was not good practice to correlate borehole breakouts multiple kilometres away to individual stress tests. If other high quality datasets were available, there is no reason that other stress methods could not be included in the workflow proposed. Particularly effective would be the use of extended leak-off tests (White et al. 2002). Hydraulic fracturing or preconditioning is commonly used to enhance caveability and the program can serve dual purpose in determining minimum horizontal stress magnitude in normal ($S_v > SH_{max} > Sh_{min}$) and strike-slip ($SH_{max} > S_v > Sh_{min}$) faulting environments.

It is important to make local considerations when applying this workflow to other assets. Assuming a linear vertical stress gradient with depth is not always applicable, the effect of topography and open pits on vertical stress is well known (Hooker et al. 1972; Zhang et al. 2021b). It would be diligent to produce an elastic model using the density block model, that way the overburden weights can be distributed correctly. The effect of topographic relief on subsurface stresses has been modelled in FLAC by Wang et al. (2023) and Figueiredo et al. (2014). Figueiredo et al. (2014) found that some overcore tests in their study did not match overburden stress models due to local structures effecting overcore results. Mining-induced stresses can also impact in situ stress measurements; an example is modelled by Han et al. (2024). Han et al (2024) show doubling of the stress in vertical abutment zones, highlighting the importance of test location in relation to mining when trying to resolve the virgin in situ stress. Outcomes of the Figueredo et al. (2014) and Han et al. (2024) studies reinforce the proposition that weighting in situ stress tests is important to mediate the effect of outliers. Failure to do so will let areas affected by local structures or induced stresses influence the estimate of the virgin in situ stress field.

The ranking process used in our workflow uses 2 MPa bins to denote quality of based on σv_a. A log ratio approach is recommended if the tests have large vertical offset. This is because lower absolute values and shallower results would otherwise skew the ranking. A log ratio approach would require a ranking scale to be created. A scale suggestion would be to use the log ratio between the highest and lowest σ_v values for a test site (3–4 overcores) as the brackets, as that would account for some uncertainty in the overcore results. Recent test work of 3-4 overcores at two different sites both yielded a log ratio of 0.225 between the largest and smallest σ_v. Therefore, Excellent ranking can be cut off at 0.113, Good at 0.225, Okay at 0.338 and Poor 0.45.

Understanding of structures, lithology, and mining-induced stresses is an important factor as they can heavily influence breakout rotation (Lin et al. 2010). As part of our assessment, a mine scale model was run and compared to the location of the stress tests. We found that our tests were not within influence zones of faults, lithology boundaries, or induced mining stresses, it would be an advisable check for these factors when repeating the method presented. Another point to consider is temporal changes in stress, mining environments change over time due to development, mass extraction, and deconfinement. Since this method aims to provide a general mine scale stress model, high agreement between observation and stress test should not automatically result in inclusion into the model. If investigation concludes localised stresses around measurements sites, due to the aforementioned factors, it would be advised to remove that measurement from the model and use It as calibration in conjunction with numerical modelling analysis.

Our dataset had A or B WSM quality standard deviation in breakout orientation. We used depth as a delimiter for better aligning the in situ stress results with average breakout orientation, however, other sites may require lateral delimiters or delimiters based on lithological group. Refinement of the method would benefit from delimiting the borehole breakout dataset by either depth, lithology, or search ellipse to reduce borehole breakout standard deviation below 15° for each delimited area and create stress domains for numerical modelling purposes. We acknowledge the statistical issues associated with analysis of categorical data in general continuous data allows for far more data analysis techniques (Chandola et al. 2009).

10 Conclusion

This study presents a pragmatic and scalable methodology for improving the estimation of site-wide in situ stress fields in cave mining environments. By applying a weighted ranking system to full tensor stress measurements based on alignment with overburden stress models, borehole breakout orientations, and semi-qualitative test quality assessments, the approach enhances confidence in the derived virgin stress field. The use of Euclidean averaging with depth-weighted fitting preserves tensorial integrity and enables interpolation of stress gradients across the site. Importantly, while the methodology focuses on full tensor stress tests, it also provides a framework for incorporating non-tensor derived stress indicators such as leak-off tests/mini-fracture tests. These methods, although not resolving the complete stress tensor, can offer valuable constraints on principal stress magnitudes or orientations when integrated with supporting datasets. Their inclusion, when appropriately ranked and weighted, can improve model confidence particularly in early-stage projects where full tensor data is sparse. The resulting stress model supports both strategic design decisions and tactical controls, such as excavation orientation, pillar design, and preconditioning programs. While developed for a single asset, the methodology is transferable to other mining contexts, with future work recommended to incorporate stress domaining for numerical models and incorporation of leak-off tests/mini-fracture tests.

Disclosure

BHP are a corporate affiliate member and mXrap consortium member of the Australian Centre for Geomechanics (ACG). The ACG produce the mXrap software suite referenced in this manuscript (Harris & Wesseloo 2015).

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