Combining acoustic scanner data with in-pit mapping data to aid in determining endwall stability: a case study from an operating coal mine in Australia

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ABSTRACT: Multiple sources of geotechnical data are collected throughout the life of a mine, during exploration and operational stages. Understanding and utilising this data is pivotal to maximise operational efficiency, productivity and safety. Photogrammetric data of an endwall experiencing multiple small-scale failures identified three joint sets. Acoustic scanner data from exploration drill holes (prior to mining) were manually interpreted by geologists experienced in acoustic scanner interpretation to determine high-confidence bedding and joint sets. Comparisons between acoustic scanner data and in-pit photogrammetry found one joint set oriented subparallel to a bedding-related set causing wedge failures. Other joint sets were identified in drill holes in advance of mining. Plotting joint set occurrence relative to structure enabled geologists to define domains of similar joint patterns and characteristics that aligned with regional structural fabric. These domains assisted mine planning with orientations of pit design and optimised coal recovery to avoid sterilisation due to wall failures.

1 INTRODUCTION

1.1 *Background*

In 2014 at an open-cut coal mine in Australia, multiple small-scale failures were identified along the western endwall of the main pit. Consequently, a 15 m wide catch bench was added to the haul road under the endwall, sterilising approximately 1 million tonnes of reserves. Investigations by the site geotechnical engineer and senior mine geologist identified a joint set (D) that was subparallel to the strike of the endwall, but with a shallower dip. This joint set was causing small wedge failures and appeared to be related to a thrust fault located west of the endwall.

In 2015, McElroy Bryan Geological Services (MBGS) and ASIMS were commissioned to review drill hole acoustic scanner data to determine the orientation and lateral extent of joint set D in areas of future mining, particularly where the orientations of mining direction and the thrust fault change (Henwood & Pell 2016) The study identified four conjugate joints sets and established ten joint domains based on the occurrence and characteristics of the various joint sets. The study area was expanded in 2019/ 2020 to cover the remaining mining footprint and included recent acoustic scanner data, which provided more detail in the south of the area.

Both the 2015 and 2019/ 2020 studies identified additional joint sets in future mining areas which were not observed in current operations. The same joint sets identified in 2015 were correlated across the study area with the additional acoustic scanner data,

and a total of 22 joint domains were described. Understanding the interaction of these joint set domains will safeguard future mine planning so that further seam sterilisation can be avoided (Hanson et al. 2015).

1.2 *Geology*

Structural geology at the mine site is complex with multiple synclines, anticlines, major thrust faults and dykes traversing the area (Fig. 1). Seams have been subjected to numerous post-depositional tectonic phases of deformation, with structural complexity decreasing from north to south.

Along the western edge of the current mining operation is Thrust B, a major northeast dipping thrust fault that extends several kilometers north of the mine site. Faulting identified in acoustic scanner logs, and associated with Thrust B, accommodate displacement at depth. The hanging wall of Thrust B creates an antiform (Anticline A) at surface and a monocline dipping west-southwest with small scale. Localised thrust faults (typically <2 m displacement) extend southeast into the study area.

Future mining will advance to the south passing through Thrust B into the foot wall of the fault block and into a synform created by the thrusting (Syncline A). Thrust B and Syncline A trend southeast through the north of the project area, turn east-southeast in the central portion before rotating south in the southern portion of the project area.

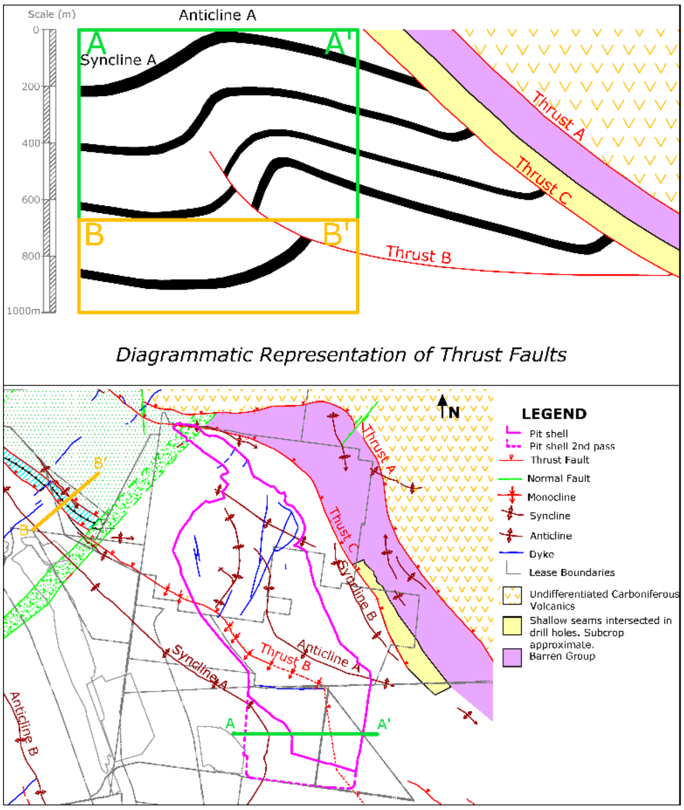

Figure 1. Project area geology and geological section

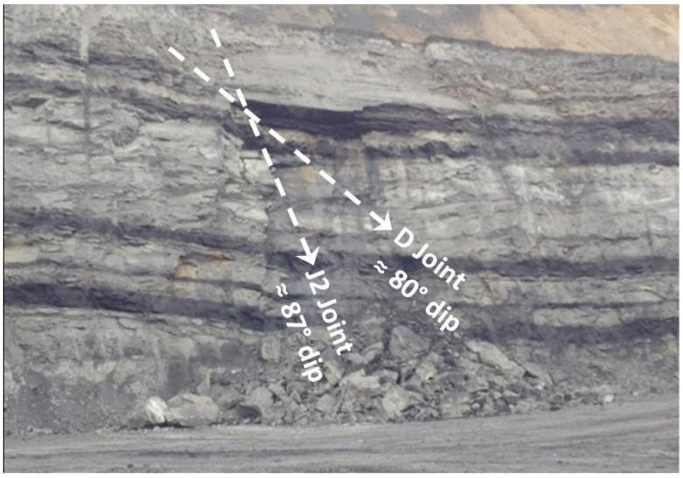

Figure 2. Endwall with wedge failure

2 DATA

2.1 *In-pit mapping and scanning*

Site geotechnical engineers and mine geologists routinely map structural features including joints, bedding and faults on exposed highwalls and endwalls using photogrammetry and laser scanning. Older data was collected using an in-pit laser scanner with fixed locations to scan larger sections of the exposed pit walls. More recently, site has moved to using drone-acquired data to reduce bias caused by increased distance and observation angle of the wall as it moves away from the fixed scanner position. All data is manually interpreted by site senior geotechnical engineers.

Investigations during 2014 by site personnel identified the cause of endwall instability as the intersection of three joints: J1, J2 (conjugate and orthogonal to bedding) and D joints (subparallel strike to J2, but with a shallower dip). The interaction of these joint sets caused small wedge failures, particularly where sets D and J2 strike subparallel to endwall orientation (Fig. 2).

2.2 *The acoustic scanner*

The acoustic scanner is a geophysical downhole logging tool that generates a high-resolution unwrapped 360° image of the drill hole wall by transmitting ultrasonic pulses and recording the reflected signal. The amplitude and travel time of the reflected signal are a function of rock properties of the wall and the nature of geological discontinuities, such as bedding, joints and fault planes that are intersected in the drill hole. The acoustic scanner tool provides an accurate and cost-effective means of determining the orientation of such geological features and has the advantage over oriented-core methods of being able to use in vertical holes. It is important to note:

- drill hole wall rugosity and water saturation of strata at the time of data collection can have a significant impact on acoustic scanner image quality (the acoustic scanner tool only performs in fluid-filled holes).
- the absence of a joint in the acoustic scanner image does not necessarily indicate the joint is not present in the strata (Rees & Graff 2013).
- vertical bias: drill hole orientation and deviation due to dipping strata may result in joints of certain orientations (e.g. subparallel to the trajectory of the drill hole) not being intersected (Fowler 2013).

Acoustic scanner data was analysed from approximately 130 drill holes, drilled between 2002 and 2018, including eight drill holes located in a neighbouring underground mine.

3 METHODOLOGY

3.1 *The ASIMS method*

ASIMS was established as a subsidiary of MBGS over 20 years ago and has developed specific methods for interpreting acoustic scanner logs and analysing the resulting data on projects within Australia and around the world (Pell et al. 2014).

ASIMS uses manual interpretation techniques to identify defects in the acoustic scanner image. This method is preferable to the more recently available automated method, where a computer-generated interpretation of the scanner data is supplied. Comparison studies conducted by ASIMS across several projects have compared both manual and automated interpretation results to core photographs and geotechnical logs. Automated software may appear to save time but various results from automated interpretations prove to be highly inaccurate (Rees & Graaf 2013). Automated methods produce excessive subhorizontal features, where crossbedding or laminae are often mistaken as bedding and bedding defects are often incorrectly classified as joints. More importantly, automated interpretations miss critical defects such as moderately to steeply dipping joints, faults, and true depositional bedding (Thomas et al. 2015).

Incorporating inaccurate orientation data with mine planning and design can ultimately be expensive, time consuming to resolve, and potentially hazardous to the mine. This issue is further accentuated in greenfields exploration prior to the start of excavation, where there are no in-pit or underground joint surveys to reconcile with the acoustic scanner interpretation. Validation can only be achieved once operations commence and as mining progresses.

An ASIMS manual interpretation is conducted by a senior geologist experienced with acoustic scanner data, identifying only high confidence defects in the scanner log, where each defect is classified according to specific attributes displayed on the image. In cored sections (Fig. 3), core photographs and geotechnical logs are referenced to assist in validating interpreted defects, in a method known as integrated interpretation (Gwynn et al. 2013). Classification groups include depositional bedding, joints (open, closed/ infilled or discontinuous), caved/ crushed zones and faults. Siderite bands and crossbedding are also identified when they are clearly visible on the scanner image. Gamma and short spaced density geophysical logs are referenced to identify bedding and siderite bands.

Geotechnical sets are defined for each classification group. The manually interpreted defect data are presented on equal angle, lower hemisphere stereonet pole plots and analysed based on the concentration and distribution of data point clusters. Statistics of each geotechnical set are provided, including the range and average orientation (dip/ dip direction/ strike).

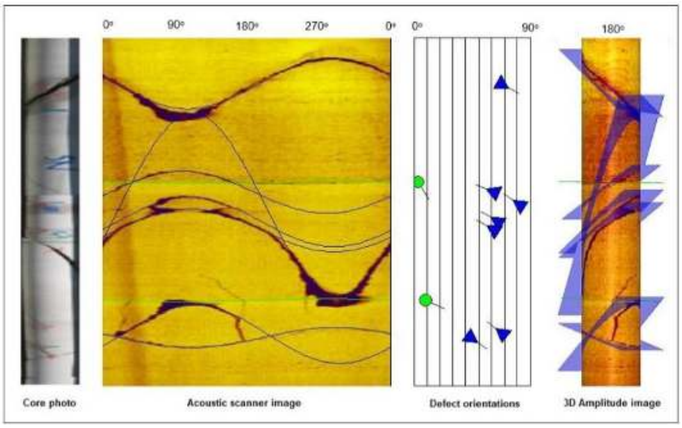

Figure 3. Example of an integrated interpretation

An integrated interpretation proved beneficial for this project to obtain robust joint, fault and depositional bedding interpretations that resulted in the definition of multiple joint sets. Automated software may have missed the moderate to steeply dipping D joint set that was causing rock mass failures at this deposit. Validating and collaborating the interpreted data with the in-pit mapping data generated confidence in the results (Rees & Graaf 2013).

3.2 *Interpretation of acoustic scanner logs*

Previously interpreted acoustic scanner logs were reviewed so that only prominent joints, depositional bedding and faults were reported. Less prominent features were removed to reduce noise; the joint sets of interest occurred predominantly within interburden strata, so joints within coal seams were also disregarded. Bedding interpretation (the strike of which is variable throughout the deposit) assisted identification of joint sets J1 and J2 and the differentiation of joint set D. All bedding and joint defects were presented as poles on equal angle, lower hemisphere, stereonet plots for the total depth and at depth increments of 100 m for each drill hole (Fig. 4). These plots were analysed to determine depositional bedding sets and joint sets within each hole.

In faulted zones (identified in acoustic scanner data, core logging and in-pit mapping), bedding often formed two distinct sets, one above the fault and one below, where strata on one side of the fault plane rotated relative to the other. The rotation observed in bedding sets also caused rotation in joint sets. Bedding rotation was used to identify joint sets that had rotated with movement along the fault and may present as different joint sets within each drill hole. Approximately 50% of drill holes that exhibit two bedding sets do not appear to be faulted. These secondary bedding features are interspersed at irregular depths throughout the hole with horizons of the main bedding set and have been interpreted as a sedimentary

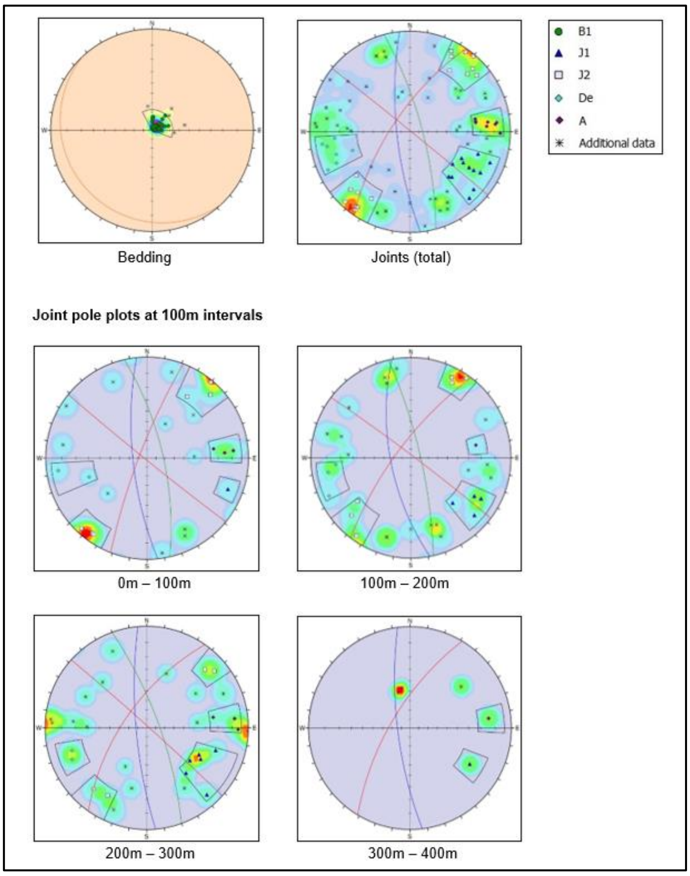

Figure 4. Stereonets showing bedding and joint sets in a drill hole and the rotation of joint sets with depth

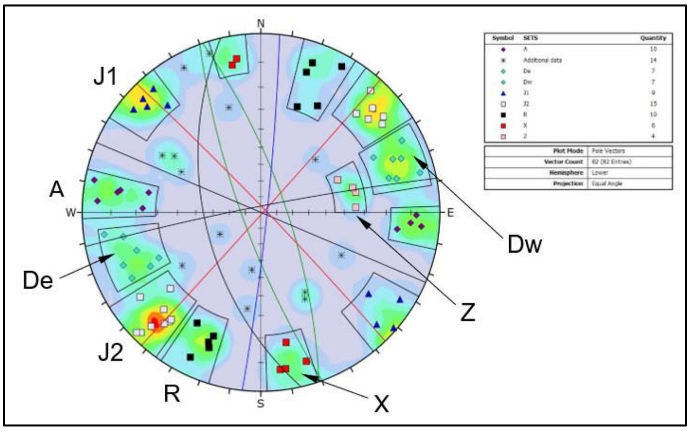

Figure 5. Stereonet illustrating typical joint set orientations (with strike)

(rather than primary depositional) feature. A review of core photographs for holes which exhibit these scattered secondary bedding sets indicate they may be associated with erosional contacts. In these instances, the second bedding set has not been considered when interpreting joint sets as it is not believed to have influenced jointing.

A baseline study provided a benchmark of the main joint set axes by analysing acoustic scanner data from approximately 20 holes within the mined area that were corroborated in-pit by site personnel using photogrammetry data. Once established, the benchmark was used to analyse and correlate holes to the south in advance of mining, identifying trends and relationships between bedding and joint sets, both laterally and with depth.

4 FINDINGS

4.1 *Joint sets*

Dominant joint sets (Fig. 5) identified within current workings and in future mining areas were assigned identification codes (as listed) to correlate throughout the deposit.

- J1 and J2: a primary pair of southeast and northeast steeply dipping sets, often orthogonal, that are generally perpendicular to bedding (formed prior to deformation). J1 and J2 rotate significantly through the project area with the folding and faulting of strata, particularly within strata associated with Syncline A. There is very high correlation between in-pit photogrammetry and acoustic scanner data for both joint sets.

- D: likely associated with east-west compression and sometimes difficult to differentiate from J2 joints, particularly in strata associated with Thrust B. D joints develop where structure rotates south along the western limb of Anticline A, in strata folded by Syncline A and either side of Thrust B. D joints are likely reactivated J2 joints that are separated into De and Dw to differentiate between the east and west moderately dipping sets.

- R: typically dip steeply to the north-northeast and are occasionally difficult to distinguish from J2 joints, particularly where Thrust B rotates south. R joints develop throughout most of the study area, may be reactivated J2 joints associated with north-south compression that produced the syncline in the south.

- A: primarily steeply dipping east and strike parallel to Thrust B as it rotates south. A joints are often orthogonal to X joints and may be associated with late stage north-south compression that folded Anticline A into a dome. Occasionally closely aligned to J1, A joints may be reactivated surfaces of J1 joints.

- X: dip steeply north, display the least rotation across the area and are closely aligned with R joints. X joints occur in strata associated with

Thrust B and may be associated with late-stage compression.

- Z: infrequently occurring and shallow dipping to the southwest in strata east of Thrust B. Z joints rotate significantly with bedding, are closely aligned with J2 and Dw joints, and likely developed in conjunction with early-stage deformation.

J1 and J2 joints are associated with primary depositional bedding, rotate in conjunction with bedding in deformed strata and therefore predate the deformation events. This relationship between bedding and joint orientation persists throughout the area.

The onset of regional and localised deformation reactivated J2 joints where they often merge with D joints, and to a lesser extend R, primarily in association with faulted strata that has rotated south with Thrust B. Merged joint sets tend to exacerbate joint dip angles causing them to shallow significantly, particularly in strata west of Thrust B.

The D joint set is of most significance in relation to the failures occurring along the western endwall first identified in 2014. Small wedge failures occurred where D joints strike subparallel to, and slightly shallower than the endwall.

The R and A joint sets, first identified in acoustic scanner data in then-unmined areas during the 2015 study, have now been observed in-pit as the mining footprint has expanded. X joints, first identified in the 2019/ 2020 study, have been recognised in future mining areas.

As with D joints, the orientations of R, A and X joint sets relative to mining faces, have the potential to form rock mass instability and should be considered for medium- to long-term planning and optimum pit design.

4.2 *Joint Domains*

Following acoustic scanner interpretation and review, the project area was divided into domains based on similar joint orientations and characteristics. Ten domains were defined in the 2015 study and a further twelve were added in 2019/ 2020 using the additional data (Fig. 6). Several domains with similar bedding and joint set characteristics occur in comparable structural settings across the deposit.

Large volumes of data have been incorporated into the domain plan that ultimately serves to clarify joint set patterns across the deposit. The domains highlight benign areas and emphasise those of potential instability, depending on azimuth angles with relation to mining faces.

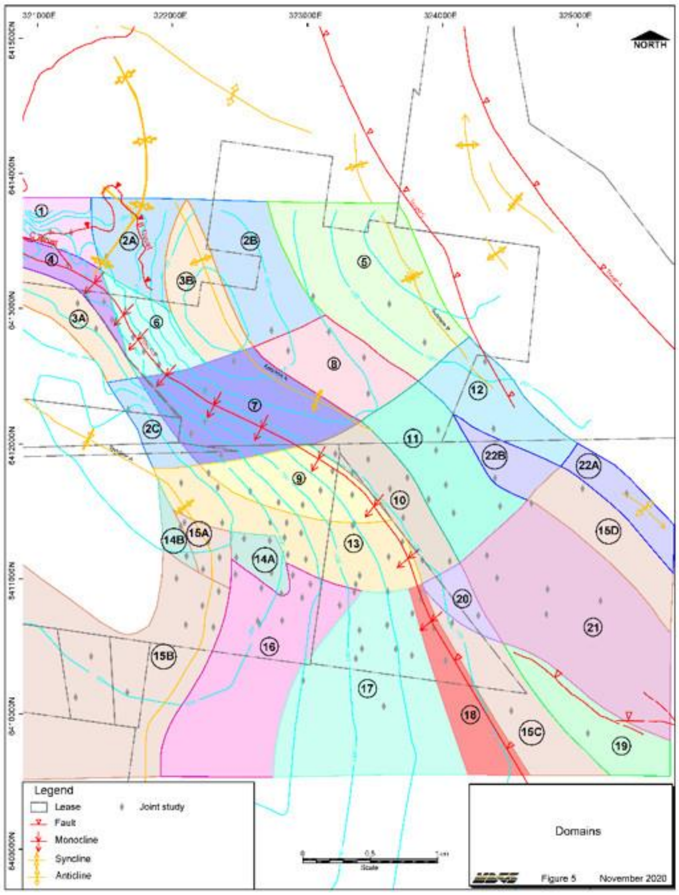

Figure 6. Joint domains identified using acoustic scanner results (note colour shading is used for the sole purpose in this paper to highlight domain boundaries)

- Domain 1: Faulting is common, J1 is weakly developed and orthogonal to J2. R and Z are present and converge closely with J2. X and R have merged to X+R (only in Domain 1).
- Domain 2: Occurs at several locations, J1 is weakly developed, and R and Z are present.
- Domain 3: Occurring at several locations, J2 and R are present, often merging to J2+R.
- Domain 4: Faulting is common, J1 and J2 are present and orthogonal. De, Dw, A, R, X and Z are present, J2 and R often merge to J2+R.
- Domain 5: J1, J2, A, R and X are present, J2 and R often merge to J2+R.
- Domain 6: Faulting is common. J2, De, Dw, A, R and X are present, J2 and Dw often merge to J2+Dw.
- Domain 7: Faulting is present. J1, J2, De, Dw, A, R, X and Z are present.
- Domain 8: J1, J2, De, A, R, X and Z are present.
- Domain 9: Faulting is present. J1 is weakly developed and orthogonal to J2. De, Dw, A, R, X, and Z are present, J2 often merges with R to J2+R.
- Domain 10: J1, J2, De, Dw, A, R, X and Z are present. J2 and De often merge to J2+De.

- Domain 11: Faulting is common. J1 and J2 are present and orthogonal. De, Dw, A, R, X and Z are present. J2 and De often merge to J2+De.
- Domain 12: J1, J2, A and X are present.
- Domain 13: J1, J2, De, Dw, A, R and X are present. J2 and De frequently merge to J2+De.
- Domain 14: Occurs at several locations, faulting is common. J1, J2, De, Dw, A, R and X are present. J2 and De often merge to J2+De.
- Domain 15: Occurs at several locations, J1 and J2 are present and orthogonal. De, Dw, A, R and X are present.
- Domain 16: J1 and J2 are present and orthogonal. De, Dw, A, R and X are present, J2 and De/Dw often merge to J2+De and J2+Dw.
- Domain 17: Faulting is common. J1 and J2 are present and orthogonal. De, Dw, A, R, X and Z are present. J2 and De often merge to J2+De.
- Domain 18: J1, J2, De, Dw, A, R and X are present.
- Domain 19: J1, J2, Dw and X are present.
- Domain 20: J1, De, R and X are present.
- Domain 21: Faulting is present. J1, J2, De, Dw, A, R and X are present. J2 and De often merge to J2+De.
- Domain 22: Occurs at several locations, faulting is common. J1, J2, De, Dw and A are present. J2 and De/Dw have merged to J2+De and J2+Dw.

5 APPLICATIONS OF INTERPRETED JOINT SETS AND DOMAINS

Several outcomes were achieved in this case study:

- Acoustic scanner data was incorporated with available site data to assist with re-designing the endwall and improving pit stability.
- Following the 2015 study, approximately 100,000 tonnes of the sterilised one million tonnes of reserves were recovered. Recovery from a neighbouring underground mine was also improved from this study.
- Design of the pit was optimised for future mining through improved geotechnical planning and design, aided by results of the joint sets and joint domains.
- Thrust B was defined with greater accuracy through interpretation of exploration data.
- New joint sets identified in unmined areas from acoustic scanner interpretations from this study have now been observed in-pit as the pit has advanced.
- Resources can be focused on potential areas of concern for rock mass instability.

6 CONCLUSIONS

Multiple joint sets present in current mining areas were identified in the acoustic scanner interpretation and reconciled with in-pit mapping data. Validation of the acoustic scanner interpretation increased confidence in the data and the joint sets identified in-pit were correlated throughout unmined areas. Consequently, additional joint sets identified ahead of mining (but not present in current mining areas) could be confidently identified. This favoured collaboration of exploration and operational data was possible because of the collection of acoustic scanner data and core photographs throughout past exploration, and on-going collection of photogrammetric data by the mine site. This work has assisted pit design to minimise wall failures and reduce further sterilisation of reserves.

The manual method of acoustic scanner interpretation recommended by ASIMS, proved highly valuable in this case study. Automated software may not have achieved the same results. The acoustic scanner data consistently corroborated with in-pit data identifying depositional bedding and persistent joint sets, resulting in a high level of confidence in the interpretation throughout the unmined sections of the deposit, particularly in those areas that have been structurally deformed by faulting and/ or folding.

Understanding how these joint sets interact with mining faces will safeguard future mine development so that seam sterilisation can be avoided and adds significant value to geotechnical applications for mine planning.

7 REFERENCES

Gwynn, X.P., Brown, M.C. & Mohr, P.J. 2013. Combined use of traditional core logging and televiewer imaging for practical geotechnical data collection. *International Symposium on Slope Stability in Open Pit Mining and Civil Engineering*. Brisbane, Australia 25–27 September 2013:1-13.

Fowler, M.J. 2013. Structural data bias in the digital age. *Proceedings of the 2013 International Symposium on Slope Stability in Open Pit Mining and Civil Engineering*. Australian Centre for Geomechanics, Perth: 29-226.

Hanson, C., Thomas, D. & Gallagher, B. (2005). The value of early geotechnical assessment in mine planning. *Proceedings of the 2005 Coal Operators' Conference*. University of Wollongong.

Henwood, R. & Pell, S. 2016. Application of acoustic scanner data in determining end wall stability. *Proceedings of the 2016 Sydney Basin Symposium.* Pokolbin.

Pell, S., Seedsman, R. & Straub, K. (2014). Geotechnical data from geophysical logs: stress, strength and joint patterns in NSW and QLD coalfields. *Proceedings of the 2014 Coal Operators' Conference*. University of Wollongong.

Rees, K.M. & Graff, J. 2013. Structural geology modelling: a summary on data integrity and modelling methods. *Proceedings of the 2013 International Symposium on Slope Stability in Open Pit Mining and Civil Engineering*. Australian Centre for Geomechanics, Perth: 315-323.

Thomas, R.D.H., Neilson, J.M., Wilson, H. F. & Lamb, P. 2015. Structural interpretation from televiewer surveys. *Proceedings of the Ninth Symposium on Field Measurements in Geomechanics.* Australian Centre for Geomechanics, Perth: 729-741.